Urban Density and Household-Electricity Consumption: An Analysis of the Italian Residential Building Stock

Valentina Antoniucci, Adriano Bisello, and Giuliano Marella

Abstract The influence of urban density on household electricity consumption is still scarcely investigated, despite the growing attention to building energy performance and the electrification of heating systems advocated at the European level. While the positive correlation between urban sprawl developments and the increasing of marginal costs of public infrastructures, services, amenities, public, and private transports are known, there has been little research on the relationship between urban form and electricity consumption in residential building stock. The present work aims to contribute to filling the gap in the existing literature, presenting the early results of ongoing research on the role of urban form in the household electricity consumption in Italy and, consequently, the related energy costs. The building typology and, in general, the structure of urban dwellings, is crucial to forecasting the electricity requirements, taking into account single housing units and their spatial composition in multi-family homes and neighborhoods. After a brief literature review on the topic, the contribution presents empirical research on the electricity consumption at the municipal level in 140 Italian cities, analyzing the diverse consumption patterns under different conditions of urban density to verify whether there exists a significant statistical correlation between them. The analysis confirms that there is a statistically negative correlation between urban density and the log of electricity consumption, even if its incidence is very limited. Further investigation may highlight whether there exists a threshold for which this relationship would be reversed, explaining the higher electricity consumption in dense metropolitan areas.

Keywords Energy sprawl · Housing market · Electricity consumption · Household behavior · Urban density

V. Antoniucci (✉) · G. Marella
ICEA Department of Civil, Architectural and Environmental Engineering, University of Padova, 35131 Padova, Italy
e-mail: valentina.antoniucci@unipd.it

A. Bisello
Eurac Research, Institute for Renewable Energy, Viale Druso 1, 3900 Bolzano, Italy

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1 Introduction

The relationship between energy consumption and urbanization is contentious. In his chapter in the Oxford Handbook of Energy and Society (2018), Peter Sadorsky states (p. 181): "[…] Urbanization leads to more economic activity and energy use. Economies of scale and energy-efficient transportation and infrastructure can reduce energy use, which makes it difficult to predict what the overall impact of urbanization is on energy intensity." The present contribution focuses on the role of urban morphology on energy consumption and electricity consumption, specifically in Italy. While the topic of energy consumption, and energy-saving mostly, is nowadays widely studied at the building level from a technological perspective, the role of the urban environment is far less analyzed. Nevertheless, it is known that the organization of infrastructures, housing, commercial dwellings, and industries has a significant consequence of global energy consumption. As Gago et al. state: "Cities occupy 2% of the earth's surface, but their inhabitants consume 75% of the world's energy resources" (Gago et al. 2013). An in-depth analysis of energy and electricity consumption may be helpful to support public policies both at the municipal and regional levels (Keirstead et al. 2012; Grilli et al. 2018; Moroni et al. 2019).

In the last decade, most of the literature focuses on the forecasting of electricity consumption (Marvuglia and Messineo 2012; Hernandez et al. 2013) and on the innovation of devices help to reduce the consumption (Verbong et al. 2013; D'Oca et al. 2014; Park et al. 2014). Nowadays, several studies approach the relevance of urbanization processes and urban structure in energy consumption, including electricity. But the empirical analysis is focused on analyzing various sectors or the overall energy intensity, mostly concentrating on Anglo-Saxon countries (Larivière and Lafrance 1999; Lenzen et al. 2004; Howard et al. 2012) and in the Far East (Holtedahl and Joutz 2004; Liu 2009; Cui et al. 2019), given the several issues on the environment caused by the continually growing population and urbanization in the latter mentioned countries. The excessive consumption of electricity has become a problem also in the West, which more and more often are experiencing blackouts and electricity shortages at the metropolitan and even the regional level (Moroni et al. 2018). As will be discussed more deeply in the next paragraphs, the relationship between electricity consumption and spatial structure concerns various features (Li et al. 2018).

On the one hand, high population density reduces the electricity consumption for transportation and infrastructures (Morikawa 2012). Still, on the other hand, the high differential between metropolitan cities around the world in electricity consumption's efficiency (Larivière and Lafrance 1999) has been demonstrated. Lastly, another gap in the current literature is the absence of empirical analysis of medium and small towns. If the higher relevance of electricity issues for metropolitan areas and megalopolis (Zhang and Lin 2012) is understandable, on the contrary, it is not possible to generalize conclusions from these kinds of studies to sprawling settlements, both in North American or in Europe. Consequently, policy suggestions may be misleading if based on results related to just one kind of urban form. The present paper provides an empirical analysis of the features affecting electricity consumption in the residential sector with a focus on the urban form. We adopt traditional variables such as population density to describe cities' morphologies (Burton 2002; Del Giudice et al. 2019b), and also recently added indicators related to the built environment already tested in Italy (Antoniucci and Marella 2016; Bisello et al. 2020). Moreover, we test our analysis with economic variables relevant to the energy consumption, according to the existing literature on the topic (Bianco et al. 2013; Giuffrida et al. 2018; Bencardino and Nesticò 2019), and we add other variables helpful in defining the consumption of residential building stock. We also decided not to include in the model any variable or proxy related to space heating (e.g., natural gas, biomass, or liquefied petroleum gas consumption).

The remainder of the paper is structured as followed: the next paragraph summarizes the electricity consumption in Italy, while Sect. 2 describes the methodology and the sample of data adopted for the statistical analysis; Sect. 3 presents the results of the multivariate regressions; and Sect. 4 discusses it. Finally, Sect. 5 provides the conclusion, policy implications, and suggestions for further research.

1.1 Electricity Consumption in Italy

Beginning in 1963, gross domestic electricity use increased until 2008, when consumption began to decrease (Torriti 2012). In recent years, electricity consumption in Italy (for all sectors) has been about 331 TWh/y (Data source: Terna a). In 2018, 57.3% of energy came from traditional sources, while 31.3% came from renewable ones. The production from renewable sources is highly diversified across regions, and it is slowly but consistently increasing.

The remaining 11.4% streams from abroad. Italy is the second country in Europe, after Germany, for imported volumes of energy with an energy-dependency rate of more than 75% (Source: Eurostat). The residential sector comprises just 21.5% of the overall electricity consumption. In comparison, the greater part is consumed by the industry sector (41.7%), followed by services (34.9%). Agriculture is less than 2% of total electricity consumption (Data: Terna 2018). In respect to 2017, only agricultural and residential use is decreasing, while other sectors present a slight increase. The per capita residential average consumption is 1.078 kWh/in (Source: Tern a, b).

Competitiveness in the Italian electricity market is highly limited by the dominant position of the former public electricity company, Ente Nazionale per l'Energia Elettrica (ENEL), which is present in all the stages of the production process. It has a dominant position also in the distribution market that was opened in 2001 to other companies. The experiences of small-scale production and distribution of electricity from renewable sources are still few and vary greatly across countries. Regions such as Trentino, South Tyrol, Emilia Romagna, and Tuscany have a tradition of local cooperatives that have contributed to the development of energy communities at the municipal and territorial levels (Moroni et al. 2018). Nevertheless, the adoption of

RES coupled with the governance model of the energy community is still related to specific experiences, not pervasive at the territorial level, nor primarily supported by National and Regional legislation. National laws promote incentives for renewable resources for several years. However, their effects are still not robust enough to support the expansion of micro-grids and substantially change household behavior (Mangialardo and Micelli 2018; Massimo et al. 2018).

2 Methodology and Sample Data

We adopt this general form of multivariate linear model according to (Rosen 1974) and already tested for similar empirical research (Larivière and Lafrance 1999):

$$(\log)Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_n X_{in} + \epsilon_i$$

where y is the dependent variable and the (log) is annual city electricity consumption per inhabitant in the residential sector. The independent variables are $\beta_0, \beta_1, \beta_2, \ldots, \beta_n$ related to two diverse groups of characteristics: the socioeconomic features and the building stocks features (see Table 1): These parameters are estimated with the method of least squares, while ϵ_i is the statistical error. The observations in the sample (n) are 140, which are all the Italian cities with more than 50,000 inhabitants. All the data refer to 2012 because, for most of the cities, this is the last year of release of the per capita electricity consumption, provided by the

Table 1 Variables

	Variables	Measure unit
Dependent variable	Per capita electricity consumption	(kWh/year)
(Log) Dependent variable	(Log) Per capita electricity consumption	(no.)
Socioeconomic features (independent variables)	Per capita income	(€/year)
	Employment rate	(%)
	GDP	(€)
Urban features (independent variables)	Population density	(inh/km^2)
	Urban density	(no.)
	Residential buildings with just one level	(no.)
	Residential buildings	(no.)
	Housing units	(no.)
	Degree days	(no./year)

Covenant of Mayors for Climate and Energy. According to the dependent variable, all the independent ones are related to this year.

The socioeconomic features represent mostly the spending capacity of households and the wealthy of the cities and territories, in general (Bianco et al. 2013; Nesticò et al. 2018; Bencardino and Nesticò 2019). Employment rates and GDPs are available only at the provincial and regional levels, while per capita income is at the urban scale (Del Giudice et al. 2019a). The data related to the first two variables are provided by the Italian National Statistics Institute (ISTAT). At the same time, per capita income is gathered from the Open Data of the Department of Finance of the Italian Ministry of Economy and Finance.

Six variables represent the urban features: Urban density, which is the focus of the empirical research, is represented by two diverse variables. The first one is the population density, which is traditionally the most-used data to express this feature (see, among others, Brueckner and Fansler 1983; Burton 2002; Galster et al. 2001; Holden and Parr 2013). The second is the urban density, designed as built density and already tested by other empirical research in Italy (Antoniucci and Marella 2016, 2017a, b). It is measured as the ratio between the number of housing units per residential building at the city level. Thus, we also tested the number of housing units and the number of residential buildings: these figures are all provided by ISTAT. They were collected during the 2011 National Census of Population and Buildings. The data is also reliable for 2012, given the small time shift and the scarce activity of the construction industry in Italy at the time (Ance 2019). Lastly, we consider the number of single-storey buildings, which helps to identify the urban-sprawl phenomenon, where the villas and semi-detached houses are more frequent than in high-density cities. These typologies mostly have one or two floors. Conventionally, the variable called degree-days represents the number of days on which the heating system is used. By law, they are calculated from the first three days when the temperature is under 12 °C to the first three days when the temperature is above this threshold.

Descriptive statistics summarized in Table 2 are coherent with the national indicators, even if some data such as employment rate and the GDP are slightly lower than the national average (56,4% and 25,700 €, according to ISTAT). The sample represents low-density cities, with 3.8 units per residential building on average, with a maximum of 14 units in the denser metropolitan areas.

3 Results of the Model

We tested for a diverse combination of variables, and the model results for the log of annual electricity consumption, with a sample of 140 observations, is described by the following empirical equation:

$$\text{Log annual city electricity consumption per inhibitant} = 2088255 + 0.00000487 * \text{population density}$$

$$+ 0.00000723 * \text{per capita income} - 0.00003977$$
$$* \text{degree days} + 0.00171222 * \text{employment rate}$$
$$- 0.00565515 * \text{urban density} + 0.000005328$$
$$* \text{single} - \text{storey buildings}$$

Table 3 presents the regression analysis of the model, and it explains the 29.46% of the residential urban electricity consumption. This percentage is not particularly high, but it is anyway satisfactory considering the number of factors involved.

To increase the adaptability of the model, we reduced the sample to the provincial capitals, and we reduced the number of variables. The best model presents an R^2 adjusted of 37.7%, as summarized in the following Table 4, which is also coherent with similar statistical analysis on the topic (Lasarte Navamuel et al. 2018).

Table 2 Descriptive statistics of tested variables

Variables	Mean	St. dev.	Minimum	Maximum
Per capita electricity consumption (kWh/year)	1,130	143	841	1,604
(Log) Per capita electricity consumption (no.)	3.05	0.05	2.92	3.20
Degree days (no./year)	1,796	641	707.00	3,043
Per capita income (€/year)	20,453	3,250	11,094	30,798
Employment rate (%)	55.26	10.55	36.6	69.00
GDP (€)	24,500	6,390	16,369	37,316
Population density (inhab/km^2)	1,355	1,678	787	10,508
Urban density (housing units/residential building) (no.)	3.80	2.10	0.97	14.06
Single-storey buildings (no.)	2,105	3,054	25	18,009
Residential buildings (no.)	13,786	13,894	2,869	137,021
Housing units (no.)	58,643	11,7422	8,351	1,137,391

Table 3 Multivariate regression results with a sample of 140 observations

Variables	Coeff.	*T* Statistic
Constant	2.88255	103.58
Degree-days (no./year)	−0.0000398	−3.84
Per capita income (€/year)	0.0000072	3.91
Employment rate (%)	0.0017122	2.67
Population density (inhab/km^2)	0.0000049	1.76
Urban density (no.)	−0.0056552	−2.43
Single-storey buildings (no.)	0.0000053	3.70
N. observation		140
R^2 adj.		29.46%

Table 4 Multivariate regression results with a sample of 111 observations (provincial capitals)

Variables	Coeff.	*T* Statistic
Constant	2.89325	92.11
Degree-days (no./year)	−0.000067	−3.35
Per capita income (€/year)	0.0000078	2.09
GDP (€)	0.0000041	3.80
Urban density (no.)	−0.0067500	−3.35
Single-storey buildings (no.)	−0.0000049	3.17
N. observation		111
R^2 adj.		37.7%

Two variables have been changed, but the meaning of the results is confirmed by the previous model. Moreover, the incidence of urban density slightly increased. The scale of coefficients depends on the form of the dependent variable as a natural logarithm.

4 The Relevance of Urban Density

The model confirms the correlation between the urban density, meaning urban built environment, and the residential electricity consumption: the higher is the urban density, the lower is the electricity consumption (0.067%). The relevance of the number of buildings with just one level, moreover with the same sign of urban density, increases the robustness of the correlation described. As already demonstrated in the literature (see, among others, Chen et al. 2018; Wang and Yang 2019), per capita income and GDP have a positive correlation with the energy consumption. The wealthier is a city, the higher are the consumption of energy and electricity specifically.

We tested further the model's specifications, sub-dividing the original sample on the average urban density (3.8 residential units per residential building), but the statistical elaborations did not provide satisfying results. Examining the low-density cluster, urban density should not be relevant to explain electricity consumption (Sadorsky 2018).

These results are not incoherent with considerations related to the so-called "urban heat island" phenomenon. Since the pioneering studies of Oke (1982, 1973), it is well-known that a high density of population increases the overall energy consumption because urban structures "consume and re-radiate solar radiations" (Rizwan et al. 2008). The temperature increase in metropolitan areas is the result of several conditions and their interlinkages such as environmental features (climate and weather, topography, etc.), human activities (public and private transports, industries, etc.), and physical and morphological features (spatial distribution and density of the buildings, the materials of surfaces, the presence of green areas, etc.). The present analysis does not intend to dispute the higher electricity consumption in metropolitan areas and megalopolises compared to less dense urban settlements. Our results fit with the Italian urban morphology that, as the previous descriptive statistics demonstrate, are characterized by a dense constellation of small towns. Thus the overall urban density is anyway less than big metropolitan areas, even in other European countries. It is worth mentioning, for instance, that Rome is the most extensive city in Europe, so given its three million inhabitants, it is a low-density city considering other capitals such as London, Paris, or Berlin. No Italian cities have the morphology, population, and building density of the European metropolitan areas but if we will conduct the same analysis not at the municipal level but at territorial level, we would probably find that the whole Po Plain territory gather together all the features of an "urban heat island".

5 Conclusion

The present contribution presents the early results of ongoing research on the incidence of urban form in electricity consumption. The electricity savings are more and more important for the overall reduction of energy consumption and meeting the current climate and energy targets. The topic is mostly analyzed from a technological perspective in a twofold way: looking at the end-user side, the focus is on the improvement of building performance (Canesi and Marella 2017) and the increase of innovative devices to save energy. Moreover, on the supply side, the research is concentrated on the production and distribution of electricity at buildings and neighborhood scale (Moroni et al. 2016).

The relevance of urban form is scarcely analyzed even if the relationship between the costs of infrastructures and public services and the urban density is long since demonstrated (see, among others, Brueckner and Fansler 1983; Liddle and Lung 2014). To investigate this, we perform several multivariate regressions on a sample of 140 Italian cities with more than 50,000 inhabitants; then, we reduce the sample to the provincial capitals (111 cities) to refine the results. To measure urban density, we adopted the traditional indicator of population density (inhabitants per square kilometer) and an original indicator of building density (number of housing units per residential buildings). Moreover, we control for socioeconomic variables and other building stock features helpful to describe the urban structure of Italian cities.

Our tests demonstrate that the lower is the density, the higher is the electricity consumption. The early results here provided may help to design better public policies. This result is consistent with the existing literature on the topic, investigating similar urban contests in Southern Europe (Lasarte Navamuel et al. 2018) on one side but contradicts the literature on the so-called "urban heat islands", in which the denser is the urban structure, the higher are the temperature and electricity consumption. This is contradictory only apparently, and it should be explained by looking at the urban structure of Italian cities. Italy has across its territory a high density of small and medium cities, that anyway does not reach the density of metropolitan agglomeration of other European countries and much less than American cities. From this perspective, there is room for further research. Additional analysis may be performed comparing cities, at the European level at least, by density. We subdivided our sample by the average density, defining two clusters below and above the average building density. Still, the analysis does not provide significant results, given the low average density of Italian cities. This kind of investigation, on the contrary, may let to identify a threshold of density for the electricity consumption in denser contexts. Above this threshold, the meaning of the urban density would be reversed, explaining the "urban heat islands". Moreover, to reach more robust results, additional explanatory variables should be found—we suggest avoiding those potentially highly correlated with electricity consumption, as the use of gas or oil. Also, the spatial specification of the model may help detect hidden variables or heteroscedasticity (Anselin 2001). In Italy, it will be of particular interest to better understand the future development of the electricity consumption in the residential sector after the forthcoming national law, which will make possible for the first time small scale energy sharing among prosumers.

The goal of energy savings should also be reached considering the development of new urban dwellings and the re-development of brownfields. It is a critical issue in countries such as Italy, whose territory is already mostly built and characterized by an old and low performing building stock (Mangialardo and Micelli 2019; Bisello et al. 2020). Densification contributes to reducing the collective costs of infrastructures, public services, and as we demonstrated at least partially, it also may reduce electricity consumption, up to a certain threshold value. Even if in comparison to heating and cooling needs, electricity consumption is less affected by the features of building stock (such as age and maintenance status) the form and structure of urban settlements may be highly relevant.

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