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RESEARCH ARTICLE

Influence of cities population size on their energy consumption and CO_2 emissions: the case of Spain

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Abstract

Half of the world population live in the cities. Cities energy consumption, environmental impact, and the opportunities they provide for our planet's sustainability make them attractive for governmental authorities. Any action taken in the cities has immediate repercussions. For this reason, many statistical data are published every year. This paper makes the best use of these data to calculate cities CO_2 emissions and their thermal and electric energy consumption. The methodology applied takes into consideration each city size by number of inhabitants and gets results per inhabitant and household. This will make possible to put into practice the right actions to reduce CO_2 emissions and to use alternative energy. This paper also defines an index to facilitate and simplify the analysis of results. This study was applied to the case of Spain to show the methodology here proposed. In fact, this type of study has never been carried out in Spain before. With this purpose, the 145 Spanish cities with more than 50,000 people were considered. Results show that cities with larger populations present higher consumptions per inhabitant and household. The smallest the population of a city is, the less energy the city consumes. However, electric energy consumption remains constant regardless of the population size. With regard to the CO2 emissions, results bring to light that the biggest cities produce the highest emissions. Furthermore, comparing emissions produced by electrical sources to the total emissions, it was concluded that the smallest cities produce the highest electrical emissions.

Keywords Population size · CO_2 emissions · Energy consumption · Cities · Buildings · Spain

Introduction

In 2007, the world had more than 6600 million people. From then on, more than a half of this population live in the cities. Prospects estimate that this percentage will reach 60% in 2030. Even more people live in specific areas, such as Oceania, North America, or the Caribbean. And in Europe, the number of urban residents reaches 70% at the moment. This percentage will turn into 84% in 2050. In addition, 70% of the world emissions from coal are produced in the cities, where 9 out of 10 urban residents breathe polluted air. Cities consume 60% of resources (Department of Economic and Social Affairs 2015). In Europe, this strong demographic increase of cities entails that almost 80% of the energy is consumed in them (Committed to local sustainable energy 2019). Therefore, buildings are key elements due to their energy use and CO_2 emissions. For this reason, this study focuses on cities. Buildings' energy consumption is electric and thermal (natural gas) (Shahrokni et al. 2014).

Energy consumption, environmental impact, and opportunities for our planet's sustainability are the main elements that make cities so attractive for governmental authorities. Actions taken in the cities bring quick results. The Sustainable Development Goal 11 of the United Nations (Fig. 1) (United Nations Educational 2019) refers to the cities: make cities and human settlements inclusive, safe, resilient, and sustainable. Two of its objectives are the following: by 2020, substantially increase the number of cities and human settlement adopting and implementing integrated policies and plans toward inclusion, resource efficiency, mitigation, and adaptation to climate change and, by 2030, reduce the adverse per capita environmental impact of cities (Department of Economic and Social

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Fig. 1 Sustainable Development Goals (United Nations Educational 2019)

Affairs 2016). And cities are involved in other goals, such as the following: Goal 7, with the use of renewable energies that ensures access to energy for everyone; Goal 12, with a sustainable and responsible consumption; and Goal 13, with a reduction of CO_2 emissions.

The European Union launched the Covenant of Mayors in 2008 after the adoption of the 2020 European Union Climate and Energy Package. The Covenant of Mayors changed its name in 2015 into Climate & Energy after the addition of the goals set for 2030. This was agreed by 53 different countries from around the world (not only from Europe). It involved almost 8000 cities and had an impact on more than 250 million people. Covenant signatories commit to adopting an integrated approach to climate change mitigation and adaptation. The objectives are to reduce CO_2 emissions by at least 40% by 2030 and to increase resilience to climate change (Covenant of Mayors for Climate and Energy 2019).

It is well-known that cities are one of the main key points for mitigating climate change and reducing greenhouse gases. However, studies carried out to date base on developing formulas to forecast energy consumption; analyzing the factors that have a major (or minor) influence on consumption; and analyzing the factors that affect the most the CO_2 emissions production. The scope of these studies is a whole country or a huge area, although they do not focus on cities as very important cores. Unlike these existing studies, this paper centers on cities as cores that consume energy (in their buildings) and produce CO2 as derivative wastes. Moreover, this paper focuses on each city in particular, since their consumption and emissions can vary depending on the size of their population. Lastly, this methodology will be used for the case of Spain, considering all Spanish cities with populations greater than 50,000 people. To the best of these authors' knowledge, a similar study to this one has never been done before: analyzing cities energy consumption and their buildings emissions considering the size of their population and analyzing each and every city of a country separately and Spain in particular. Only a recent study analyzes how cities energy consumption and CO2 emissions are related to their climate (Zarco-Soto et al. 2020).

Therefore, cities are so important. And so are buildings, since they are CO2 producers and energy consumers. For this reason, this paper focuses on analyzing cities and investigating the impact that their size has on them. Note that the word size used in this paper will refer from now on to the population size, or in other words, to the number of inhabitants. The information used in this paper is public. Consequently, it was not necessary to invest economical resources or conduct specialized surveys according to the data here needed. A large amount of information is published in this regard. However, this information needed to be handled so as to get results regarding energy consumption and CO_2 emissions. The methodology here used is similar to the one of those studies that intend to expose the relation between different variables and to get values, rather than developing prediction formulas (Zarco-Soto et al. 2020; Urquizo et al. 2017; Hekkenberg et al. 2009). In the case of this paper, this research addresses the dependence of cities population size on other variables. This study's findings will allow governments and administrations for taking actions to promote energy saving and efficiency. It will allow companies as well for investing in renewable energy, which helps reducing CO_2 emissions. And consequently, it will help to achieve the sustainable development goals. Nevertheless, it is crucial to identify the starting point to achieve these aims.

In summary, this article shows a methodology similar to that applied in other types of studies but adapted to the analysis of the influence that the size of the city has on energy consumption and CO2 emissions. It is applicable to any geographical area and can be as large or as small as desired. The analysis is made for each city based on its size. With the vision provided by the results obtained, conclusions can be drawn on how to act in the future with regard to the energy needs of cities and the mitigation of CO2 emissions. In particular, and as an example, the case of the application of the methodology to all Spanish cities with more than 50,000 inhabitants is shown, obtaining a series of conclusions with the results obtained. And based on the sample used, it can be expected that the results obtained will be valid when considering other geographical areas. To the knowledge of the authors, this type of study, and with this specific scope, has not been carried out previously.

This paper is structured as follows: the "Literature review" section presents studies that relate cities size to their energy consumption and CO_2 emissions; the "Methodology" section describes the proposed methodology, which can be applied to any country or region using the available public information; the "Application of this study to the case of Spain" section details the way that the proposed methodology is applied for the case of Spain; the "Results and discussion" section presents findings and proceeds with their discussion; and lastly, the "Conclusions" section explains conclusions of this study.

Literature review

This study analyzes electric and thermal (natural gas) consumption and CO_2 emissions considering cities sizes. Taking this into account, the following literature review will address these three mentioned contents block. Later, this study is applied to the case of Spain, reason why the literature related to this country is as well reviewed at the end of this section. There is not much literature about this subject. Therefore, literature corresponding to the next level (not only in terms of cities) will also be reviewed.

Most existing studies regarding energy consumption base on developing consumption forecasts. They take into consideration different variables that may affect consumption, such as population. They always analyze it in a global way and not in terms of a city.

In general terms, Wang et al. (2019) review all studies that assess urban energy performance. It makes an exhaustive study of published works and brings to light the rising interest this topic has in the whole world. The number of published papers went from 9 in 2007 to 82 in 2017. Even so, the mentioned paper points out that the number of studies is small. It includes energy performance studies with different geographical scopes: from a whole country to just one building. It also presents different points of view, such as the welfare that comes along with energy or safe energy supply.

Regarding electric energy consumption in national terms, most studies that relate electric energy use to population are about Turkey. Kankal et al. (2011) make consumption forecasts using the following variables: gross domestic product (GDP), population, employment, importation, and exportations. Moreover, its literature review section presents two tables that summarize the studies to date about energy forecasts in terms of country. One of the tables refers just to Turkey and the other one to the rest of countries. These tables present the type of energy forecasted, as well as the methodology and variables used to make calculations. Forecasts using population as a variable were made on the following countries: Taiwan, Italy, South Korea, and New Zealand. From that date on, more studies considering population as a variable were carried out to estimate energy consumption. Continuing with studies about Turkey, Günay (2016) makes use of six variables for its model. Population and GDP per capita are the variables that had a major impact. Aydin (2014) forecasts primary energy in Turkey based on linear regressions. It uses population and GDP. It makes an energy consumption prediction for 2025.

Regarding other countries, Bianco et al. (2013) estimate the electric energy consumption in Italy using GDP, GDP per capita, and historical electricity consumption as variables. It uses a simpler regression analysis and it leads to quite good estimations. For the case of Pakistan, Zaman et al. (2012) analyze the impact of population growth, GDP per capita growth, and foreign investments on electricity use. Population growth is the variable that has a major impact on electricity consumption growth.

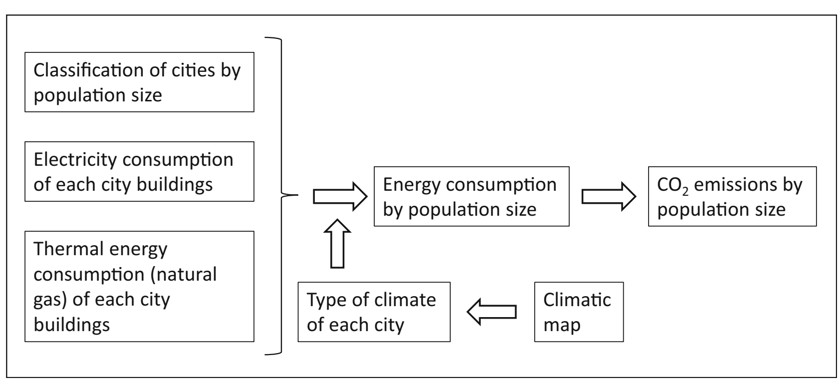
In terms of no national electricity consumption forecasts, Hor et al. (2005) focus on England and Wales and base on weather variables, GDP, and population growth. They use different models and changes in the weather variables are considered. In terms of city, Wangpattarapong et al. (2008) analyze the factors that affect residential electric consumption in Bangkok Metropolis. They base on climatology, income, number of houses, and shipment of air-conditioner. And Ranjan and Jain (1999) get four equations to model electricity consumption in Delhi for different seasons.

The same as electricity consumption, studies about thermal energy consumption focus on getting formulas to forecast consumption. These studies address a country. And they have in common GDP in addition to population. Bianco et al. (2014) make consumption estimates in the Italian residential sector based on population, GDP per capita, heating degree-days, and gas price. Wadud et al. (2011) forecast the national energy consumption in Bangladesh based on the price of natural gas, population, and GDP. Consumption estimates in China are made by Li et al. (2011) based on population, GDP, and investment in the natural gas sector. Azadeh et al. (2011) forecast consumptions in Bahrain, Saudi Arabia, Syria, and the United Arab Emirates. They use population and GDP as variables. Behrouznia et al. (2010) make use of the same variables but focus on Argentina, Brazil, Colombia, Venezuela, and Cuba. Sarak and Satman (2003) based on population, degree-days, and natural gas pipelines (the already existing pipelines and the ones planned) to analyze the residential natural gas consumption in Turkey. Zhang (2004) makes a comparison between total energy consumption of the residential sector in China, Japan, Canada, and the USA. It bases on the relation between consumption per household and heating degree-days. The greatest consumption is observed in Japan, followed by the USA, Canada, and China in the last place. In terms of city, Szoplik (2015) reviews natural gas consumption of Szczecin (Poland) considering the following factors: temperature and calendar.

With regard to CO_2 emissions, most studies analyze how different factors impact them. Population is included among which. Unlike electricity and natural gas, only a few studies forecast emissions (Pao et al. 2012). As an exception, some studies analyze in detail the emissions produced by a city. Feng and Zhang (2012) is an example of it. This paper centers on Beijing and takes into consideration different situations to forecast energy consumption and CO_2 emissions.

Many countries have analyzed the variables that have an impact on the CO_2 emissions. For all of them, the scope was diverse. And it did not only include the emissions related to natural gas. Population is one of the variables they used the most. In all cases, it is observed that population has a huge and important impact on emissions, regardless of the country of study. Wen and Shao (2019) analyze how the following factors impact CO_2 emissions in the Chinese commercial sector: population, urbanization (urban population divided by total population), economic growth, foreign direct investment, energy structure, and energy intensity. Lin and Ahmad (2017) study CO_2 emissions in Pakistan considering population and GDP. Solarin and Lean (2016) evaluate the impact of urbanization, GDP, and natural gas consumption on the CO_2 emissions of India and China. Wang et al. (2016a) examine the countries that are part of the Association of Southeast Asian Nations (ASEAN). Laos and Cambodia are not included though, due to the lack of data for the time period considered. In other words, the countries of study are Singapore, Malaysia, Indonesia, Thailand, the Philippines, Brunei, Vietnam, and Myanmar. This study analyzes the effect of urbanization and energy use on carbon emissions. For the case of Ghana, Asumadu-Sarkodie and Owusu (2016) focus on the relation between population growth, GDP, energy use, and CO_2 emissions. Wang et al. (2016b) evaluate the relation between urbanization and CO_2 emissions for the BRICS countries (Brazil, Russia, India, China, and South Africa). Alam et al. (2016) analyze the impact that population growth, energy consumption, and income have on CO_2 emissions in Brazil, China, India, and Indonesia. Unlike in the previous studies described, in this one the effect of population is only observed in Brazil and India, but not in China and Indonesia. The same happens in Brizga et al. (2013). It analyzes the impact of population, industrialization, carbon intensity, energy intensity, and energy mix on the CO_2 emissions in the former Soviet Union. However, it concludes that population changes barely affect emissions. This is also observed in Sohag et al. (2017). This study centers on analyzing the impact of energy consumption, population and economic growth, trade openness, and sectoral GDP on CO_2 emissions in 83 middle-income countries. Among its findings, population growth does not significantly impact these emissions. Ali et al. (2016) come to the same conclusion for Nigeria when

Fig. 2 Methodology flowchart



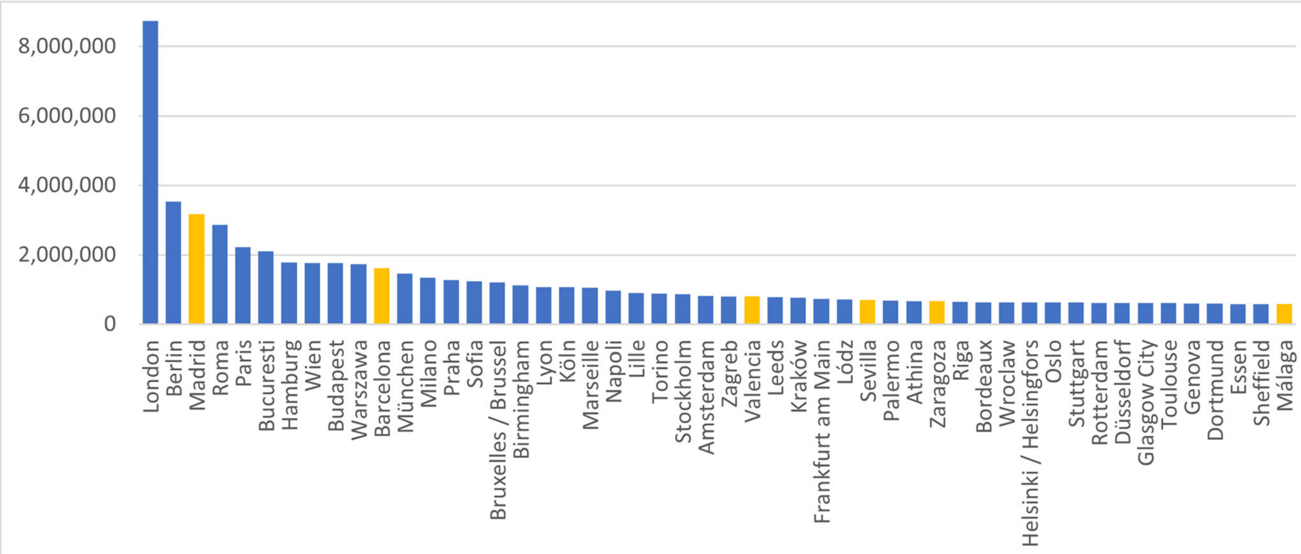


Fig. 3 Most populated cities in Europe

analyzing the effect of urbanization, economic growth, trade openness, and energy consumption on CO_2 emissions. It concludes that urbanization presents no meaningful impact on CO_2 emissions.

In terms of regions and not only of countries as in the studies mentioned before, Zhang and Lin (2012) analyze how urbanization affects CO_2 emissions and energy consumption in the different Chinese regions. They also analyze the differences between them. Wang et al. (2017) focus on the impact of seven factors on emissions in 30 Chinese regions. Population is one of these factors.

Additionally, in terms of city and referring not only to CO_2 emissions, but also to air pollution in general, Liu et al. (2018) analyze 83 cities in China. They take population size and seasonality into consideration. Results show that the bigger the population size is, the more pollution the city produces.

Table 1 Classification of Spanish cities by population size

Size	Cities
Group 1: from 50,000 to 125,000 people	Alcalá de Guadaíra, Alcobendas, Alcoy/Alcoi, Algeciras, Aranjuez, Arganda del Rey, Arona, Arrecife, Ávila, Avilés, Barakaldo, Benalmádena, Benidorm, Boadilla del Monte, Cáceres, Cádiz, Castelldefels, Cerdanyola del Vallès, Ceuta, Chiclana de la Frontera, Ciudad Real, Collado Villalba, Cornellà de Llobregat, Coslada, Cuenca, Ejido (El), Elda, Estepona, Ferrol, Fuengirola, Gandía, Getxo, Girona, Granollers, Guadalajara, Huesca, Irún, Jaén, Linares, Línea de la Concepción (La), Lorca, Lugo, Majadahonda, Manresa, Melilla, Mérida, Mijas, Molina de Segura, Mollet del Vallès, Motril, Orihuela, Ourense, Palencia, Paterna, Pinto, Ponferrada, Pontevedra, Pozuelo de Alarcón, Prat de Llobregat (El), Puerto de Santa María, Reus, Rivas-Vaciamadrid, Roquetas de Mar, Rozas de Madrid (Las), Rubí, Sagunto/Sagunt, San Bartolomé de Tirajana, San Fernando, San Sebastián de los Reyes, San Vicente del Raspeig, Sanlúcar de Barrameda, Sant Boi de Llobregat, Sant Cugat del Vallès, Santa Coloma de Gramenet, Santa Lucía de Tirajana, Santiago de Compostela, Segovia, Siero, Talavera de la Reina, Telde, Toledo, Torrelavega, Torremolinos, Torrent, Torrevieja, Utrera, Valdemoro, Vélez-Málaga, Viladecans, Vilanova i la Geltrú, Vila-Real, Zamora
Group 2: from 125,000 to 250,000 people	A Coruña, Albacete, Alcalá de Henares, Alcorcón, Almería, Badajoz, Badalona, Burgos, Cartagena, Castellón de la Plana, Dos Hermanas, Elche/Elx, Fuenlabrada, Getafe, Granada, Huelva, Jerez de la Frontera, Leganés, León, Lleida, Logroño, Marbella, Mataró, Móstoles, Oviedo, Pamplona/Iruña, Parla, Sabadell, Salamanca, San Cristóbal de la Laguna, San Sebastián/Donostia, Santa Cruz de Tenerife, Santander, Tarragona, Terrassa, Torrejón de Ardoz, Vitoria/Gasteiz
Group 3: from 250,000 to 500,000 people	Alicante/Alacant, Bilbao, Córdoba, Gijón, Las Palmas, L'Hospitalet de Llobregat, Murcia, Palma de Mallorca, Valladolid, Vigo
Group 4: from 500,000 to 1,000,000 people	Málaga, Seville, Valencia, Zaragoza
Group 5: more than 1,000,000 people	Barcelona, Madrid

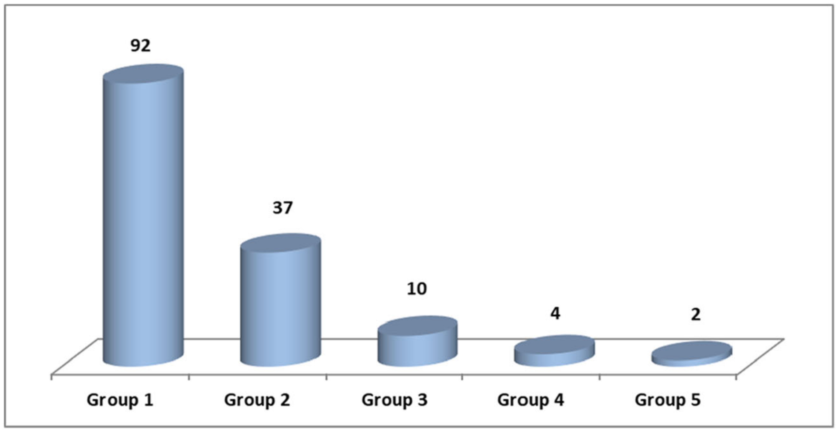


Fig. 4 Number of cities of each group

In Europe, Cárdenas-Rodríguez et al. (2016) evaluate air pollution in 249 cities according to urban structure. This study concludes that the most populated cities present higher pollution. In the USA, Fragkias et al. (2013) analyze 942 metropolitan areas considering the period from 1999 to 2008. The conclusion in this case is the same: the bigger an urban population is, the more CO_2 emissions. Makido et al. (2012) focus on 50 Japanese cities and conclude that the bigger a city is (in terms of population), the more CO_2 emissions per capita.

When reviewing studies about electric and thermal energy consumption and CO_2 emissions in Spanish cities, it is observed once again that there are hardly any. Once the existing ones are analyzed, it is noted that they focus on the whole nation. And as a variable they use the country's population instead of the population of each city in particular. Pérez-García and Moral-Carcedo (2016) forecast demand in Spain. To achieve this aim, it starts taking into consideration different key factors that have an impact on it. One of these factors is residential consumption, which is calculated based on population growth. Blázquez et al. (2013) analyze the factors that affect residential electricity demand considering provinces. Population, household size, degree-days, household income, and homes with gas access are some of these factors. Labandeira et al. (2006) estimate demand for energy from different energy sources. They also analyze the impact that changes in the prices of energetic products have on households depending on their location: rural, urban, or intermediate. Labandeira et al. (2004) make a similar study that includes a simulation of the effects of an energy tax on CO_2 emissions.

Regarding natural gas consumption in Spain, there is no specific study to the authors' knowledge, neither in terms of cities nor in terms of population.

Studies that relate Spain to CO_2 emissions are neither about cities nor population. Most of these studies do not exclusively focus on Spain, but they include this country as part of a larger geographical scope. Cansino et al. (2015) analyze different factors to establish their influence on CO_2 emissions. Population is one of these factors. It concludes that both economic activity and population growth are responsible for an increase of emissions. Chen et al. (2018) analyze the impact of six different factors on CO_2 emissions in the OECD (Organization for Economic Co-operation and Development). Spain is one of the OECD members. Population size is one of the analyzed factors. It is observed that the impact of population size is lower than the impact of energy intensity and GDP per capita. Dong et al. (2018) addresses 128 countries. Spain is among them. They focus on the connection between CO_2 emissions, economic growth,

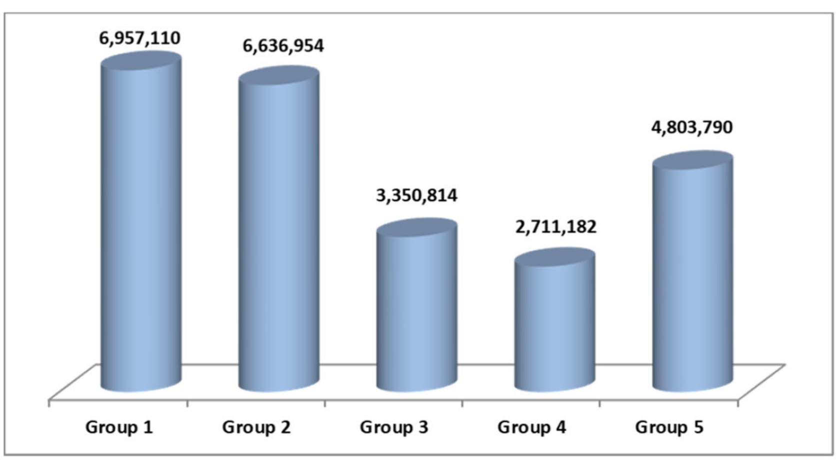


Fig. 5 Population of each group of cities

Table 2 Statistical data by population and household of the five defined groups of cities

	Population						Number of households					
Population size	Total	Mean	Std. dev.	Median	Maximum	Minimum	Total	Mean	Std. dev.	Median	Maximum	Minimum
Group 1	6,957,110	75,621	17,654	74,785	121,133	50,334	2,588,844	28,140	6739	27,976	45,559	15,434
Group 2	6,636,954	179,377	36,578	178,288	246,976	125,317	2,541,152	68,680	15,707	69,765	104,385	42,006
Group 3	3,350,814	335,081	59,460	327,952	443,243	257,349	1,283,517	128,352	17,663	127,111	154,421	97,044
Group 4	2,711,182	677,796	89,888	677,186	787,808	569,002	1,052,531	263,133	42,245	265,415	312,339	209,362
Group 5	4,803,790	2,401,895	1,104,622	2,401,895	3,182,981	1,620,809	1,928,425	964,213	421,534	964,213	1,262,282	666,143

Table 3 Statistical data of cities consumption by group of cities

	Total (MWh/year)						Thermal (MWh/year)		
Population size	Total	Mean	Std. dev.	Median	Maximum	Minimum	Total	Mean	Std. dev.
Group 1	27,404,178	297,871	107,709	286,756	664,016	140,786	8,549,523	92,930	80,299
Group 2	29,729,294	803,494	284,437	740,029	1,560,678	354,096	11,512,947	311,161	226,943
Group 3	12,952,786	1,295,279	312,517	1,201,674	1,822,658	898,790	3,725,669	372,567	332,690
Group 4	10,065,882	2,516,471	939,424	2,323,573	3,717,939	1,700,796	2,652,327	663,082	678,304
Group 5	26,156,830	13,078,415	7,526,515	13,078,415	18,400,465	7,756,365	12,417,911	6,208,955	3,904,657

	Thermal (MWh/year)			Electric (MWh/year)					
Population size	Median	Maximum	Minimum	Total	Mean	Std. dev.	Median	Maximum	Minimum
Group 1	69,761	323,698	0	18,854,655	204,942	50,307	197,277	340,318	120,861
Group 2	308,306	928,818	0	18,216,347	492,334	107,846	498,166	714,245	309,446
Group 3	252,449	1,089,772	1	9,227,117	922,712	268,655	840,360	1,368,528	635,937
Group 4	437,697	1,627,614	149,319	7,413,555	1,853,389	317,360	1,849,919	2,162,239	1,551,479
Group 5	6,208,955	8,969,965	3,447,946	13,738,919	6,869,460	3,621,858	6,869,460	9,430,500	4,308,420

population growth, and renewable energy growth. They conclude that population growth has a meaningful impact on emissions. Spain is also included in Sharma (2011). This study analyzes 69 countries to check the factors that impact their CO_2 emissions: urbanization, per capita GDP, trade openness, and energy consumption. Among other conclusions, urbanization and GDP per capita are two of the main factors responsible for an increase of emissions. Martínez-Zarzoso et al. (2007) establish how population growth affects CO_2 emissions of 23 European countries. It distinguishes between the 15 countries that joined the European Union before 2004 (Spain was one of them) and the other 8 that joined in 2004. Results show that population growth has a major impact on the new countries rather than on the old ones.

As observed, there is too little literature on the subject energy consumption and emissions considering cities population size, not to say hardly any. The existing literature focuses on forecasting national energy consumption or on analyzing the factors that mostly affect CO_2 emissions.

Methodology

The methodology here proposed calculates cities energy consumption using the official statistical data published by governments (population, households, thermal and electric energy consumption). Consumptions are calculated per inhabitant and household to analyze their performance taking into consideration the city they belong to. Using these results, CO_2 emissions can be also calculated per inhabitant and household. This way, it is possible to analyze cities performance depending on their population size. Moreover, this information is very useful to estimate each city need for renewable energy so as to mitigate their emissions. The same analysis can be carried out eliminating the impact of climate. This makes possible to analyze the effect of population size alone on energy consumption, eliminating the impact that weather conditions may have on both consumption and emissions. In order to clarify this concept, Fig. 2 presents a flowchart with the methodology to use. This methodology is similar to the one proposed by Zarco-Soto et al. (2020).

Classification of cities by population size

The first step is to select the cities case study to evaluate their energy consumption and emissions. Cities are ordered by size and they are grouped by number of inhabitants. Depending on the country or zone considered, cities with a specific number of inhabitants are taken into consideration. Cities are grouped based on the services they have, so that cities expected to present similar performances belong to the same group. Depending on the size, both commercial and administration services will be proportional to the number of inhabitants.

The main statistical data of electric, thermal, and total energy consumptions are presented for each size group:

Number of cities:

$$n_i = \sum_j 1 \tag{1}$$

Mean:

$$\overline{E}_i = \sum_j E_{ij} \tag{2}$$

Standard deviation:

$$s_i = \sqrt{\frac{\sum_{ij} \left(E_{ij} - \overline{E}_i\right)^2}{(n_i - 1)}} \tag{3}$$

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

$$\mathrm{Median}_i = \frac{\left(\frac{n_i}{2}\right)\text{th term} + \left(\frac{n_i}{2}+1\right)\text{th term}}{2} \tag{4}$$

Maximum:

$$E_{i\ max} = \max\left(E_{ij}\right) \tag{5}$$

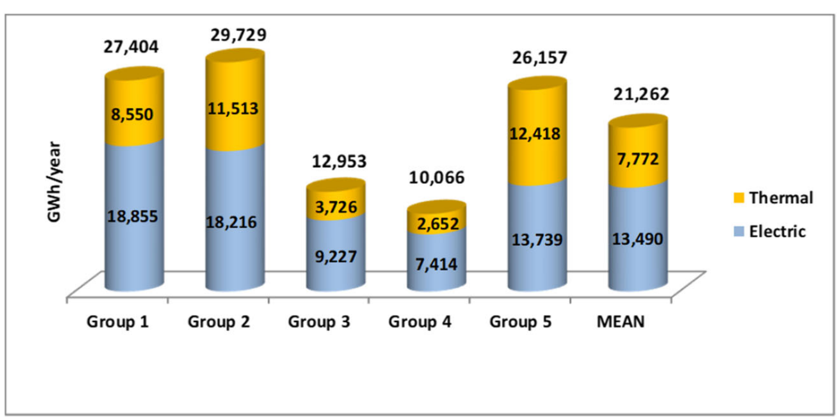


Fig. 6 Thermal, electric, and total mean energy consumption by group of cities

Minimum:

$$E_{i\ min} = \min\left(E_{ij}\right) \quad (6)$$

where n_i is the number of cities that belong to group i; $\overline{E}_i$ is the mean energy consumed in group i; E_{ij} is the energy consumption of city j, which is located in group i; s_i is the standard deviation of the energy consumed in the cities of group i; the energy consumed will be thermal, electric, or total depending on the case study; and cities consumptions should be listed in ascending order to calculate the median.

An index was defined to analyze the energy consumption variations of each group. This index is similar to the one defined in Valor et al. (2001) for monthly electric energy consumption and in Zarco-Soto et al. (2020) for energy consumption by climate. The aim of this index is to evaluate variations of consumptions of each group. The size variation index (*SVI*) is defined as follows:

$$SVI_i = \overline{E}_i/\overline{E} \quad (7)$$

where SVI_i is the index of the group of cities that have size i, $\overline{E}_i$ is the energy consumption mean value of group i, and $\overline{E}$ is the mean energy consumption of all cities (of all groups). This index makes possible to analyze performance of each cities group.

Thermal and electric energy consumption

To characterize this study, each city was considered as a core where people carry out their work and daily tasks every day. In addition to homes, cities have different services that are also necessary for people's lives, such as stores and administrative offices. There are more of these services or less depending on the city size. Energy uses related to cities industrial activity were not considered for this study. Otherwise, cities energy consumption could be distorted by their level of industrialization. Consumption of means of transport was neither considered. Consequently, the energy consumption taken into consideration for each city was the electricity and the thermal energy consumed by homes, stores, and administrative offices. These buildings and services are essential for the urban life. This energy is therefore the one consumed by citizens. If a city is bigger than another, it will have more stores and administrative offices than a smaller one. For this reason, this paper considered that the energy consumed by every household is the one properly consumed at home plus a proportional part of the energy consumed by stores and administrative offices. Although this last energy is indispensable to live in the city, citizens do not directly consume it for their personal use.

The available statistical information published by official organizations was used to calculate the thermal and electric energy consumptions per inhabitant and household of each

Table 4 Statistical data of household consumptions by group of cities

	Total (MWh/year)					Thermal (MWh/year)					Electric (MWh/year)				
Population size	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum
Group 1	10.65	3.53	9.86	18.79	5.66	3.39	2.89	2.20	9.16	0.00	7.26	1.09	7.09	9.64	5.37
Group 2	11.65	3.50	11.82	17.28	6.04	4.49	3.03	5.07	8.80	0.00	7.16	1.00	6.96	8.93	5.42
Group 3	10.02	2.22	9.74	14.47	7.79	2.99	2.72	1.93	8.65	0.00	7.03	1.30	6.96	9.26	5.30
Group 4	9.40	2.97	8.45	13.70	7.00	2.40	2.47	1.46	6.00	0.71	7.00	0.69	7.08	7.70	6.12
Group 5	12.87	2.16	12.87	14.39	11.34	6.03	1.40	6.03	7.02	5.04	6.84	0.76	6.84	7.38	6.30

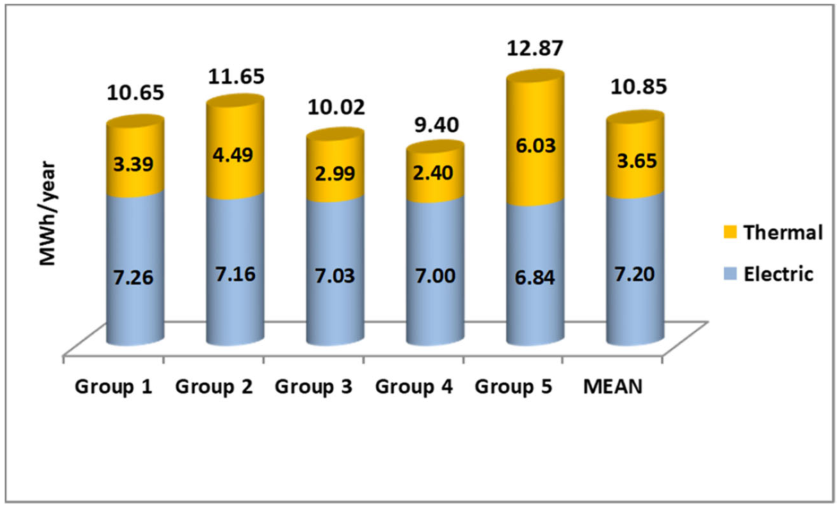


Fig. 7 Thermal, electric, and total mean energy consumption per household by group of cities

city. The electricity consumption scope was defined using the classification 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). The items used were the ones that corresponds to the scope of this study: 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, and 92 to 98. With regard to the thermal energy consumption, facilities considered were those that use natural gas with pressures equal or less than 4 bar. They correspond to homes, stores, public administrations, and services. And they present consumptions mainly between 5000 and 50,000 kWh per year.

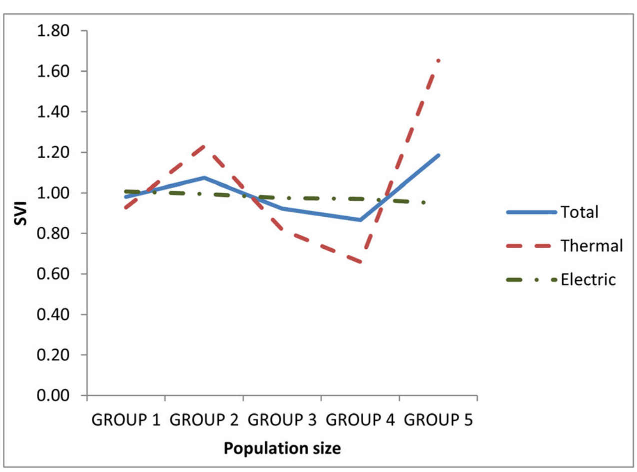


Fig. 8 Variation of the *SVI* index for energy consumptions per household by group of cities

CO_2 emissions

The electricity generation mix of each country defines the CO_2 emissions produced by electric energy consumption. Similar information is also required for emissions produced by thermal energy consumption. Therefore, it is necessary to identify the sources of electric energy and the emissions produced by natural gas.

Elimination of climate influence

In order that the influence of city size is not masked by any other factor, the impact of climate can be eliminated in the study. A previous classification of all cities according to their climate must be carried out. In addition, the consumption mean of each climate zone and the consumption mean of all cities must be known. Thus, a correction factor for the energy consumed for each climatic zone is obtained:

$$K_{ci} = \overline{E}_c / \overline{E}_{ci} \tag{8}$$

where $\overline{E}_{ci}$ is the mean energy consumed in the climate zone i; $\overline{E}_c$ is the mean energy consumed in all cities (of all climate zones); and K_{ci} is the proportionality factor by which the energy consumption of cities in the climate zone i will be affected.

Application of this study to the case of Spain

This study is carried out for Spain as an application of the methodology proposed in this paper. To the authors' knowledge, no study like this was made before, neither with the level of detail nor the scope proposed in this paper. And that is not all. Only a few studies analyze energy consumption or CO_2 emissions in Spain in terms of cities population size. The study carried out in this paper addresses all Spanish cities with populations of more than 50,000 people.

In order to relate Spanish and European cities, it is important highlight that more than 6% out of the 944 cities in Europe with more than 50,000 inhabitants are Spanish. And 6 from the 50 most populated European cities are also Spanish. In particular, Madrid is one of the five first most populated cities in Europe (Fig. 3). Turkey was not considered. Taking into account both this and the sample size, the conclusions obtained for Spain can be expected to be extrapolated to other geographical areas, at least in Europe, which would have to be confirmed with a similar study. Data used for this analysis correspond to 2016 (Eurostat 2018).

Classification of Spanish cities by population size

From the 46.5 million people that live in Spain, 24.5 million (more than 50%) live in cities of over 50,000 inhabitants. In particular, 9 million people live in the 10 most populated cities of Spain, which represents almost 20% of Spain's total population (Instituto Nacional de Estadística 2018a). For this reason, cities are so important in Spain for making proper plans to mitigate CO_2 emissions as far as possible and to meet the demand for energy using renewable energy sources.

This study includes the 145 Spanish cities with populations greater than 50,000 people. The conurbation was not taken into account to assign population to the different cities. Each city was considered as a core instead. And it was associated with its corresponding number of inhabitants. Cities were classified in five different groups according to their population size. These groups will be the ones used for this study: from 50,000 to 125,000 people; from 125,000 to 250,000; from 250,000 to 500,000; from 500,000 to 1,000,000; and more than 1,000,000 people. Table 1 shows these five groups of cities in alphabetical order.

Thermal and electric energy consumption of Spanish cities

Data used for this study correspond to 2016 and to the following official sources: Spanish National Statistics Institute (Instituto Nacional de Estadística 2018b), National Commission on Markets and Competition (Comisión Nacional de los Mercados y la Competencia 2017) (they are both dependent on the Ministry of Economic Affairs and Digital Transformation); and Secretary of State for Energy (Secretaría de Estado de Energía), which depends on the Ministry for Ecological Transition and Demographic Challenge (Secretaría de Estado de la Energía 2018). Available energy consumption data are by

Table 5 Statistical data of energy consumptions per inhabitant by group of cities

Population size	Total (MWh/year)					Thermal (MWh/year)					Electric (MWh/year)				
	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum
Group 1	3.99	1.16	3.90	5.78	1.67	1.26	1.02	0.82	3.11	0.00	2.73	0.34	2.73	3.86	1.67
Group 2	4.49	1.31	4.79	6.47	2.40	1.74	1.16	2.03	3.76	0.00	2.75	0.31	2.73	3.57	2.25
Group 3	3.92	1.01	3.77	6.08	2.91	1.21	1.15	0.72	3.64	0.00	2.71	0.34	2.62	3.37	2.33
Group 4	3.71	1.31	3.28	5.59	2.67	0.97	1.02	0.58	2.45	0.26	2.74	0.33	2.74	3.14	2.33
Group 5	5.28	0.70	5.28	5.78	4.79	2.47	0.49	2.47	2.82	2.13	2.81	0.22	2.81	2.96	2.66

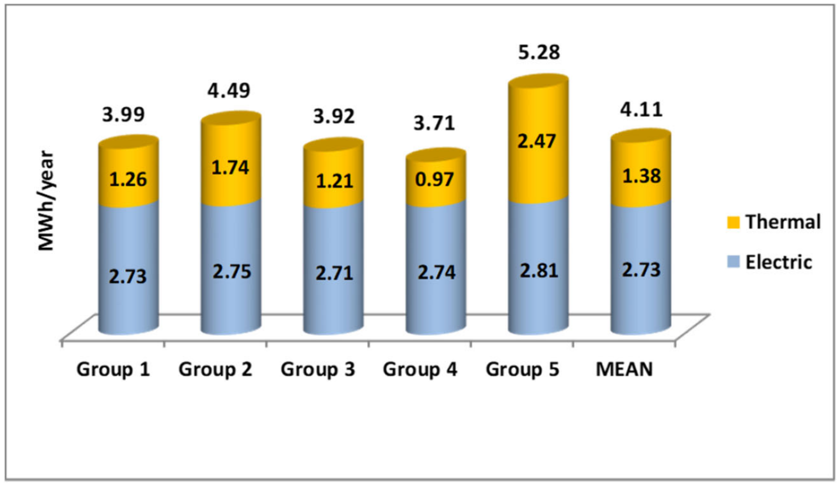


Fig. 9 Thermal, electric, and total mean energy consumption per inhabitant by group of cities

province. For this reason, consumption data of each city are obtained using the mentioned provincial data.

CO_2 emissions of Spanish cities

The Directive 2010/31/UE of the European Parliament and the Council of 19 May 2010 lays down requirements as regards the integrated energy performance of buildings. Based on this Directive, Spanish government set CO_2 emission factors and they are applicable since 14 January 2016. It set the natural gas CO_2 emission factor at 0.252 tCO_2/MWh. Likewise, it set CO_2 emissions at 0.291 tCO_2/MWh for electricity points of consumption considering all types of generators and sources (Ministerio de Industria, Energía y Turismo, and Ministerio de Fomento 2016).

Results and discussion

Sample of study

The results analyzed in this section were got after handling the data provided by official organizations. They were separated in five groups as defined in the "Classification of Spanish cities by population size" section according to the cities size. Thermal and electric energy consumptions were considered. Consumptions of homes, stores, administrative offices, and public services were included. All of them are part from each city.

The resulting number of cities of each group is shown in Fig. 4. Logically, the bigger the city population is (from groups 1 to 5), the less cities in the same group. Taking this into consideration, it is observed that only 2 cities present populations of more than a million people. Meanwhile, more than 60% of the analyzed cities have between 50,000 and 125,000 people. However, total number of inhabitants of each group does not follow the same increasing or decreasing pattern. Groups 1 and 2 present the same number of inhabitants approximately and next group 5, even though only two cities belong to this group. The least populated group is number 4, which groups four cities. Their populations oscillate from 500,000 to 1,000,000 people (Fig. 5).

Table 2 presents the main statistical data of the 145 cities that form the sample of study (both by population and number of households). Regarding the number of households, performances of all groups are similar to the ones mentioned for population.

Total energy consumption

For each city of each group, Table 3 presents the statistical data of the total, thermal, and electric energy consumptions in MWh per year. The largest total energy consumption corresponds to the group of cities with populations between 125,000 and 250,000 people. And it is slightly higher than consumptions of groups 1 and 5. The shortest total energy consumption is observed in group 4. The situation is very

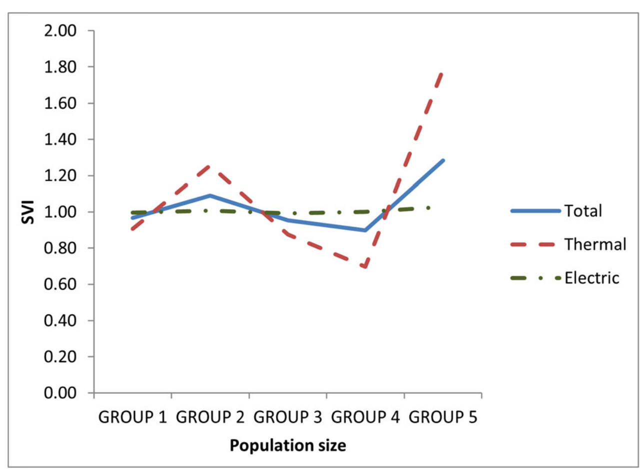


Fig. 10 Variation of the *SVI* index for energy consumptions per inhabitant by group of cities

similar in terms of electricity consumption. In this case group 1 presents the largest consumptions. Consumptions of group 2 are like consumptions of group 1. With regard to the thermal energy use, group 5, followed by 2, is the first one with the highest energy consumptions. Group 1 is the third one. It presents a thermal energy use nearly 35% lower than the maximum. It is observed once again that cities of group 4 present the shortest energy consumptions.

Figure 6 shows in a graphic way graphically consumptions of each group in GWh per year and the values that a mean group would present. Only consumptions of groups 3 and 4 are under the consumption of the group with the mean value.

Energy consumptions per household

Household consumptions were examined with the aim of analyzing cities consumption habits. Table 4 presents the main statistical parameters of the total, thermal, and electric energy consumptions, in MWh per year, of these five groups. Figure 7 shows their mean values. The highest total consumptions are observed in the biggest cities, which belong to group 5. Cities of groups 2 and 1 come next. Cities of groups 5 and 2 reach an energy consumption 18% and 7% higher than the mean, respectively. On the contrary, the energy use in the cities of group 4 is the shortest one. It is 13% lower than the mean and over 25% lower than the group of highest consumptions. The tendency observed for the thermal energy consumption follows the same pattern as the total consumption. It is much more pronounced though. It varies between a consumption 65% higher than the mean value in the case of group 5 and 34% lower than the mean for group 4. Therefore, the difference between consumptions of both groups is great as noted. However, when examining the electricity use, it is brought to light that cities of group 5 (which are the biggest ones) consume the least amount of energy. Meanwhile, the highest consumption is observed in the smallest cities (group 1). Nevertheless, variations are slight since consumptions of 7.2 MWh per year are observed in every group.

The *SVI* index previously defined was used to analyze the consumption variations observed in each group of cities. Figure 8 shows the *SVI* index for the total, thermal, and electric energy consumptions of households in each group, respectively. The mean consumption of each group increases progressively in groups 1, 2, and 5. The reason could be that the bigger a city is, the more energy it consumes. This is not so for groups 3 and 4 though, whose 14 cities have populations between 250,000 and 1,000,000 people. The difference between the groups with the highest and lowest total energy consumptions is 32% compared to the mean value. Results of the *SVI* index can be analyzed and compared to the thermal energy consumption. Findings show that the dispersion between group 4 (group with the shortest energy use) and group 5 (group with the highest energy use) nearly reaches 100% compared to the mean value. Moreover, groups' performances in terms of thermal energy consumption are similar to the total energy consumption, although they are a lot more noticeable. Energy consumption increases progressively in every group, except for groups 3 and 4. Nevertheless, a stable and nearly identical electricity consumption is observed in every group. Only 6% variation between the extreme mean values is noticed, which are observed in groups 1 and 5. This nearly constant energy consumption could be due to electrical appliances and electrical and electronic devices. They are responsible for a base electricity consumption that always exists in every home.

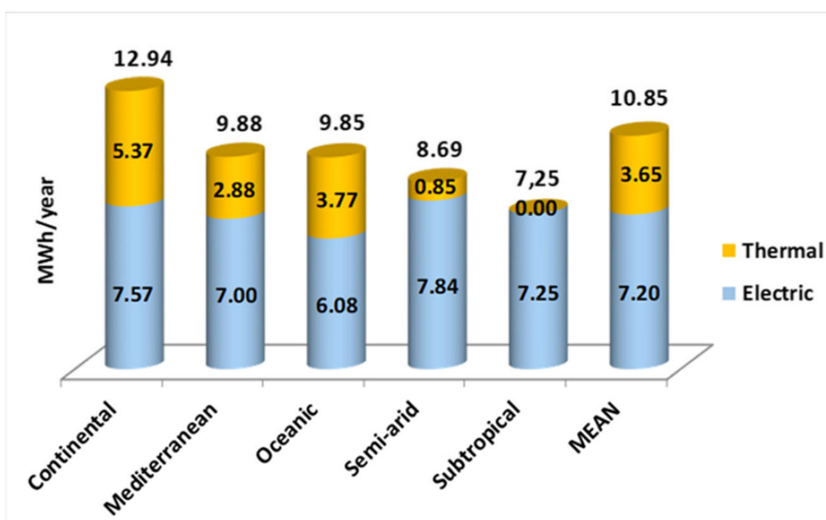


Fig. 11 Thermal, electric, and total energy consumption per household of each Spanish climate zone (Zarco-Soto et al. 2020)

Energy consumptions per inhabitant

Table 5 shows the main statistical data regarding energy consumption per inhabitant, in MWh per year. It enables getting familiar with citizens' consumption habits. Mean values are shown in Fig. 9. Performance observed is similar to the one presented in the analysis per household, although it presents more pronounced values in the total and thermal energy consumptions and a little less in the electricity use. The highest energy consumption is noted in the cities of group 5, which are the biggest ones in terms of population. They reach an energy consumption 28% higher than the mean value. Cities of groups 2 and 1 come next. Nevertheless, cities of groups 3 and 4 do not share this increasing tendency. On the contrary, the total energy use in the cities of group 4 is 10% lower than the mean. Regarding the tendency of the thermal energy consumption is like the one of the total energy. It grows from group 1 to group 5, except for groups 3 and 4. Consumption of group 5 is nearly 80% higher than the mean. Consumption of group 4 is 20% lower than the mean. With regard to the electricity use, a steady consumption is once more noticed in all groups. Its annual mean value is 2.73 MWh and, it varies from 2.71 MWh (minimum value) to 2.81 MWh (maximum value).

The analysis of consumption variations in each group was carried out using the *SVI* index previously defined. Figure 10 shows the index for the total, thermal, and electric energy consumptions per inhabitant for each group of cities defined. Conclusions drawn with this figure are the same as the ones drawn for households: mean value increases as the cities size grows except for the case of groups 3 and 4, in which a decrease of the energy use is observed; the variation of mean consumptions per group is 38% compared to the mean value, and it reaches almost 110% in the case of the thermal energy consumption. However, variation is 4% for the electricity consumption, reason why it can be considered as constant in all groups; variations observed in the mean thermal energy consumptions are very noticeable.

Energy consumptions per household without the influence of climate

The analysis performed up to here can be completed taking into account that the cities of each group are placed in geographical locations with different climates. And therefore this can influence their consumptions. Zarco-Soto et al. (2020) analyze energy consumptions of Spanish cities with populations greater than 50,000 people considering climate. This study shows that the energy consumed in the cities is different depending on the climate they have. Figure 11 shows the total, thermal, and electric energy consumptions per household of each climate zone defined for Spain.

Table 6 Statistical data of household consumptions by group of cities without the influence of climate

Population size	Total (MWh/year)					Thermal (MWh/year)					Electric (MWh/year)				
	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum
Group 1	10.77	2.89	10.52	15.77	5.87	3.51	2.39	3.21	8.09	0.00	7.26	0.94	7.25	9.73	5.40
Group 2	11.06	2.52	12.09	14.49	5.78	3.97	2.12	4.78	7.25	0.62	7.09	0.89	7.14	9.18	5.46
Group 3	11.22	2.06	11.51	13.82	6.53	4.03	1.94	4.31	7.09	0.59	7.19	1.08	7.04	9.52	5.54
Group 4	8.97	2.35	9.28	11.49	5.87	2.04	1.61	1.74	4.08	0.60	6.93	0.77	7.18	7.54	5.82
Group 5	12.33	0.27	12.26	12.46	12.07	5.58	1.15	5.58	6.39	4.77	6.75	0.38	6.75	7.02	6.48

To carry out this new analysis, cities need to be assigned to the climate they present. The Spanish climatic map (Zarco-Soto et al. 2020) is used for it. The 145 cities are located on this map one by one. This makes possible to analyze their energy consumption regardless of the climate they have and therefore to evaluate energy consumption based on size. This was done considering the values presented in Fig. 11. From now on the influence of climate on the energy consumption of cities has been eliminated. Table 6 shows the main statistical data for the energy consumptions by the five defined groups of cities size, once the influence of climate was eliminated. Figure 12 shows their mean values. The highest energy consumption is once again observed in the biggest cities (group 5). They present consumptions 13% over the mean. The next ones are the cities of groups 2 and 3, which present similar energy consumptions, and then the cities of group 1. Note that the shortest energy consumption is observed in the cities of group 4. Regarding thermal energy, the highest consumption is observed in group 5. It is even 50% higher than the mean value. The tendency is much the same: the bigger the population size of a city is, the more energy it consumes (except for the cities of group 4, which keep on having the shortest consumptions). With respect to the electricity consumption, it remains the fact that every group presents an almost constant value of 7.2 MWh per year.

The *SVI* index was used in the same way as before to analyze energy consumptions variations of each group. Figure 13 shows the oscillations of the *SVI* index for the total, thermal, and electric energy consumption per household without the influence of climate. It shows the average performance of each group of cities.

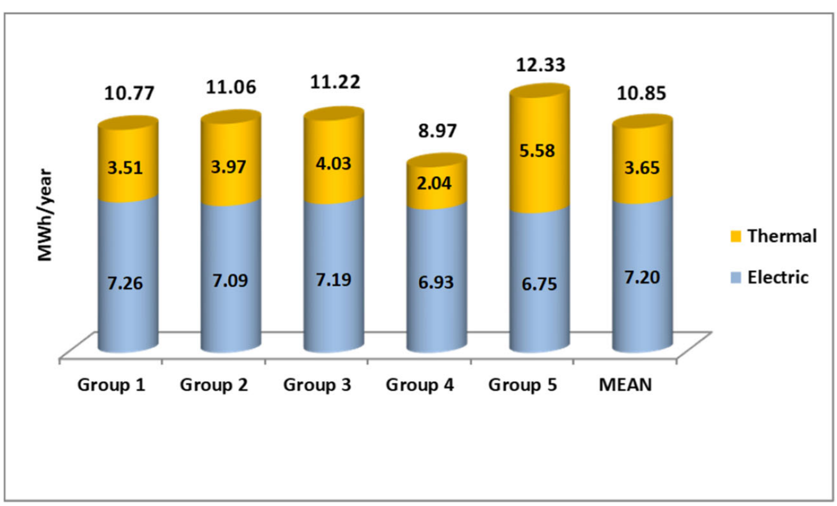
Total and thermal mean energy consumptions increase as the cities size grows, except for group 4, whose population varies from 500,000 to 1,000,000 people. Total and thermal maximum mean energy consumptions are observed in group 5. And they are 13% and 53% higher than the mean value. There is an oscillation greater than 100% between the thermal energy consumptions of groups 5 and 4, which are the most extreme ones in terms of maximum mean energy consumption. With regard to the electricity consumption, it remains nearly constant in all groups. This shows that there is a minimal base consumption in every home.

Energy consumptions per inhabitant without the influence of climate

Energy consumption per inhabitant was also analyzed only considering the effect that the cities size has on it, without the influence of climate. For that purpose, the total, thermal, and electric energy consumptions per inhabitant of each climate zone studied in Zarco-Soto et al. (2020) were considered (Fig. 14). Table 7 shows the main statistical data of the energy consumptions per inhabitant in each of the defined groups of cities once the influence of climate was eliminated. Figure 15 presents their mean values. Cities of group 5 have the highest energy consumption. It is 24% over the mean. Groups 2 and 3 are next. They share similar consumptions. And the same is observed now as with consumptions per household: cities of group 4 are the ones with the shortest energy use. Thermal energy consumption performance is analogous, and cities of group 5 present a consumption nearly 70% over the mean. Lastly, electricity use presents a constant consumption of 2.7 MWh per year in every group.

Figure 16 shows the variation of the *SVI* index for the total energy consumptions per inhabitant without the effect of climate. Performance observed is like the one presented for households: cities total and thermal mean energy consumptions increase as their population size grows, except for the four cities of group 4; maximum consumptions are observed in group 5 (they are 24% higher than the mean value in the case of the total energy consumption and 68% higher than the mean in the case of the thermal energy use); regarding the

Fig. 12 Thermal, electric, and total mean energy consumptions per household by group of cities without the influence of climate



electricity use, it presents once again an approximately constant value, which in this case is 2.7 MWh per year for all cities.

Therefore, it can be concluded that cities total and thermal energy consumptions per household and per inhabitant rise as the cities size increases, except for the case of the four cities with populations between 500,000 and 1,000,000 people, and the electric energy consumption is approximately the same for all cities regardless of their populations.

CO_2 emissions

Spanish government set CO_2 emissions depending on the energy sources: 0.252 tCO_2/MWh for generators based on natural gas and 0.291 tCO_2/MWh for all types of electricity generators and sources (Ministerio de Industria, Energía y Turismo, and Ministerio de Fomento 2016). For this reason, once energy consumptions are identified depending on the energy source, CO_2 emissions can be calculated for each case.

Keeping a similar line of reasoning as in the previous sections, the emissions produced are analyzed and then studied once the influence of climate is eliminated. This makes possible to evaluate performance of each group of cities.

Figure 17 shows CO_2 emissions per household. It is easily observed that the biggest cities present higher emissions, followed by cities of groups 2 and 1. Cities of group 4 have the shortest emissions. Groups 5 and 2 are the only ones with emissions over the mean (16 and 6% over the mean, respectively). On the contrary, emissions of the group that produces the shortest emissions are 12% under the mean. If thermal emissions are now analyzed, all groups present similar performances. These performances are more pronounced though. Group 5 emissions are the highest ones. They are 65% over the mean. On the contrary, group 4 emissions are the shortest ones. They are 30% lower than the mean. Evaluating emissions produced by electrical sources, cities of group 5 (the

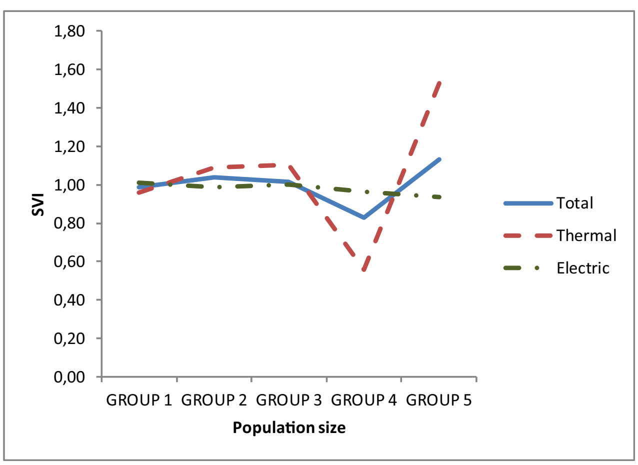


Fig. 13 Variation of the *SVI* index for energy consumptions per household by group of cities without the influence of climate

Table 7 Statistical data of energy consumptions per inhabitant by group of cities without the influence of climate

Population size	Total (MWh/year)					Thermal (MWh/year)					Electric (MWh/year)				
	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum	Mean	Std. dev.	Median	Maximum	Minimum
Group 1	4.03	0.98	4.21	5.26	1.84	1.30	0.86	1.33	2.69	0.00	2.73	0.32	2.78	3.72	1.72
Group 2	4.26	0.95	4.83	5.51	2.27	1.53	0.81	1.74	2.69	0.22	2.73	0.30	2.74	3.68	2.25
Group 3	4.29	0.85	4.37	5.26	2.47	1.55	0.78	1.69	2.69	0.22	2.74	0.31	2.69	3.47	2.36
Group 4	3.55	1.05	3.60	4.76	2.27	0.82	0.68	0.68	1.69	0.23	2.73	0.33	2.82	3.03	2.25
Group 5	5.12	0.24	5.09	5.26	4.92	2.32	0.53	2.32	2.69	1.94	2.80	0.08	2.80	2.86	2.74

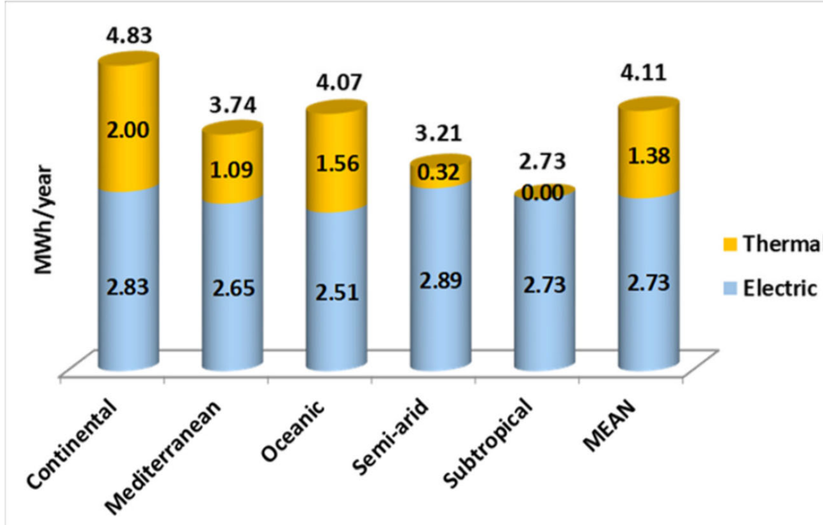


Fig. 14 Thermal, electric, and total energy consumption per inhabitant by climate zone (Zarco-Soto 2020)

biggest cities) present the shortest emissions. However, the cities that produce higher emissions are the ones that belong to groups 1 and 2. Nevertheless, variations among emissions of all groups are minimal: 2,10 tCO_2 per year. If now each of the groups is analyzed individually, it is observed that emissions of electrical sources are the highest ones. And they vary from 77% (group 4) and 57% (group 1).

Figure 18 shows CO_2 emissions per inhabitant. These emissions present performances similar to the ones described for households. Group 5, followed by groups 2 and 1, produces the highest emissions. Group 4 presents the shortest emissions. Emissions vary from 25% over the mean (group 5) and 10% under the mean (group 4). With regard to emissions produced by thermal energy sources, their performance follows the same pattern: they oscillate from 77% over the mean in the case of the biggest cities to 30% under the mean in the case of cities of group 4. Regarding electrical sources, variations are minimal among all groups. Therefore, they can be considered as constant per inhabitant regardless of the group. It is now observed the same as for the emissions per household: emissions produced by electrical sources are the highest ones. Group 4 presents the highest emissions (77% over the mean) and group 5 the shortest ones (57%).

Once the influence of climate per household is eliminated, CO_2 emissions increase progressively as the city size grows (Fig. 19). The only exception in this case are the four cities with populations between 500,000 and 1,000,000 people (group 4). Cities of group 5 produce 11% more than the mean. Cities of groups 1 and 4 are the only ones whose CO_2 emissions are under the mean. In particular, emissions of group 4 are 16% lower than the mean. This group presents the shortest emissions. In thermal terms, performance is very similar: emissions increase as the cities size grows, except for the case of group 4. Emissions of this group are 45% lower than the mean, whereas group 1 presents emissions 50% over the mean. With regard to the electrical analysis, the pattern is just the opposite: the smallest cities produce higher CO_2 emissions, whereas the shortest emissions are observed in the biggest cities. However, variations between both extremes are only 6%. Regarding the emissions percentage of one or

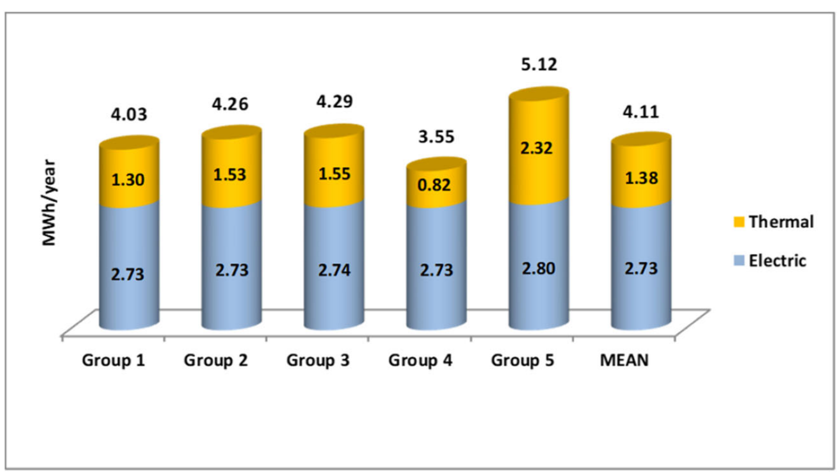


Fig. 15 Thermal, electric, and total mean energy consumptions per inhabitant by group of cities without the influence of climate

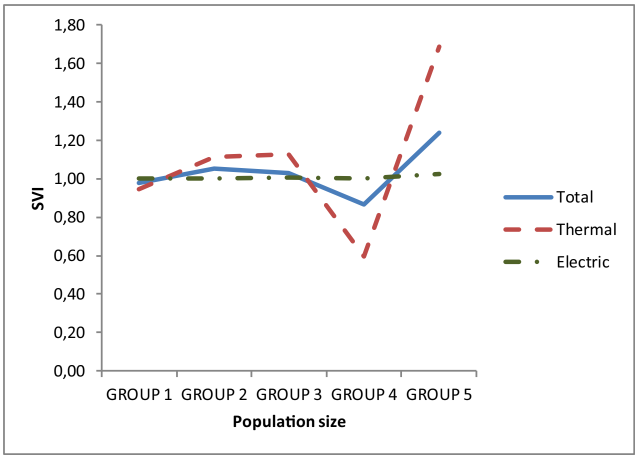


Fig. 16 Variation of the *SVI* index for energy consumptions per inhabitant by group of cities without the influence of climate

another type, electrical emissions take precedence. They vary between 80% (case of group 4) and 58% (case of group 5).

Analyzing CO_2 emissions per inhabitant once the influence of climate is eliminated, it is observed that the bigger the cities sizes are, the higher the emissions. This is not so for group 4 (Fig. 20). The two cities of group 5 produce 20% more emissions than the mean and group 4, 13% less. It happens the same with emissions from thermal sources, although they are more noticeable: the biggest cities produce 65% over the mean, whereas cities of group 4 produce 40% less. Regarding emissions from electrical sources, variations between their most extreme emissions are barely 2%. With regard to percentages over the total, emissions from electrical sources take precedence. They oscillate between 58% (in the case of the biggest cities) and 79% (in the case of cities of group 4).

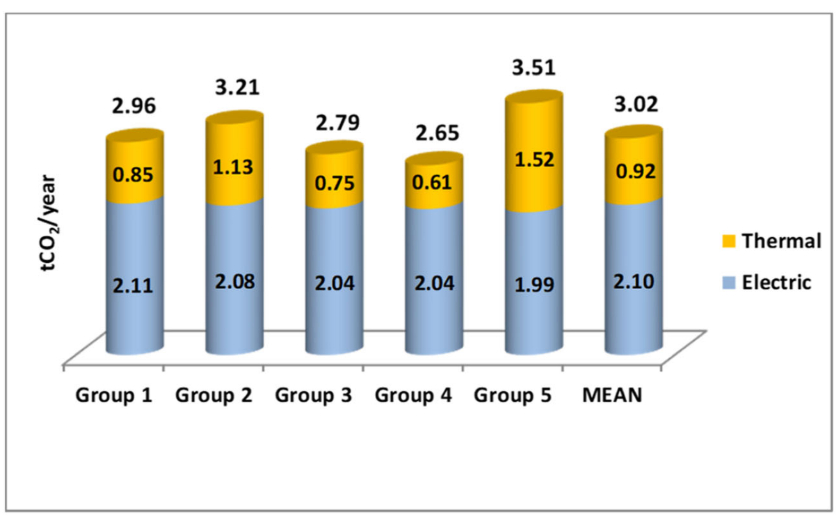
Therefore, when the influence of climate is eliminated, it is observed that emissions are higher as the city size grows, especially emissions from thermal sources. This does not happen in the case of the four cities with populations between 500,000 and 1,000,000 people. Emissions from electrical sources remain barely constant per inhabitant, although they slightly increase when the city size enlarges. However, it is just the opposite per household. Despite minimal variations, the bigger the city is, the shorter the emissions from electrical sources. If the influence of climate is not eliminated, performance is very similar to the exposed one. In this case, the 10 cities of group 3 (populations between 250,000 and 500,000 people) are also the exception. According to pollution sources, emissions from electrical sources are the most important ones. They oscillate between 55 and 80% over the total percentage approximately. In each group of cities, the proportion of electrical emissions increases as the cities size decreases. Group 4 is the exception in this case, since electrical emissions of this group mean the highest percentage.

Conclusions

Cities are one of the places where a great impact is observed when taking actions to help fulfilling the sustainable energy aims of the United Nations and the environmental guidelines of each country. This is due to the fact that more than half of the world population lives in the cities. It even reaches 70% in the case of Europe. In particular, over a half of Spain's population lives in the 145 Spanish cities of more than 50,000 people. Therefore, any measure taken on cities is so important.

The scope of this paper was to present a methodology to calculate and analyze cities energy consumptions (both thermal and electric) and CO_2 emissions depending on population and only making use of public existing data. This methodology is applicable to any geographical area. The analysis of the results obtained can help government organizations and companies to carry out adequate planning of the infrastructures necessary for the growth of energy consumption in cities and the reduction of their emissions.

Fig. 17 Thermal, electric, and total CO_2 emissions per household by group of cities



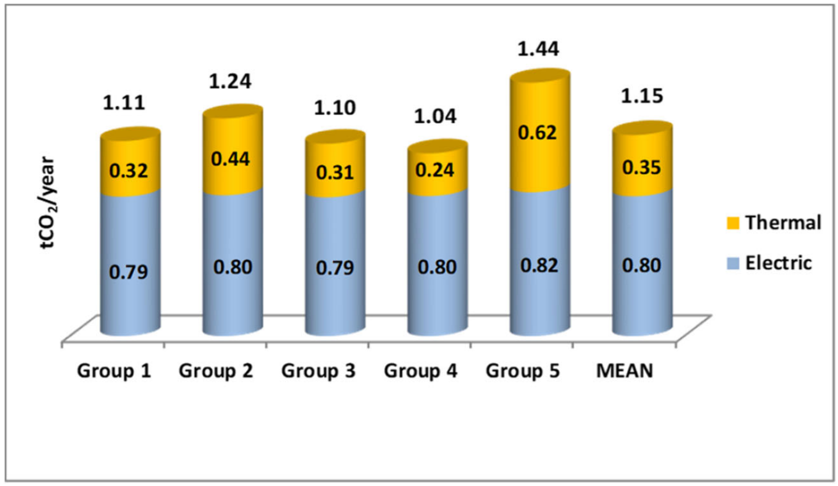


Fig. 18 Thermal, electric, and total CO_2 emissions per inhabitant by group of cities

An application of this methodology was explained for the 145 cities of Spain that have more than 50,000 people. For that purpose, these cities were identified and classified in five different groups based on their number of inhabitants. Next, the energy consumption of each group was analyzed per household and per inhabitant. Moreover, this study was completed eliminating the influence that climate has on the energy consumption of cities. With this aim, it was necessary to locate each city on the climate map of Spain. An index was also defined to make this analysis easier.

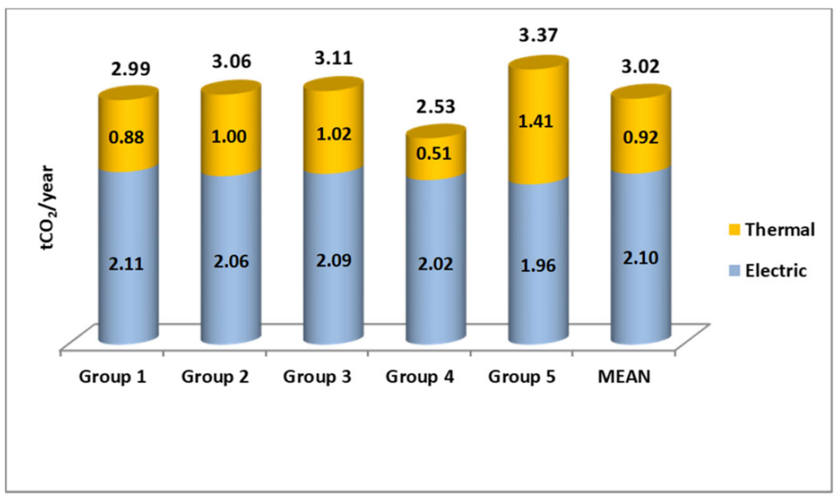


Fig. 19 Thermal, electric, and total CO_2 emissions per household by group of cities without the influence of climate

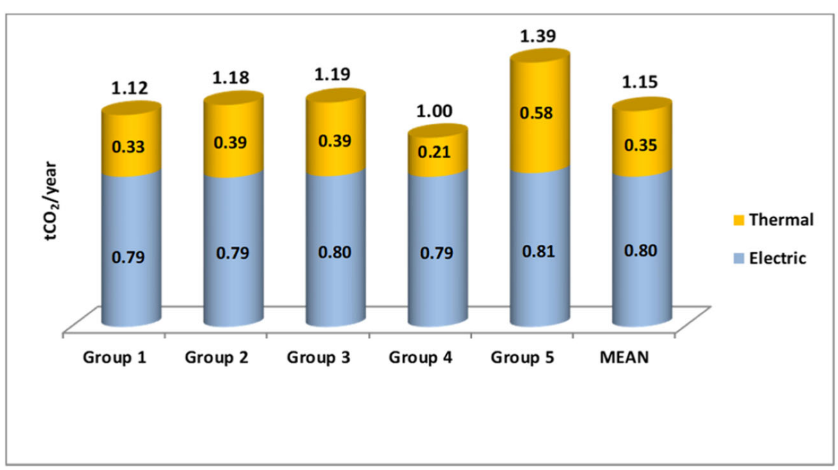


Fig. 20 Thermal, electric, and total CO_2 emissions per inhabitant by group of cities without the influence of climate

After the mentioned analysis, a series of findings have been found. The bigger a city is, the higher total and thermal energy it consumes. However, it is not so for the four cities that have populations between 500,000 and 1,000,000 people, since their energy consumptions are the shortest ones. Furthermore, electric energy consumption remains practically constant regardless of the city population size. Therefore, this consumption is more inelastic. This is due to all those electrical and electronic devices in addition to electrical appliances that always are in every home. They are responsible for a base electricity consumption.

Finally, CO_2 emissions were calculated: total and emissions from thermal or electrical sources. This makes possible to estimate the need for renewable energy to eliminate or mitigate pollutant emissions. The bigger a city is, the more emissions it produces (especially emissions from the thermal sources). It was also observed in this case that the four Spanish cities with populations between 500,000 and 1,000,000 people are an exception. With regard to emissions from electrical sources, it was concluded that they remain barely constant. Finally, emissions from electrical sources are responsible for approximately between 55 and 80% of the total pollution in each group. These percentages enlarge as the city size decreases. However, the cities with populations from 500,000 to 1,000,000 people are the exception. For these cities, it was concluded that emissions from electrical sources take precedence.

Taking into account the size of the study sample in Spain, the results obtained suggest that the behavior of cities, each considered as an entity that consumes energy and produces emissions, will be similar in other geographical areas.

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Author contribution Irene M. Zarco-Soto and Pedro J. Zarco-Periñán wrote the manuscript, established the methodology, and conducted the research and analysis. Irene M. Zarco-Soto, Pedro J. Zarco-Periñán, and Rafael Sánchez-Durán contributed to the study conception and design. All authors have contributed to this manuscript, reviewed, and approved the current form of the manuscript to be submitted.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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