Cities and Energy Consumption: Strategies for an Energy Saving Planning

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Abstract A growing body of international researchers has been studying the complex relationship between cities and energy consumption so to support local policy makers' decisions and foster the transition towards a low-carbon future. However, despite the great interest of the literature for this topic, a consistent number of interactions between urban features and energy use at urban scale still lacks consensus. Therefore, this research aims to identify the urban factors that significantly affect a city's energy and carbon footprint, thus supporting policy-makers in the definition of effective strategies and policies that can be implemented on an urban scale to reduce energy consumption and resulting CO_2 emissions. Using a holistic approach rather than a sectorial one, we consider together a comprehensive set of urban factors—-physical, functional, geographical, and socio-economic—describing the complexity and multidimensionality of cities for measuring their impacts on CO_2 emissions. The results of the statistical analyses show that the two main categories of urban factors directly affecting CO_2 emissions per capita are the geographical and physical features, whereas the functional and socio-economic characteristics of urban areas have an indirect effect on CO_2 emissions. In other words, the climate condition of a city and its physical structure (both in terms of urban density and buildings characteristics) are in large part responsible for the use of energy and the resulting CO_2 emissions within the urban perimeter. Given that the geographical factors of cities cannot be changed by human intervention, the key role of urban policies and spatial planning in addressing energy and environmental issues becomes of strategic importance for addressing climate change.

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1 Introduction

According to IEA (2016), urban areas consume about two-thirds of primary energy demand and produce over 70 per cent of global carbon dioxide emissions (CO_2). Consequently “cities are the heart of the decarbonisation effort” (IEA 2016) and can be the solution to climate change.

In order to support local policy makers’ decisions and foster the transition towards a low-carbon future, a growing body of international researchers has been studying the complex and multidimensional relationship between cities and energy consumption.

Urban planning policies, indeed, can effectively improve energy saving in cities and reduce urban emissions only if the interactions between urban factors and energy use are investigated and are found to be significant. However, despite the great interest of the literature for this topic, a consistent number of interactions between urban features and energy use at urban scale still lacks consensus. Therefore, this research aimed to investigate the relationship between cities and energy consumption to identify the urban factors that significantly affect a city’s energy and carbon footprint, thus supporting policy-makers in the definition of effective strategies and policies that can be implemented at an urban scale to reduce energy consumption and resulting CO_2 emissions.

This paper includes five sections. Section 2 provides a review of recent studies on the relationship between cities and energy consumption. The review highlights the knowledge gap between what is known and what is still under debate. Section 3 focuses on the methodology for developing the statistical models performed to investigate the relationship between urban features and energy consumption. More specifically, it presents the set of physical, functional, geographical, socio-economic and energy variables selected for the model, as well as the data collection procedure. Section 4 shows the results of the statistical analyses performed on the dataset. The results are carefully interpreted and discussed considering previous findings found in the scientific literature in order to highlight two types of significant relationships: (1) the relationships between the different urban factors, which may indirectly affect CO_2 emissions; (2) the direct relationships between urban factors and CO_2 emissions. Section 5, lastly, provides some concluding remarks that could be helpful for supporting policy makers in the definition of effective strategies to be implemented at an urban scale to reduce energy consumption and resulting CO_2 emissions. Furthermore, this Section highlights the main limitation of this work and outlines potential directions for future research on this topic.

2 Literature Review[1]

The review of the literature combined interdisciplinary researches that investigate the multidimensional relationship between cities and energy consumption. Using a holistic perspective, the critical review of these contributions revealed that different studies have considered different categories of urban features influencing energy consumption and CO_2 emissions. We have classified and summarized these features into four groups, each including a different number of variables (Fig. 1): (1) physical features; (2) functional features; (3) geographical features; (4) socio-economic features. Giving that there is no single way of identifying different categories (Stead and Marshall 2001), this classification is based on the General System Theory (von Bertalanffy 1969) applied to the urban phenomenon (Gargiulo and Papa 1993). In particular, according to the systemic principles, cities can be defined "as sets of elements or components tied together through sets of interactions" (Batty 2008) and an urban system can be represented as a set of four subsystems: physical subsystem; functional subsystem; geomorphological subsystem; anthropic subsystem (Papa et al. 1995). The four categories of urban features previously introduced reflect the aforementioned four urban subsystems.

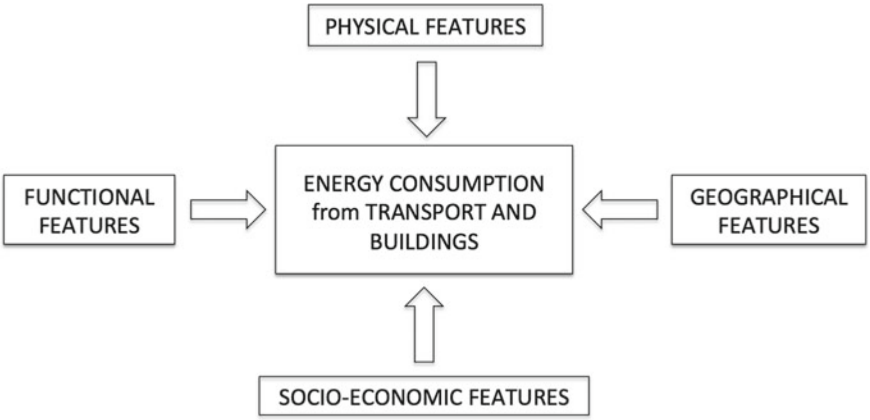

Fig. 1 Theoretical approach

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[1] This section summarizes the results of the literature review on the relationship between cities and energy consumption on a city scale discussed in detail in a previous article (Gargiulo and Russo 2017).

2.1 Physical Features and Energy Consumption

Two main groups can be recognized in the debate on the relationship between urban form and energy consumption: those who support the compact city (Banister et al. 1997; Clark 2013; Ewing and Rong 2008; Marshall 2008; Newman and Kenworthy 1989) and those who question the magnitude of its environmental benefits (Baur et al. 2013; Brownstone and Golob 2009; Echenique et al. 2012; Mindali et al. 2004). While compact development advocates support the idea that people living in dense urban settlements are less automobile dependent, tend to live in multifamily houses, and thus consume less energy than do residents in sprawl areas, critics suggest that the energy savings associated with the intensification of land use are too small to be considered significant, and they may be associated with negative externalities such as congestion, higher housing price, and less availability of green areas.

2.2 Functional Features and Energy Consumption

There are relatively few studies that investigate the impacts of urban functional features on energy consumption. Although some results may appear contradictory, the general argument that emerges is that the positive effect of mixed-use development on energy saving from transport is not significant by it self, but becomes significant when combined with high density and supply of transit services (Banister et al. 1997; Holden and Norland 2005).

2.3 Geographical Features and Energy Consumption

The relationship between geographical features and energy consumption has been interpreted by the literature as that between climate—specifically HDDs—and energy consumption from buildings. In this context, it is widely argued that an increase in HDDs is associated with an increase in CO_2 emissions from heating (Creutzig et al. 2015; Ewing and Rong 2008). As far as the geographical location of cities is concerned, only one research finds that the proximity to the ocean does not affect energy consumption (Creutzig et al. 2015). Future research should further investigate the importance of these aspects as well as that of urban topography with respect to energy consumption.

2.4 Socio-economic Features and Energy Consumption

It is widely recognized that social and economic factors affect energy consumption. However, while there is great consensus about the relationships between economic variables—income (Battarra et al. 2016; Brownstone and Golob 2009; Clark 2013; Ewing and Rong 2008; Holden and Norland 2005; Kennedy et al. 2009; Newman and Kenworthy 1989), fuel price (Creutzig et al. 2015; Ewing and Rong 2008; Newman and Kenworthy 1989), and car ownership (Banister et al. 1997; Mindali et al. 2004)—and energy consumption, there is far less agreement about the way social characteristics, such as demographic growth, household composition, education, and race may influence energy use.

3 Methodology

The review of the scientific literature described above represents the starting point for the selection of the variables to be included in the statistical model in order to assess the relationship between urban characteristics and energy consumption on a city scale. The final dataset chosen for this analysis includes 18 variables describing the urban system and 5 variables measuring CO_2 emissions from energy use (Table 1). These data were collected for a sample of 73 Italian provincial capitals uniformly distributed across the country (Fig. 2), which account for 12.340.751 inhabitants, corresponding to the 21% of the total Italian population (recorded in 2011).

3.1 Urban Variables

Following the general system theory applied to the urban phenomenon (see Sect. 2), the 18 urban variables were classified into four categories, which reflect the four subsystems of a city: (1) physical features; (2) functional features; (3) geographical features; (4) socio-economic features.

(1) This category of urban features describes the physical component of a city, i.e. the spaces that people live in. (2) The functional features describe the functional subsystem of a city, which refers to the frequency and variety of activities occurring within the urban perimeter.

The choice of including in the dataset four variables identifying the economic base of a city comes from the consideration that urban economics may be a factor influencing the energy and carbon footprint of an urban settlement because different activities produce and consume different amount of energy (Habitat—UN 2011). Nevertheless, the relationship between the economic base of a territory and CO_2 emissions have not been explored yet. Thus, including these variables in this analysis represents one small step forward in the scientific debate on the relationship between

Table 1 List of the urban and energy variables selected for the analysis

Category	Variable	Description	Source
Physical features	Housing density	Housing units per square kilometer	ISTAT (2011)
	House size	Average floor area per capita	ISTAT (2011)
	House age	% of buildings built after 1980	ISTAT (2011)
	House material	% of masonry buildings	ISTAT (2011)
	Green areas	% of green areas	ISTAT (2011)
Functional features	Land use mix	Jobs per square kilometer	ISTAT (2011)
	Functional specialization	Concentration of manufacturing activities	ISTAT (2011)
		Concentration of commercial activities	ISTAT (2011)
		Concentration of public activities	ISTAT (2011)
		Concentration of touristic activities	ISTAT (2011)
Geographical features	Degree days	°C per day/year[a]	DPR 412/09
	Coastal location	Binary variable (0 = coastal; 1 = inland)	ISTAT (2009)
	Topography	Binary variable (0 = non mountain; 1 = mountain)	ISTAT (2009)
Socio-economic features	Income	Average income per capita	Ministry of Economy and Finance (2012)
	Car ownership	Number of cars per 1.000 inhabitants	ISTAT (2011)
	Household composition	% of children (<15 years old)	ISTAT (2011)
	Education	Graduates per 1.000 inhabitants	ISTAT (2011)
	Ethnicity	% of foreign residents	ISTAT (2011)
Energy consumption	CO_2 emissions	Residential CO_2 emissions per capita	Sustainable Energy Action Plans (2005)

(continued)

Table 1 (continued)

Category	Variable	Description	Source
		Transport CO_2 emissions per capita	Sustainable Energy Action Plans (2005)
		Tertiary CO_2 emissions per capita	Sustainable Energy Action Plans (2005)
		Municipal CO_2 emissions per capita	Sustainable Energy Action Plans (2005)
		Total CO_2 emissions per capita	Sustainable Energy Action Plans (2005)

Calculated as the sum of daily positive differences between a temperature of reference of 20 °C (for Italy) and the average daily outdoor temperature, extended to the whole year

cities and energy consumption. (3) The geographical features describe the climatic and topographic characteristics of Italian capital cities. (4) The five socio-economic variables included in the dataset describe the main characteristics of the population living in the 73 Italian capital cities that may affect energy consumption and CO_2 emissions on an urban scale. Table 2 shows some descriptive statistics for the sample of this analysis.

3.2 Energy Variables

Data on the energy and carbon footprint of the Italian cities considered in this research were collected using the Sustainable Energy Action Plans (SEAP)[2]. More specifically, each SEAP provided data on the amount of CO_2 emissions due to energy consumption by sector. The sectors considered were the following: transport and residential buildings, tertiary buildings and municipal buildings. Table 3 provides some descriptive statistics on CO_2 emissions by sector for the sample of 73 Italian cities.

The SEAP quantifies the emissions that occurred in the baseline year, which is the year against which the achievements of the emission reductions in 2020 shall be compared. Different cities chose different baseline years, mainly depending on data availability. Therefore, we identified the most frequent baseline year in the sample, which is 2005 (corresponding to 35 out of 73 cities, equal to 48% of the sample), and transformed the other data. In order to report all emissions data to the same baseline

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[2] The European Commission (2010) has launched the Covenant of Mayors initiative in 2008, after the adoption of the 2020 EU Climate and Energy Package. This initiative aims to "endorse and support the efforts deployed by local authorities in the implementation of sustainable energy policies". The Covenant of Mayors successfully managed to involve a great number of local and regional authorities, which committed to (1) prepare a Baseline Emission Inventory (BEI) and (2) develop and implement a Sustainable Energy Action Plan (SEAP) within the year following their formal adhesion to the initiative.

Table 2 Descriptive statistics on urban characteristics for the sample of 73 Italian capital cities

Variable	Minimum	Maximum	Average	Standard deviation	Unit of measurement
Housing density	28.36	3214.38	579.96	623.96	Housing units/km^2
House size	31.67	49.71	42.05	4.01	m^2/inhabitants
House age	2.61	53.00	22.64	10.49	%
House material	23.43	91.19	53.40	14.13	%
Green areas	0.09	30.70	3.97	5.52	%
Land use mix	15.39	2496.70	422.98	467.74	Jobs/km^2
Concentration of manufacturing activities	0.21	2.11	0.96	0.44	Location quotient
Concentration of commercial activities	0.48	1.65	1.02	0.21	Location quotient
Concentration of public activities	0.33	1.97	1.03	0.39	Location quotient
Concentration of touristic activities	0.09	8.67	1.08	1.12	Location quotient
Degree days	707	3001	1860.33	599.69	°C per day/year
Coastal location	0.00	1.00	0.44	0.50	Binary variable
Topography	0.00	1.00	0.32	0.47	Binary variable
Income	12,183	26,744	20,411	2895	€
Car ownership	412.19	745.12	614.21	62.06	Car/1ooo person
Household composition	9.92	17.50	12.87	1.39	%
Education	55.50	242.21	150.51	38.64	Grad./1ooo person
Ethnicity	0.50	15.43	7.23	4.18	%

Fig. 2 Map of the 73 Italian provincial capitals included in the sample

year, we used time series data on greenhouse gas (GHG) emissions provided by the ISTAT for Italian regions. More specifically, for each region, the ISTAT offers data on GHG emissions for the following years: 1990, 1995, 2000, 2005, 2010. Based on these data, we calculated the annual change in emissions and we used this value for estimating the CO_2 emissions at 2005 for the 52% of the sample with a different baseline year.[3]

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[3] The following example better illustrates the procedure here adopted. Novara is a city in Piedmont region and the baseline year of its BEI was 1998; data by the ISTAT for Piedmont show that GHG emissions were 8.8 t per capita in 1995 and 9.8 t per capita in 2005, corresponding to a 10.4%

Table 3 Descriptive statistics on CO_2 emissions by sector for the sample of 73 Italian capital cities

Variable	Minimum	Maximum	Average	Standard deviation	Unit of measurement
Residential CO_2 emissions	0.59	3.57	1.85	0.70	t per capita
Transport CO_2 emissions	0.07	4.58	1.78	0.89	t per capita
Tertiary CO_2 emissions	0.00	2.35	1.13	0.53	t per capita
Municipal CO_2 emissions	0.00	0.40	0.11	0.08	t per capita
Total CO_2 emissions	1.95	8.77	4.87	1.47	t per capita

4 Results

The dataset selected and described in the previous Section was explored and analyzed using different statistical methods—exploratory data analysis, correlation analysis, regression analysis—each of which provided useful insights into the complex relationship between cities and their carbon footprint. The statistical software SPSS 20 was used for these analyses.

Exploratory data analysis (EDA) was performed in order to identify potential outliers and evaluate the distribution of the data, thus gaining a better knowledge of the research dataset and sample. After EDA, the data were analyzed using a correlation analysis, which enabled the measurement of the association between the eighteen urban variables in order to identify redundant information and, most importantly, significant interconnections amongst these factors. Lastly, multiple linear regression analysis was performed to estimate the relationship between CO_2 emissions per capita and a number of determinants selected from the initial set of eighteen urban variables. Models were estimated separately for three categories of CO_2 emissions (i.e. residential, transport, and total CO_2 emissions per capita).

The results provided by these statistical analyses are discussed here considering previous findings found in the scientific literature discussed in Sect. 2 (for more details see Gargiulo and Russo 2017). In particular, in order to address the research goal, the results are described highlighting the two main types of relationships affecting energy consumption and CO_2 emissions on a city scale: namely, (1) the primary relationships between the urban features and CO_2 emissions, which directly affect a city's energy and carbon footprint; and (2) the secondary relationships among the

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increase during the ten years of reference, i.e. 1.04% annual increase, which corresponds to a 7.32% growth between 1998 and 2005.

different urban features, which indirectly (but significantly) affect a city's energy and carbon footprint.

4.1 Correlation Analysis

Correlation analysis was used to determine the strength and direction of the linear relationships between each pair of both urban and energy variables. Before performing the correlation analysis, the four variables positively skewed were log transformed to normalize their distribution and calculate Pearson's correlation coefficients. Table 4 reports the correlation coefficients for the twenty-three variables, and the values above 0.65 are in bold and red color. The threshold of 0.65 was later used to identify the best subset of urban variables to be included in the regression model to avoid multicollinearity issues.

The correlation analysis allowed the assessment of the relationships among the different physical, functional, geographical and socio-economic characteristics, which may indirectly affect energy consumption and CO_2 emissions on a city scale, and therefore represent a crucial result of this research.

With respect to this type of relationships, a number of significant associations ($r > 0.65$) emerge. Housing density is highly positively correlated with the concentration of jobs per square kilometer ($r = 0.98$) and is negatively correlated with the percentage of buildings built after 1980 ($r = -0.66$); subsequently the concentration of jobs per square kilometer is also negatively correlated with the percentage of buildings built after 1980 ($r = -0.66$). In other words, densely built cities have also higher land use mix, as well as a higher concentration of older buildings. Another significant association is that between house size (i.e. average floor area per capita) and household composition (i.e. percentage of children), which are negatively correlated ($r = -0.63$), meaning that a greater concentration of children corresponds to a lower average floor area per person. Moreover, income is positively correlated with the share of graduates ($r = 0.73$) and foreigners ($r = 0.69$), as well as with the number of jobs per square kilometer ($r = 0.67$): richer cities have higher levels of education, higher concentration of foreign residents and higher concentration of jobs. With respect to the geographical characteristics or urban areas, not surprisingly, degree-days are negatively correlated to coastal location ($r = -0.69$), i.e. colder cities tend to be inland cities and vice versa, and, less predictably, are positively correlated with the percentage of foreign residents ($r = 0.69$), i.e. warmer cities attract less foreigners than colder ones. The last strong correlation is that between manufacturing cities and those with a high concentration of public activities ($r = -0.79$), thus meaning that cities are likely to be either specialized in manufacturing or in public activities, not both.

A number of similarities and differences emerge when these results are compared with those found in the scientific literature. More specifically, given the equivalence

Table 4 Correlation analysis, Pearson's correlation coefficients

	Housing density (ln)	Average floor area per capita	Percentage of buildings built after 1980	Percentage of masonry buildings	Percentage of green areas (ln)	Jobs per kmq (ln)	Concentration of manufacturing	Concentration of commercial	Concentration of public activities	Concentration of touristic activities (ln)	Degree days	Coastal location	Topography	Average income per capita	Cars per 1.000 inhabitants	Percentage of children	Graduates per 1.000 inhabitants	Percentage of foreign residents
Housing density (ln)	1.00																	
Average floor area per capita	0.00	1.00																
Percentage of buildings built after 1980	**-0.66****	-0.12	1.00															
Percentage of masonry buildings	-0.12	0.35*	-0.11	1.00														
Percentage of green areas (ln)	0.61**	0.09	-0.45**	-0.14	1.00													
Jobs per kmq (ln)	**0.98****	0.07	**-0.66****	-0.10	0.63**	1.00												
Concentration of manufacturing	0.05	0.18	-0.18	0.02	0.13	0.11	1.00											
Concentration of commercial	-0.16	0.03	0.22	-0.06	-0.08	-0.16	-0.11	1.00										
Concentration of public activities	0.07	-0.18	0.01	-0.05	-0.06	0.01	**-0.79****	-0.46**	1.00									
Concentration of touristic activities (ln)	-0.04	0.04	0.08	0.22	0.01	-0.04	-0.22	0.17	-0.07	1.00								
Degree days	0.09	0.46**	-0.21	0.08	0.36**	0.18	0.42**	-0.04	-0.38**	0.03	1.00							
Coastal location	0.06	-0.36**	0.01	0.01	-0.18	-0.01	-0.30*	0.05	0.22	0.21	**-0.69****	1.00						
Topography	-0.32**	-0.17	0.39**	-0.04	-0.31**	-0.36**	-0.29*	0.05	0.23	0.05	-0.08	-0.12	1.00					
Average income per capita	0.59**	0.52**	-0.42**	0.12	0.61**	**0.67****	0.08	-0.13	0.00	-0.06	0.53**	-0.29*	-0.24*	1.00				
Cars per 1.000 inhabitants	-0.41**	0.10	0.50**	-0.10	-0.24*	-0.39**	-0.19	0.04	0.13	0.05	-0.08	-0.12	0.24*	-0.14	1.00			
Percentage of children	-0.15	**-0.67****	0.31**	-0.28*	-0.15	-0.17	0.11	0.13	-0.18	-0.01	-0.23*	0.12	0.13	-0.46**	0.05	1.00		
Graduates per 1.000 inhabitants	0.40**	0.48**	-0.30*	0.00	0.42**	0.46**	-0.23*	-0.19	0.31**	0.04	0.31**	-0.24*	-0.16	**0.73****	0.12	-0.58**	1.00	
Percentage of foreign residents	0.42**	0.50**	-0.46**	0.23*	0.45**	0.50**	0.47**	-0.05	-0.43**	0.07	**0.69****	-0.37**	-0.33**	**0.69****	-0.25*	-0.19	0.31**	1.00

of housing and population density[4], the relationship between population density and heating degree days (Ewing and Rong 2008) does not come out as a significant result here (r = 0.09), and that between population density and house size (Ewing and Rong 2008; Lee and Lee 2014) also turns out to be not significant here (r = 0.00).

Even opposite to those found in the literature are the results on the relationship between density and income: while Brownstone and Golob (2009) find a negative association for a sample of California households, the correlation found for the seventy-three Italian cities is positive (r = 0.59). This difference does not have to surprise if we consider the substantial differences of the two contexts in both socio-economic development and historical background.

Only two similarities can be found comparing the results presented above and those found in the literature; namely, the relationship between density and land-use mix (Chen et al. 2008) and the relationship between house size and household composition (Ewing and Rong 2008).

The few similarities and many differences in the results substantiate the argument that researches on the relationship between cities and energy consumption should pay more attention on these aspects rather than mainly focus on the direct relationships between urban features and energy use. The relationship between cities and energy consumption is complex and multidimensional because of the complexity and multidimensionality of cities, therefore in order to better understand this complexity is necessary to consider both the direct relationships between the different urban features and energy consumption and the relationships among the urban features, which may indirectly but significantly affect energy consumption and CO_2 emissions.

4.2 Regression Analysis

Three regression models (OLS) were estimated in order to measure the direct relationships between urban and energy features. In these three models, the dependent variables are three of the five categories of CO_2 emissions—residential, transport and total—and the eleven independent variables are housing density, house material, green areas, concentration of manufacturing activities, concentration of commercial activities, concentration of touristic activities, degree-days, topography, income, car ownership and household composition.

The selection of the eleven independent variables was based on the results of the correlation analysis: variables with a Pearson's correlation coefficient greater than 0.65 were discarded (i.e. average floor area per capita; percentage of buildings built after 1980; jobs per square kilometer; concentration of public activities; coastal location; graduates per 1.000 inhabitants; percentage of foreign residents).

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[4] For the sample of 73 Italian cities, the Pearson's correlation coefficient between housing density and population density is 0.99.

Table 5 OLS results for residential CO_2 emissions

	Residential CO_2 emissions per capita		
	Coefficient	*p*-value	VIF
Degree-days	0.753	0.000	1.000
Adjusted R^2	0.420		

Both dependent and independent variables included in the three multiple regression analyses are in natural log form[5], with the exclusion of the dummy variable "Topography". Therefore, the regression coefficients can be interpreted "as the average percentage change in the dependent variable corresponding to a percentage change in the independent variable" (Creutzig et al. 2015). The predictors initially included in each of the three regression models were then reduced by applying the backward stepwise method[6].

The results for the regression model with residential CO_2 emissions per capita as dependent variable (Table 5) show that emissions from buildings change considerably with changes in climate conditions: every 1% increase in degree-days corresponds to a statistically significant 0.75% increase of residential emissions. This result is in line with previous findings (Creutzig et al. 2015; Ewing and Rong 2008). Furthermore, the model also shows that only one determinant explains two-fifth of the variance in residential emissions per capita. The other independent variables, including those describing the physical subsystem of a city, are not statistically significant, and thus removed from the final model (backward elimination procedure).

The results for the regression model with transport CO_2 emissions per capita as dependent variable (Table 6) show that emissions from transportation moderately depend on the geographical and functional characteristics of urban settlements. Emissions are higher in colder cities with a concentration of touristic activities. Moreover, valley cities (topography $= 0$) emit 41% more for transportation than mountain cities (topography $= 1$).

When residential and transportation emissions are considered together with emissions from municipal and tertiary buildings, results become even more interesting. Table 7 shows that total CO_2 emissions per capita decrease with increasing housing density, increase with increasing house age, degree days, the concentration of green areas and that of commercial activities, and that mountain cities emit less than valley ones.

The geographical features are the most important factors: every 1% increase in degree days corresponds to a statistically significant 0.39% increase of total emissions; valley cities emit 0.13% more CO_2 emissions per capita than mountain ones.

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[5] See paragraph 3.4.3.2 for more details on the loglinear model.

[6] "*Backward elimination of variables chooses the subset models by starting with the full model and then eliminating at each step the one variable whose deletion will cause the residual sum of squares to increase the least. This will be the variable in the current subset model that has the smallest partial sum of squares*" (Rawlings et al. 2001).

Table 6 OLS results for transport CO_2 emissions

	Transport CO_2 emissions per capita		
	Coefficient	*p*-value	VIF
Degree days	0.391	0.066	1.012
Concentration of touristic activities	0.228	0.015	1.030
Topography	−0.410	0.027	1.019
Adjusted R^2	0.140		

Table 7 OLS results for total CO_2 emissions

	Total CO_2 emissions per capita		
	Coefficient	*p*-value	VIF
Housing density	−0.128	0.002	2.265
% of masonry buildings	0.234	0.037	1.061
% of green areas	0.092	0.006	2.493
Concentration of commercial activities	0.243	0.079	1.020
Degree-days	0.391	0.000	1.236
Topography	−0.132	0.046	1.151
Adjusted R^2	0.458		

With respect to the physical variables, every 1% increase in housing density corresponds to a statistically significant 0.13% decrease of total emissions. This result substantiates the argument that compact cities consume less energy and emit less CO_2 than sprawl ones (Bereitschaft and Debbage 2013; Clark 2013; Creutzig et al. 2015; Ewing and Rong 2008; Makido et al. 2012). Similarly, every 1% increase in the percentage of masonry buildings corresponds to a 0.23% increase of total emissions, thus meaning that house material significantly affects the energy performance of buildings when residential, tertiary and municipal buildings are considered together. If tertiary and municipal buildings are excluded, indeed, this correlation is not found significant (Table 5). Furthermore, if we look at the matrix of correlation coefficient (Table 4), tertiary CO_2 emissions and the percentage of masonry buildings have a correlation coefficient of 0.49, which suggests that the different construction materials have a significant influence on the energy use of tertiary buildings.

Another interesting finding is that every 1% increase in the percentage of green areas corresponds to a 0.09% increase of total CO_2 emissions. This result is particularly interesting because, up to now, green areas have always been considered for their microclimatic benefits. Vegetation, indeed, can effectively contribute to mitigate the urban heat island phenomenon (Dimoudi and Nikolopoulou 2003; Gargiulo et al. 2016, 2017; Oliviera et al. 2011; Zoulia et al. 2009), i.e. the increase in urban temperatures compared to the surrounding rural areas. However, the studies on the

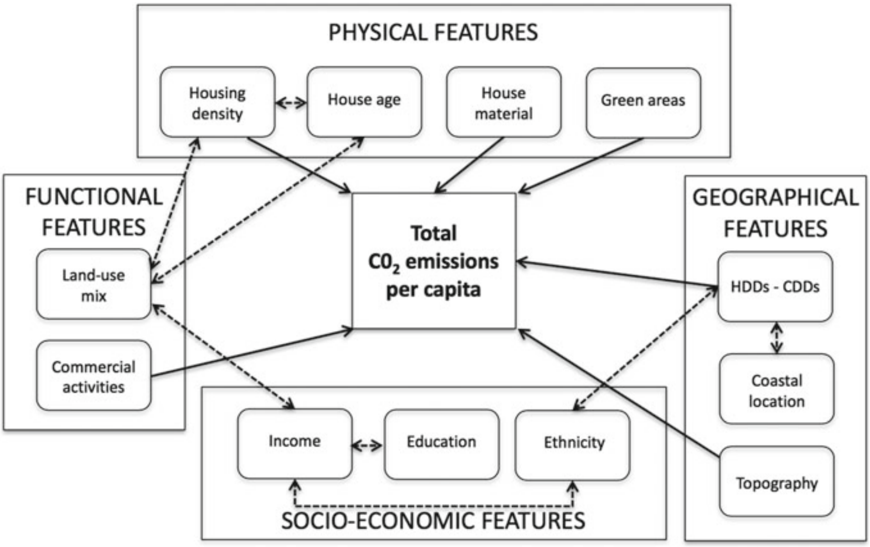

Fig. 3 Direct and indirect relationships between the urban features and total CO_2 emissions

positive effects of green spaces are limited to the cooling effect during summer time. Therefore, they did not consider the potential negative impacts of vegetation during winter time, which may increase energy use for space heating by increasing winter air temperatures. This negative effect can explain the positive correlation between the density of green areas and total CO_2 emissions that is shown in Table 7.

These results are show that two categories of urban features mostly affect CO_2 emissions on a city scale: namely, physical and geographical features. Although the geographical characteristics of urban areas cannot be modified by human actions, the physical attributes can be transformed through land-use planning decisions, and thus are of main interest for planners and policy makers.

4.3 Discussion

The complex relationship between cities and energy consumption/CO_2 emissions involves two main types of interactions: (1) the direct relationships between urban and energy variables; and (2) the relationships among the different urban features, which indirectly but significantly affect the carbon and energy footprint of cities.

Based on this conceptual framework, the main results of this research are summarized in Fig. 3, which includes both types of interactions: solid arrows represent the relationships between the urban features and total CO_2 emissions (found through the regression analysis); dashed arrows represent the relationships amongst the four groups of urban features (found through the correlation analysis).

When considering both direct and indirect effects, all the four groups of urban variables affect total CO_2 emissions per capita. More specifically, three physical variables (i.e. housing density, house material and green areas), one functional variable (i.e. the concentration of commercial activities), and two geographical variables (i.e. degree-days and topography) have a direct effect on CO_2 emissions: lower density of dwelling units and lower air temperatures, as well as valley topography and higher concentrations of masonry buildings, green areas and commercial activities increase CO_2 emissions per capita.

On the other hand, three socio economic variables (i.e. income, education and ethnicity) and one functional variable (i.e. land-use mix) indirectly affect CO_2 emissions through the mediators of other urban features.

In particular, a higher level of education and a higher share of foreign residents are both associated with higher income that, in turn, is associated with higher land-use mix that corresponds to higher housing density, which reduces CO_2 emissions per capita. However, at the same time, a higher concentration of foreigners also corresponds to higher degree-days, which increases CO_2 emissions per capita.

5 Conclusions

As a factor of economic growth, technological progress and social change, energy can be considered the driving force behind urban development. Nevertheless, using and producing energy is responsible for about 65% of global greenhouse gas (GHG) emissions (Marrero 2010), which, in turn, are responsible for climate change. The dramatic consequences of climate change—such as the warming of the atmosphere and the oceans, the intensification of extreme weather events, and the issue of food security, to name a few—are expected to increase in the coming years, especially if no action is taken.

Therefore, in order to prevent climate change and preserve our planet for future generations, the European Commission has recently proposed new ambitious energy goals to cut its GHG emissions substantially and turn Europe into a highly energy efficient and low-carbon economy. In particular, key EU targets for 2030 require EU countries to increase energy efficiency by 27%, and cut GHG emissions by 40% compared with 1990. Thus, European countries have to consider energy inside the urban planning process (Papa and Fistola 2016), in order to pursue together social, economic and environmental goals.

In this context, urban areas should be at the center of these sustainable policies, because "urban energy systems provide significant opportunities for increased efficiency in delivering transport and building services" (IEA 2016). Cities, indeed, consume up to 75% of global energy and account for 78% of carbon emissions (CO_2) produced by human activities (Habitat-UN 2011; IEA 2016). Thus, urban areas play a key role in addressing climate change.

Based on these considerations, this research aimed to identify the urban factors that significantly affect a city's energy and carbon footprint, thus supporting policy-makers in the definition of effective strategies and policies that can be implemented at urban scale to reduce energy consumption and resulting CO_2 emissions.

Two main innovations were introduced in this research. The first innovation concerns the approach: we used a holistic approach rather than a sectorial one, thus considering at the same time a comprehensive set of urban factors—physical, functional, geographical, and socio-economic—describing the complexity and multidimensionality of cities for measuring their impacts on CO_2 emissions. Second, we didn't limit the analysis to the direct relationships between the urban features and energy consumption, but we also investigated the relationships among the different urban features, which indirectly but significantly affect energy consumption on an urban scale.

This integrated approach allowed the identification of the existing trade-offs between different urban features and energy saving, providing a broader and more complete picture on such a complex topic.

The first step in this research was to review the scientific literature on the relationship between cities and energy consumption over the past twenty years. This review allowed the identification of the urban and energy variables to be included in the statistical models later developed to investigate this relationship. In particular, a set of eighteen urban variables and five energy variables was collected for a sample of seventy-three Italian capital cities, uniformly distributed across the country. The complete dataset was then explored and analyzed using different statistical methods, each of which provided useful insights into the complex relationship between cities and their carbon footprint.

The results of the regressions analysis show that three physical features—housing density, house material, green areas—and two geographical features—degree-days and topography—significantly affect total CO_2 emissions per capita ($R2 = 0.46$, p value < 0.05): with each 1% increase in housing density, total CO_2 emissions decrease by 0.13%; every 1% increase in the percentage of masonry building respect to concrete ones corresponds to a 0.23% increase in emissions; every 1% increase in the density of green spaces corresponds to a 0.09% increase in emissions; every 1% increase in degree-days corresponds to a 0.39% increase in emissions; and total CO_2 emissions decrease by 0.13% when passing from valley to mountain cities. The significant effects of housing density and degree-days on CO_2 emissions substantiate previous findings (Bereitschaft and Debbage 2013; Clark 2013; Creutzig et al. 2015; Ewing and Rong 2008; Gargiulo and Lombardi 2016; Makido et al. 2012). On the other hand, results on the influence on CO_2 emissions of construction materials, green areas and topography have not been found in the literature so far, and therefore require further investigation for being validated. Green areas, in particular, have always been considered a positive element within the urban context because of their capability of reducing air temperature during summer time; the potential negative effects of green spaces on urban temperature during the winter have not been investigated so far.

The results of the correlation analysis show that more compact cities have a higher density of jobs that, in turn, corresponds to a higher average income, a higher number of graduates and a higher share of foreign residents. These findings partially contradict previous results found in the literature. More specifically, Brownstone and Golob (2009) as well as Ewing and Rong (2008) find that density and income are negatively correlated in the US: richer people are more likely to live in sprawl counties. Within the Italian context, in contrast, the association between density and income is positive: higher levels of income are concentrated in urban settlements with a higher share of jobs and dwelling units. This difference can be explained considering the dissimilarities between North American and Italian cities in terms of urban development due to the very different historical backgrounds and economic growth paths. These considerations highlight the importance of sample homogeneity for the investigation of the relationship between cities and energy consumption, because the physical, functional and socio-economic characteristics of urban areas may significantly differ among cities of different countries. Therefore, when the relationship between cities and energy consumption is investigated at global scale (i.e. considering a sample of cities of different countries), cities should be clustered in order to account for historical and socio-economic differences, which might confound the final results.

Integrating both correlation and regression analysis results (Fig. 3), this research shows that the two main categories of urban factors directly affecting CO_2 emissions per capita are the geographical and physical features, whereas the functional and socio-economic characteristics of urban areas have an indirect effect on CO_2 emissions.

In other words, the climate condition of a city and its physical structure (both in terms of urban density and buildings characteristics) are in large part responsible for the use of energy and the resulting CO_2 emissions within the urban perimeter. Given that the geographical factors of cities cannot be changed by human intervention, the key role of urban policies and spatial planning in addressing energy and environmental issues becomes of strategic importance for addressing climate change.

In this regard, two main policy implications are drawn from the results of both correlation and regression analysis; one at the building scale and one at the urban scale. (1) At the building scale, interventions should focus on buildings materials, especially for reducing the energy use of masonry buildings. (2) At the urban scale, planning strategies should encourage compact developments in order to reduce energy consumption and total CO_2 emissions. Furthermore, besides the lower energy footprint of compact cities, in Italy higher densities of housing units correspond to higher densities of jobs, which in turn are characterized by higher incomes, and therefore strategies for promoting urban compactness can also have positive economic effects.

This work confirms the complexity and multidimensionality of the relationship between cities and energy consumption and the importance of both building and urban interventions to increase energy saving and decrease CO_2 emissions on a city scale (Zanon and Verones 2013). Furthermore, the results of this research, which only partially support previous findings, suggest that important trade-offs exist between the different urban characteristics and the energy and carbon footprint of cities (Doherty et al. 2009; Lee and Lee 2014; Papa et al. 2014, 2016). Measuring all of the trade-offs is a very challenging task, and this research proposed a first step in this direction.

5.1 Limitations and Future Developments

This research has several limitations. The first limitation is data availability. Because of data limitations, indeed, (1) data on urban areas and energy consumption/CO_2 emissions refer to two different time periods, and moreover, (2) some urban sectors that significantly affect energy consumption and resulting CO_2 emissions, such as industry, could not been considered. Furthermore, if more data were available, a more numerous sample of cities would have allowed the construction of different regression models for each group of cities obtained with the cluster analysis, thus providing more detailed information about the energy behavior of different typologies of urban areas.

The second limitation concerns the statistical methods used to estimate the relationship between cities and energy consumption: the correlation analysis and the multiple regression analysis do not allow the identification of a causal link between the variables considered. In other words, a strong correlation between two variables does not imply a direct link between these variables but it could be the results of an indirect interaction that involves other variables. Therefore, future research should focus on using different statistical model to study the complex relationship between cities and energy consumption, such as, for example, a multilevel structural equation model, which simultaneously tests multiple causal relations (Lee and Lee 2014).

The third limitation concerns the research's sample: the results of the analyses previously described refer to a sample of Italian cities, therefore they may not apply to different geographical contexts. As previously highlighted, indeed, urban and energy features significantly differ from one country to another, and these differences may translate into different results.

An interesting future development of this work would be to apply the same methodology to different countries and compare the results in order to identify similarities and differences and better support policy makers in the definition of effective urban strategies for reducing energy consumption and CO_2 emissions on a city scale.

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