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METHODS, TOOLS AND BEST PRACTICES TO INCREASE THE CAPACITY OF URBAN SYSTEMS TO ADAPT TO NATURAL AND MAN-MADE CHANGES

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FOCUS

LAND USE, MOBILITY AND ENVIRONMENT

TeMA Journal of
Land Use, Mobility and Environment

CALL FOR PAPERS: TEMA VOL. 11 (2018)

The Resilience City/The Fragile City. Methods, tools and best practices.

The fragile/resilience city represents a topic that collects itself all the issues related to the urban risks and referred to the different impacts that an urban system has to face with. Studies useful to improve the urban conditions of resilience (physical, environmental, economical, social) are particularly welcome. Main topics to consider could be issues of water, soil, energy, etc.. The identification of urban fragilities could represent a new first step in order to develop and to propose methodological and operative innovations for the planning and the management of the urban and territorial transformations.

The Journal also welcomes contributions that strategically address the following issues:

- new consideration of the planning standards, blue and green networks as a way to mitigate urban risks and increase city resilience;
- the territorial risks and fragilities related to mobility of people, goods, knowledge, etc.;
- the housing issue and the need of urban regeneration of the built heritage;
- socio-economical behaviour and the "dilemma" about emergency and prevention economy;
- the city as magnet of the next future's flows (tourism, culture, economy, migration, etc.).

Publishing frequency is four monthly. For this reason, authors interested in submitting manuscripts addressing the aforementioned issues may consider the following deadlines

- first issue: 10th January 2018;
- second issue: 10th April 2018;
- third issue: 10th September 2018.

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The Journal welcomes papers on topics at the interdisciplinary intersection of transport and land use, including research from the domains of engineering, planning, modeling, behavior, economics, geography, regional science, sociology, architecture and design, network science, and complex systems

TeMA Journal of
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CALL FOR PAPERS: SPECIAL ISSUE 2018

Urban Travel Behavior in the Middle East and North Africa

The characteristics of urban travel behaviors and the attitudes of passengers in the Middle East and North Africa (MENA) is less-studied. When it comes to the effects of urban form, residential self-selections, and lifestyles, it is entirely not investigated in majority of the countries of the region. There is a considerable knowledge gap about the circumstances of how people think and decide about their short-term, medium-term, and long-term mobility for commute and non-commute travels. The we do not know if the land use traits such as population and employment densities as well as mix of land uses, accessibility to public transportation and neighborhood amenities, and connectivity of street networks are as influential as they are in western counties or in higher income societies. There is a very limited understanding about the extent to which the personal preferences, lifestyles, and in general psychology of the people of the region affect their transport behaviors. The complexity of the analysis methods applied for studying urban travel phenomena of the MENA region is even less-developed. Longitudinal or discrete choice molding methods are applied in mobility research considerably less than studies coming from high-income countries.

This special issue collects the results of some of the most-recent studies on the MENA countries to fill out a part of the gap in English-language publications. The main topics covered by the issue include the following with focus on the MENA region:

- The role of urban form and land use in forming urban travel behavior;
- Urban sprawl and urban travel behavior;
- The effects of historical urban transformations on urban mobility decisions;
- Car ownership and use; car dependency;
- The impacts of socioeconomics and culture in forming the transport patterns;
- Lifestyles and personal preferences and urban travels; Perceptions of mobility, safety, security, neighborhoods;
- The interactions of travel behavior and health effects of different ages, genders, and income groups;
- Travel behavior of public transport riders;
- and similar topics.

The target countries of this issue are the ones that are referred to as the MENA counties in most of the definitions. Studies on the cities of Turkey and Pakistan are also of particular interest and welcome. Manuscripts about all city sizes are reflected by the issue. The authors interested in submitting manuscripts addressing the aforementioned issues may consider the deadline of 31st January 2018. All submissions will go through rigorous double-blind review, and if accepted will be published. Interested authors are requested to contact Houshmand Masoumi at masoumi@ztg.tu-berlin.de, to discuss submission and review procedure.

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CITIES AND ENERGY CONSUMPTION: A CRITICAL REVIEW

ABSTRACT

The relationship between cities and energy consumption has been of great interest for the scientific community for over twenty years. Most of the energy consumption, indeed, occurs in cities because of the high concentration of human activities. Thus, cities are responsible for a big share of carbon dioxide emissions (CO2). However, the debate on this topic is still open, mainly because of the heterogeneity of published studies in the selection, definition and measurement of the urban features influencing energy consumption and CO2 emissions, as well as in the choice of the energy sectors to be considered, in the territorial scale of analysis, and in the geographical distribution of the sample. Therefore, the goal of this research is to systematize and compare the approach, methodology and results of the relevant literature on the relationship between cities and energy consumption over the last twenty years. Furthermore, this critical review identifies the knowledge gap between what is known and what is still under debate and, based on that, it proposes a conceptual framework that will help to outline a new direction for future research and support local policy makers in the definition of strategies and actions that can effectively reduce urban energy use and CO_2 emissions.

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KEYWORDS:
Cities; energy consumption; CO_2 emissions; compact city; sustainability.

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城市与能源消耗:
一种批判性评论

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摘要

在 20 多年时间里，城市与能源消耗之间的关系一直是科学界关注的问题。大部分能源消耗的确是发生在城市中，因为在这里人类活动高度集中。因此，城市要为很大一部分二氧化碳（CO2）的排放负责。但是，围绕这个话题仍然存在争论，这主要是因为已经在已经发表的研究中，在选择、定义和测量能够影响能源消耗和 CO2 排放的城市功能时存在异质性，并且在选择要考虑的能源部门、在分析的地域范围、以及在样本的地理分布方面也有不一致。因此，本研究的目标是实现过去 20 年中有关城市与能源消耗之间关系的相关文献的途径、方法和结果的系统化和对比。此外，这项批判性评论还确定了已知内容与争议内容之间的知识差距，并据此提出一个概念框架，有助于概述未来研究的新方向，并支持本地政策制定者确定能够有效降低城市能源使用和 CO2 排放的战略和行动。

关键词：
城市；能源消耗；CO_2排放；紧凑城市；可持续性。

1 INTRODUCTION

Adopting the Paris Agreement in 2015, for the first time governments from all over the world agreed to "hold the increase in the global average temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (FCCC, 2015). Local governments play a key role in the implementation of actions aimed at decarbonisation (OECD, 2014). 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 (Papa et al., 2014). However, urban growth shows no sign of slowing, and the energy and carbon footprint of cities doesn't seem to decrease. Therefore, energy efficiency improvements in urban areas are urgently needed to meet national and global ambitious sustainable goals (Barresi & Pultrone, 2013; Morelli et al., 2013).

To support local policy makers' decisions and foster the transition towards a low-carbon future, a growing body of international research has been studying the complex and multidimensional relationship between cities and energy consumption. These studies differ from each other in a wide variety of ways. First of all, they take into account different types of urban characteristics (e.g. density, household size, income, etc.) and consider different types of energy consumption (e.g. total, transport, or residential energy consumption). Additionally, the samples of cities analyzed differ in scale, size and geographical location. Therefore, it is no surprise that this heterogeneity in approaches and methodologies leads to a variety in results. Literature does not provide a comprehensive critical review highlighting the gap between what we know – and we all agree about – and what we need to know about how cities affect energy consumption and CO_2 emissions (Jabareen, 2006). So the aim of this paper is to critically categorize and compare recent interdisciplinary scientific literature on the relationship between cities and energy consumption to develop a conceptual framework to guide future research based on the resultant new knowledge.

The paper is structured as follows. In Section 2 we present the approach used for this review and sets the temporal and contextual limitations of this work. In Section 3 we describe the critical review of the relevant literature on the relationship between urban areas and energy use, comparing approaches, methodologies and results of the different contributions. Finally, in Section 4 we propose a conceptual framework that provides new understanding based on the integration of the results previously described, and helps stimulating the debate on this topic. This framework aims to help define a new direction for future research and support local policy makers in the definition of strategies, policies and actions that can effectively reduce urban energy use and carbon dioxide emissions at city scale.

2 APPROACH

The relationship between cities and energy consumption is multidimensional, especially because cities are complex and dynamic systems (Batty, 2008; Papa, 2009); therefore, a comprehensive review about this topic calls for a holistic approach that considers a wider range of urban factors – physical, functional, geographical, social, economic – influencing the energy and carbon footprint of cities. Moreover, an integrated approach rather than a sectorial one also allows the identification of the existing trade-off between different urban features and energy saving (Doherty et al., 2009; Lee & Lee, 2014; Papa et al., 2016; Battarra et al., 2016; Gargiulo & Lombardi, 2016), providing a broader and more complete framework on such a complex topic.

A good review on the relationship between urban form and travel patterns can be found in Stead & Marshall (2001), while a detailed review on the relationship between urban structure (construction, maintenance and use of residential dwellings) and residential and transport related energy use can be found in Rickwood et al. (2008). However, urban form and structure are just two aspects of a bigger picture. In both reviews an integrated approach is missing, which takes into account the variety of urban factors affecting energy consumption and CO_2 emissions at city level.

Based on these considerations, this review combines interdisciplinary researches that investigate the multidimensional relationship between cities (in their complexity) 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: (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 & Marshall, 2001), this classification is based on the General System Theory (von Bertalanffy, 1969) applied to the urban phenomenon (Gargiulo, 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.

The first group of urban features – physical features – includes those variables measuring the *physical subsystem* of a city, which consists of the spaces/areas of an urban system that have been transformed in order to accommodate all different types of human activities. This set of variables describes the so-called urban form of a city. There is a little doubt that urban form – typically measured in terms of density – has been given a brighter spotlight within the overall scientific debate. Nevertheless, there are other physical factors whose influence on energy consumption and CO_2 emissions has been investigated by the reviewed studies, including those measuring polycentricity (Bereitschaft & Debbage, 2013; Chen et al., 2011; Lee & Lee, 2014) and fragmentation (Chen et al. 2011) as well as green areas (Banister et al., 1997; Gargiulo et al. 2016; Gargiulo et al., 2017; Holden & Norland, 2005; Ye et al., 2015).

The second group of urban features – functional features – includes those variables describing the type and scale of activities carried out in a given city and, therefore, it reflects the urban *functional subsystem*. Some examples of functional factors include the proportion of jobs in the city center (Camagni et al., 2002; Mindali et al., 2004; Newman & Kenworthy, 1989) or the mix of housing, business and services (Holden & Norland, 2005; Jabareen, 2006) within a specific area.

The third group of urban features – geographical features – comprises those factors that refer to the specific context of reference and describe the differences in geographic aspects such as topography – e.g. percentage of coastal area (Creutzig et al. 2015; Ewing & Rong, 2008) – and climate – e.g. heating/cooling degree days (Baur et al., 2013; Creutzig et al. 2015; Ewing & Rong, 2008; Kennedy et al., 2009). This group provides a characterization of the whole urban territory, so reflecting the city's *geomorphological subsystem*.

Finally, the fourth and last group of urban features – socio-economic features – reflects the urban *anthropic subsystem*, which consists of all of the city's inhabitants as well as those people conducting activities for a limited amount of time within the urban perimeter. These urban features describe both social and economic aspects: examples of social variables analyzed by the reviewed studies include the level of education (Brownstone & Golob, 2008; Holden & Norland, 2005) and the proportion of young population (Banister et al., 1997), while examples of economic indicators are the income (Baur et al., 2013; Clark, 2013; Creutzig et al., 2015; Ewing & Rong, 2008; Holden & Norland, 2005; Kennedy et al., 2009; Makido, 2012) and the number of vehicles per inhabitant (Banister et al., 1997; Brownstone & Golob, 2009; Mindali et al., 2004).

In addition to this first categorization, the review also allowed the identification of different categories of energy consumption and/or CO_2 emissions. Therefore, we have distinguished between: (a) energy consumption/CO_2 emissions from the transport sector; (b) energy consumption/CO_2 emissions from the residential sector; (c) total energy consumption/CO_2 emissions. Based on this structure (Figure 1), we have developed a conceptual framework that integrates the different connections between urban features and energy consumption/CO_2 emissions that have been empirically evaluated by published studies.

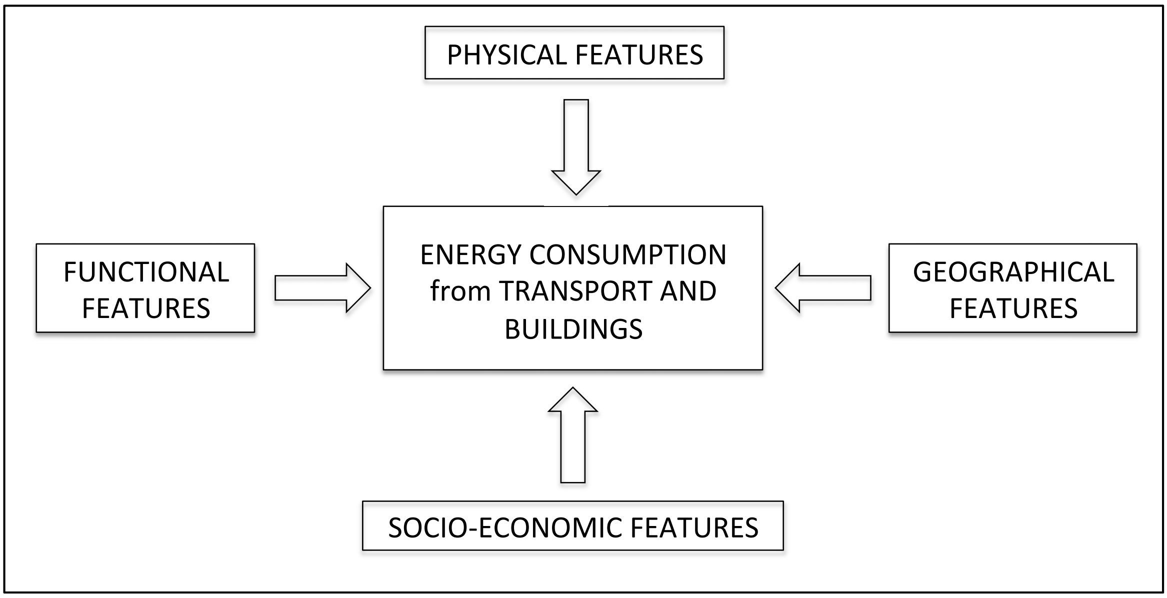


Fig. 1 Structure of the review

In particular, this review includes empirical and modeling peer-reviewed studies that encompass a variety of cities samples, many of which located in Western Europe, in the United States and East Asia. Although some studies up to 2000 are reviewed, greater attention is given to those studies published after 2000. As to the scale of analysis considered in this paper, we limited our analysis to those studies that evaluate the connections between urban areas and energy use at urban scale. Table 1 presents a synthesis of the review. In particular, each article has been categorized based on the urban feature/s (axis y) and the type of energy consumption/CO_2 emissions (axis x) considered. This table helps identifying on what researchers' attention has mainly focused and where critical knowledge gaps concentrate.

3 RELATIONSHIPS BETWEEN URBAN FEATURES AND ENERGY CONSUMPTION

3.1 PHYSICAL FEATURES AND ENERGY CONSUMPTION

The aim of this paragraph is two fold: to shed light on the lack of a shared definition of urban form and to clarify the ongoing debate on the relationship between urban compactness and environmental sustainability.

Despite numerous efforts to define urban form, a shared approach for measuring the physical component of a city is still missing (Jabareen, 2006; Levy, 1999; Marshall, 2005; Newton, 2000). The complexity of connections between the city and both natural and anthropic activities makes the definition of urban form a challenging task that depends on multiple factors, which are often underestimated or even unrecognized (Lynch 1981). Nevertheless, there is a wide consensus of opinions that urban form – in all its definitions – can have an influence on energy consumption and CO_2 emissions, and consequently a great number of studies have investigated this relationship. In this context, the dichotomy between compact and dispersed city appears to be a key factor in the identification of a sustainable urban form. However, although it has long been argued that sprawling cities tend to consume higher amounts of energy than compact ones (Banister et al., 1997; Clark, 2013; Ewing & Rong, 2008; Marshal, 2008; Newman & Kenworthy, 1989), there has also been some criticism (Baur et al., 2013; Brownstone & Golob, 2008; Echenique et al., 2012; Mindali et al. 2004). Therefore, the relationship between urban compactness and environmental sustainability is not straightforward, yet (Chen et al., 2008, Williams et al., 2000).

URBAN FEATURES	**CATEGORIES OF ENERGY CONSUMPTION/CO_2 EMISSIONS**		
	ENERGY CONSUMPTION / CO_2 EMISSIONS FROM TRANSPORT	ENERGY CONSUMPTION / CO_2 EMISSIONS FROM BUILDINGS	TOTAL ENERGY CONSUMPTION / CO_2 EMISSIONS
PHYSICAL	Banister et al. (1997) Baur et al. (2013) Bereitschaft & Debbage (2013) Brownstone & Golob (2009) Camagni et al. (2002) Clark (2013) Creutzig et al. (2015) Echenique et al. (2012) Holden & Norland (2005) Kennedy et al. (2009) Lee & Lee (2014) Makido et al. (2012) Marshal (2008) Mindali et al. (2004) Newman & Kenworthy (1989) Nuzzolo et al. (2014)	Chen et al. (2008) Chen et al. (2011) Echenique et al. (2012) Ewing & Rong (2008) Holden & Norland (2005) Kennedy et al. (2009) Lee & Lee (2014) Makido et al. (2012) Ye et al. (2015)	Baur et al. (2013) Creutzig et al. (2015) Echenique et al. (2012) Kennedy et al. (2009)
FUNCTIONAL	Banister et al. (1997) Camagni et al. (2002) Creutzig et al. (2015) Holden & Norland (2005) Mindali et al. (2004) Newman & Kenworthy (1989)	Holden & Norland (2005)	Creutzig et al. (2015)
GEOGRAPHICAL	Bereitschaft & Debbage (2013)	Ewing & Rong (2008) Kennedy et al. (2009) Makido et al. (2012)	Baur et al. (2013) Creutzig et al. (2015)
SOCIO-ECONOMIC	Banister et al. (1997) Baur et al. (2013) Brownstone & Golob (2009) Camagni et al. (2002) Clark (2013) Creutzig et al. (2015) Holden & Norland (2005) Kennedy et al. (2009) Makido et al. (2012) Mindali et al. (2004) Newman & Kenworthy (1989)	Ewing & Rong (2008) Holden & Norland (2005) Kennedy et al. (2009) Makido et al. (2012)	Baur et al. (2013) Creutzig et al. (2015) Kennedy et al. (2009)

Tab.1 Scientific researches categorized by urban feature and type of energy consumption / CO_2 emissions

When applying the general system theory to the urban phenomenon, and considering the physical subsystem, urban form should be measured in terms of housing density (i.e. the number of dwelling units in a given area) rather than population density (i.e. the number of inhabitants in a given area). Housing density, indeed, specifically refers to the built-up area of a city and provides a more precise idea of the physical urban development. However, most studies have considered population density a reliable and effective variable for the measurement of urban compactness (Breheny, 2001). Among these studies – both empirical and modeling – many agree that population density is negatively correlated with energy consumption and CO_2 emissions from transport and buildings. In particular, as far as the transportation sector is considered, Newman & Kenworthyy (1989) find a strong negative correlation between population density and annual gasoline use per capita for a global sample of 32 cities, using an analysis of correlation. Similar results are shown by Camagni et al. (2002) for the case study of Milan, that find a significant inverse relationship between population density and the index of mobility impact (which refers to the mobility demand generated in each municipality within the city's perimeter), using an analysis of regression. Same results are found by Banister et al. (1997) for five cities in the UK, that argue that "higher density urban areas may help reduce the need to travel", and by Kennedy et al. (2009), whose analysis of ten big cities in the world shows that GHG emissions from ground transportation fuels are negatively correlated with population density.

If the residential sector is considered, supporters of compactness are Holden & Norland (2005), who compare eight residential areas within the Oslo region and show that "in densely developed areas, residents use less energy than do residents in areas with lower-density housing. This is mainly the result of more efficient energy supply systems – such as remote heating systems based on heat pumps – than can be introduced in areas with a large number of housing units per area unit". In line with this argument, the study carried out by Chen et al. (2008) for a sample of 45 Chinese cities evaluates the relationship between population density and a set or urban environmental variables, including domestic electricity and natural gas consumption. Through an analysis of correlation, the authors find a weak inverse relationship between urban compactness and domestic energy consumption.

More recently, new support to the theory that compact developments are more energy efficient than dispersed ones came from Makido et al. (2012), Clark (2013), Bereitschaft & Debbage (2013), and Creutzig et al. (2015): Makido et al. (2012) use a correlation analysis and a multiple linear regression analysis to investigate the relationship between urban form and CO_2 emissions in 50 Japanese cities and find that higher population density is associated with less CO_2 emissions from the passenger transport sector; according to Clark (2013), "higher population density – particularly in core areas – correlates with lower levels of per capita travel, and transport-related energy consumption and carbon emissions in the United States", but it is also associated with diminished housing affordability and increased congestion; same geographical context – the U.S. – for the study carried out by Bereitschaft and Debbage (2013), that find for every standard deviation increase in residential density, CO_2 emissions from on-road vehicles decreases of approximately 1.9 million tons. On the other hand, Creutzig et al. (2015) find a strong negative correlation between population density and both transport energy use and GHG emissions for a sample of 274 global cities, using both a correlation and a regression analysis.

Along the same line of thoughts, however using a modeling approach rather than an empirical one, Marshal (2008), Lee & Lee (2014) and Nuzzolo et al. (2014) support the greater sustainability of denser urban areas, and quantify the impact of density on transport energy consumption and emissions. In particular, by comparing five U.S. urban growth scenario – high sprawl, business as usual (BAU), reduced sprawl, no sprawl, infill – Marshal finds that the reduced sprawl, no sprawl and infill scenarios decrease on-road gasoline CO_2 emissions compared to BAU, between 2005 and 2054, by 41%, 53% and 60% of a wedge respectively. Weaker but similar results are estimated by Nuzzolo et al., who compare five different scenarios – compact, transit oriented development, sprawl, trend, and BAU – for the city of Rome, and find that the compact scenario reduces CO_2 emissions and energy consumption deriving from car use by 24%. Analogously, Lee & Lee estimate for 125 urbanized areas in the U.S. that a 10% increase in population-weighted density – *"estimated as the weighted mean of census block group level densities, with each block group's population being used as the weight"* – decreases CO_2 emissions from travel and residential energy consumption by 4.8% and 3.5% respectively.

Criticizing all findings previously described, a smaller but consistent body of literature doubts the inverse correlation between population density and energy consumption/CO_2 emissions from transport and buildings. In particular, Mindali et al. (2004) highlight the inconsistency of the data collection method used by Newman and Kenworthyy in the 1989 study and find very different results using the same sample and data set but a multivariate statistical approach: when cities are divided into clusters – one of North American and Australian cities and one of European cities – urban density has no effect on energy consumption from transport for both groups. Similarly, Baur et al. (2013) critic the robustness of the sample used by Newman and Kenworthyy, in terms of geographical heterogeneity and numerosity. Also for a group of 62 European cities of different size they find that "population density is not, per se, a strong determinant of greenhouse gas emissions (neither for transportation GHG emissions, nor for total urban GHG emissions)". Similar results, but limited to California, are shown by Brownstone & Golob (2009), who argue that higher housing density decreases household vehicle use and resulting CO_2 emissions, but the impacts are too modest in magnitude to be considered significant – i.e. a 40% increase in housing density corresponds to a 5.5% fuel use reduction. In line with these findings, Echenique et al. (2012) use different models to estimate the sustainability of four spatial options – compaction, sprawl, edge expansion, and new town – for three different English city regions. They find that compaction decreases vehicle distance travel, but only by 5% compared to the trend, and the associated CO_2 reduction benefits are too small compared to "the potential socioeconomic consequences of less housing choice, crowding, and congestion".

In addition to the studies just described, which measure urban form in terms of population density, other researchers considered more complex indicators for assessing urban compactness and the way it affects energy consumption. Ewing & Rong (2008) measure urban form using Ewing et al.'s (2003) county sprawl index, which is calculated based on population density as well as street accessibility and clustering of development. For a sample of 266 U.S. counties, the authors indirectly estimate that urban sprawl positively affects residential energy use and, therefore encourage compact development. Similarly, Ye et al. (2015) analyze the case study of Xiamen and propose a normalized compactness index (NCI) based on Thinh et al.'s (2002) metric, which measures urban compactness in terms of gravity or attraction of a specific urban area. They find a positive correlation between the NCI and residential energy consumption, and interpret these results suggesting "that a compact city with heat and energy conservation from less-exposed wall and roof areas per capita, and more multifamily houses sharing foundations and resources, has residential energy savings".

A plurality of indicators is used by Chen et al. (2011) and Makido et al. (2012), who describe urban form using five and four different variables respectively. In particular, Chen et al. (2011) adopt a panel data analysis to study the relationship between five landscapes metrics – total urban class area, number of urban patches, mean perimeter-area ratio, Euclidean nearest neighbor distance, largest patch index – and energy intensity in production and living, in five Chinese cities. They find that (1) bigger cities consume more energy; (2) fragmentation in urban development increases energy consumption; (3) connectivity between patches is negatively correlated with energy consumption; (4) the largest patches index is negatively correlated with energy consumption, which suggests that concentration of urban activities should be encouraged, supporting the environmental sustainability of compact development. A similar approach is that employed by Makido et al. (2012), who consider three spatial metrics – the buffer compactness index (BCI), the compactness index (CI), and the area weighted mean patch fractal dimension (AWMPFD) – in addition to population density (measured in terms of urban area per capita and previously discussed), to estimate the relationship between urban form and CO_2 emissions from transport and buildings in Japan. Using a multiple linear regression analysis, the authors find that the BCI in the only spatial metric significantly correlated with energy consumption; in particular, increased BCI (i.e. increased compactness and monocentricity) decreases emissions from the passenger transport sector, but increases residential CO_2 emissions.

Although studies on the relationship between urban form and energy consumption mostly focus on the dichotomy between compact and sprawl development, some researchers include other physical urban variables in their analysis, such as house size, house typology, house age and availability of green spaces. In this context, it is shared opinion that bigger house size is associated with higher CO_2 emissions from transport (Lee & Lee, 2014) and buildings (Baur et al., 2013; Ewing & Rong, 2008; Holden & Norland, 2005), and that attached new houses are more energy efficient than detached old ones (Ewing & Rong, 2008; Holden & Norland, 2005). As far as green areas are concerned, results are not unanimous. In particular, Banister et al. (1997) find that the amount of open space in positively correlated with transport energy use in the case of Banbury and negatively correlated in the case of Oxford, while Ye et al. (2015) find that a greater connectivity and a weaker accessibility of green spaces is associated with higher CO_2 residential energy use. Furthermore, the study by Gargiulo et al. (2016), which specifically focuses on the influence of green spaces on urban microclimate, for the case study of Naples finds that there is a threshold value (i.e. 5.000 square meters) for green areas size that most effectively reduce residential summer cooling, and thus resulting CO_2 emissions.

To summarize, two main groups can be recognized in the debate on the relationship between urban form and energy consumption: those who support the compact city and those who question the relevance of its environmental benefits. 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.

3.2 FUNCTIONAL FEATURES AND ENERGY CONSUMPTION

Some of the studies on the relationship between urban form and energy consumption (described in the previous paragraph) also evaluate the energy and carbon footprint of a number of urban features that measure the functional organization of an urban system. It is of interest to note that the scientific literature does not offer any research that is exclusively focused on the relationship between urban functional features and energy consumption, but functional and physical features are always considered together. This may be because these two types of urban characteristics are very much connected to each other, and are both associated to the aforementioned compact city concept: in general, high-density and mixed-use development are typical of what can be defined a compact urban settlement (Burton, 2000), while the segregation of different land uses is typical of urban sprawl (Anderson, 1996).

In this context, the study carried out by Holden & Norland (2005) – earlier described for its results in terms of physical features and energy consumption – finds that the mix of housing, business and services does not have any significant effect on energy consumption from transport. Furthermore, the authors find a similar result for housing density, and suggest that "high density and high local mix must be combined with proximity to a center offering everyday services to bring about a reduction in energy use for everyday travel". However, stronger results are those found by Camagni et al. (2002), which use the ratio of jobs to resident population to measure the functional mix of a specific urban area, and find that this indicator is significantly inversely correlated with mobility, thus showing that higher mobility impact is associated with residential areas rather than with mixed ones. Similar results are those of Banister et al. (1997), that also use the ratio of jobs to population as a measure of functional mix, and find that mixed developments consume less energy from transport if local jobs and facilities are appropriate for local residents.

The proportion of jobs in the city center – calculated as the percentage of jobs within the central business district (CBD) – is one more indicator that describes the functional characteristics of different urban development and that has been considered by the scientific literature for its impact on energy consumption. In particular, Mindali et al. (2004) divide Newman & Kenworthy's (1989) sample of 32 global cities in two groups (i.e. North American and Australian cities; European cities) and find a strong negative correlation between this variable and gasoline consumption for both groups. This result confirms Newman and Kenworthy results from 1989. However, Newman and Kenworthy also find no correlation between the absolute number of jobs in the city center and gasoline use for their sample of 32 global cities. The two results together suggest that the effect of the strength of the city center on gasoline consumption is not straightforward and that it may be that "it is largely the transportation policies applied to central cities that determine whether or not a significantly centralized work force is going to have a positive or negative effect on gasoline use" (Newman & Kenworthy, 1989).

Finally, it is of interest to also look at the indicator employed by Creutzig et al. (2015) for measuring the economic activity of the world cities included in their sample. The authors use the "center of commerce index" (Worldwide Mastercard, 2008), which classifies 75 leading urban centers based on their role in enabling commerce worldwide, and find a positive correlation between this proxy and the total final energy use. This finding highlights the role of production activities as key factors affecting the carbon footprint of urban areas.

In summary, 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.

3.3 GEOGRAPHICAL FEATURES AND ENERGY CONSUMPTION

Ewing & Rong (2008) are the first to consider topographic and climatic variables in their analysis on the relationship between cities and residential energy consumption. In particular, they find a positive correlation between heating degree days (HDDs) and energy use for heating, as well as between cooling degree days (CDDs) and energy use for cooling. Furthermore, they include data describing the topographic configuration of the 266 U.S. counties in their sample, but employ these two dummy variables – coast and valley – only to evaluate their relationship with climate. Thus, the authors don't provide any information about the way territorial geography may affect energy consumption. In this context, Creutzig et al. (2015) conduct a similar analysis by including HDDs, CDDs and coastal city location in their study of 274 global cities. Their analysis of regression shows that HDDs are positively correlated with both final energy and GHG emissions and "explain an important fraction of the energy use variability of cities", while CDDs and coastal city location do not significantly affect either energy use or GHG emissions. The positive effect of HDDs on residential energy use found by both Ewing & Rong (2008) and Creutzig et al. (2015) is further confirmed by Kennedy et al. (2009), who analyze 10 global cities and find that the amount of fuel used for heating and industrial activities increases with HDDs. On the contrary, Baur et al. (2013) don't find any significant influence of HDDs on total GHG emissions for 62 European cities, possibly because their data on GHG emissions were previously corrected for seasonal variations, as specified by the authors. Similarly, in their analysis on urban form, air pollution and CO_2 emissions in 86 U.S. metropolitan areas, Bereitschaft & Debbage (2013) show that the two climate factors considered – temperature and moisture – are not associated with total CO_2 emissions, but only with O_3 concentrations and $PM_{2.5}$, VOC_s, and NO_x respectively. More controversial are the results of Makido et al. (2012), who use cities' average temperature instead of HDDs, and find a negative effect on residential CO_2 emissions. In this case, the authors admit the difficulties in interpreting such results and suggest the inclusion of HDDs rather than the average temperature in a future research.

To synthetize, 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. 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. Future research should further investigate the importance of these aspects as well as that of urban topography with respect to energy consumption.

3.4 SOCIO-ECONOMIC FEATURES AND ENERGY CONSUMPTION

Researchers have extensively studied the impacts of economic and social factors on energy use. As far as the economic features are concerned, most of the attention has been focused on the effects of three main variables – income, fuel price and car ownership – on transportation first, and on residential and total energy consumption later. In particular, Newman & Kenworthy (1989) find that these three indicators are responsible for about 60% of gasoline use, while the remaining 40% depends on urban form and land use factors. With respect to income, it is widely recognized that higher standard of living results in higher emissions from both transport (Brownstone & Golob, 2009; Clark, 2013; Holden & Norland, 2005; Newton & Kenworthy, 1989) and buildings (Ewing & Rong, 2008; Kennedy et al. 2009). In this regard, the results by Creutzig et al. (2015) are of particular interest. When considering the whole sample of 274 global cities, the authors find that final energy consumption is strongly positively associated with economic activity, but in the moment that they divide the sample in eight groups based on gross domestic product (GDP) per capita, density, fuel price, and HDDs, they find that "energy consumption for urban transport increases with GDP at low GDP levels, but decreases with GDP at high GDP levels". These findings give new insight into the question, and open up new avenues for future research. With regard to fuel price, Newman & Kenworthy (1989) argue that this economic factor is inversely correlated with transport energy consumption, and Ewing & Rong (2008) find a similar negative relationship between energy price and residential energy demand. More recently, Creutzig et al. (2015) find a negative relationship between fuel price and total energy use and emissions, thus supporting both previous results. Finally, if we consider car ownership, as reasonably expected, studies find that higher levels of car ownership are associated with higher energy use from transport (Banister et al., 1997; Mindali et al., 2004). As far as the social features of urban areas are concerned, the impacts of different social aspects on energy consumption have been investigated by the scientific literature, but weak consensus exists among researchers. According to Camagni et al. (2002), for example, population growth rate positively affects mobility, while on the contrary, Baur et al. (2013) find that this indicator doesn't significantly influence total GHG emissions. Similar contradictory results are found when household composition is investigated: while Brownstone & Golob (2009) show that in California fuel use increases with the number of children, Ewing & Rong (2008) don't find any significant relationship between residential energy consumption and either the number of children or the number of adults, in the

U.S. There is the same debate when the level of education is considered, because those who find that education positively affects transport energy use – "households headed by a respondent with a college degree tend to have a vehicle fleet with greater overall lower fuel economy than their less educated counterparts. This effect is accentuated if the household is headed by a respondent with a postgraduate degree" (Brownstone & Golob, 2008) – are criticized by those who don't find any significant correlation (Holden & Norland, 2005). One last social aspect considered for its potential impacts on energy consumption is ethnicity; in particular, both Ewing & Rong (2008) and Brownstone & Golob (2009) find that energy consumption varies by race, but this relationship needs more specific research to be fully understood.

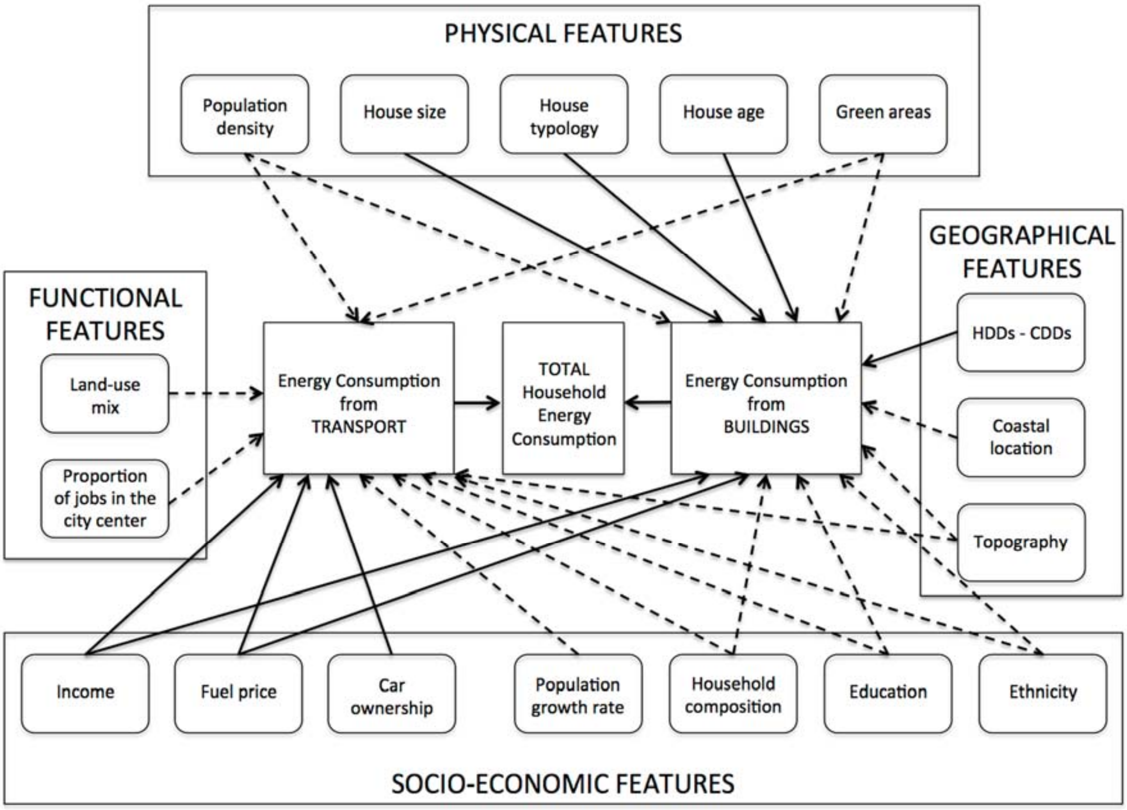
To summarize, it is widely recognized that social and economic factors affect energy consumption. However, while there is great consensus about the relationships between economic variables – income, fuel price, and car ownership – and energy consumption, there is far less agreement about the way social characteristics, such as demographic growth, household composition, education, and race may influence energy use.

4 A CONCEPTUAL FRAMEWORK TO GUIDE FUTURE RESEARCH

The review of the scientific literature on the relationship between cities and energy consumption allows the construction of a conceptual framework (Figure 2), which has two main goals: (1) to provide a state of the art summary on this topic, and (2) to suggest some directions for future research. The conceptual framework is built based on the integration of the findings previously described, and it takes into account the four categories of urban features that have been used to represent the urban system (according to the general system theory applied to the urban phenomenon). In particular, for each group of features, the main variables are specified and the relationships between these variables and the two types of energy consumptions – from transport and from buildings – are identified. Two different types of arrows are used: solid arrows represent those relationships for which there is a wide consensus within the scientific community, both in terms of "sign" (i.e. positive or negative relationship) and significance; on the contrary, dashed arrows indicate those relationships that require further investigation because of the conflicting results found in the literature so far.

At the top of the figure are the five physical features – population density, house size, house typology, house age, and green areas – that emerge from the literature review as key factors significantly affecting energy consumption at city scale. As far as population density is concerned, two dashed arrows connect this variable with both types of energy consumption; this is because, although there are numerous studies on the relationship between urban form and energy use, and the majority agree that population density is negatively correlated with both transport and building energy use, there is still a lack of consensus among researchers about the size of this correlation, and thus its significance. Similarly, further research is needed to explore the way green spaces affect energy consumption. On the contrary, the scientific findings about the relationships between the other three physical features – house size, house typology, and house age – and residential energy consumption are sufficiently reliable and widely shared in the literature, thus these arrows are solid.

At the left of the figure are the two functional variables – land use mix and the proportion of jobs in the city center – influencing energy consumption from transport, but in both cases the relationship is not straightforward, either because of the relatively small number of studies on this issue or because of the strength of these two relationships depend on other external variables (e.g. urban density and transit service), as previously described in par. 3.2. Therefore, embracing the complexity of the urban system, additional effort should be made to investigate the influence of the urban functional subsystem on energy consumption.



Note: Solid arrows indicate relationships that are shared by the scientific community; dashed arrows indicate relationships that are not shared by the scientific community, and thus require further investigation.

Figure 2. Conceptual framework and key relationships between the four groups of urban features and energy consumption

At the right of the figure are the three geographical features – heating and cooling degree days, coastal location and urban topography – that affect household energy consumption. In particular, a solid arrow connects HDDs/CDDs and residential energy use, because it is widely argued that climate conditions significantly influence fuel consumption for heating and cooling. On the other hand, with regard to the other two geographical features, too little research has been done in order to assess the impacts of coastal location on residential energy use and of topography on either residential energy use or transport energy use. Thus, three dashed arrows associate these two variables and the two types of energy consumption.

At the bottom of the figure are the seven socio-economic features – income, fuel price, car ownership, population growth rate, household composition, education, and ethnicity – that are in part responsible of both transport and residential energy use, according to the reviewed literature. While there is wide consensus on the relationship between economic variables and energy consumption, there is less of a consensus on the impacts of social factors on energy use. In particular, it is widely demonstrated that income and fuel price are correlated – positively and negatively respectively – with energy consumption, from both transport and buildings, and that an increase in car ownership results in higher transport energy use. On the contrary, more complex are the influences of the four considered social features on energy use, which may explain the dissimilarity in findings among studies. Future research, indeed, should focus more on the influence of household composition, education and ethnicity on energy consumption. Furthermore, more scientific attention should be paid to measure the consequences of demographic growth on energy consumption, especially today that urbanization processes are extremely pervasive.

4.1 RELATIONSHIPS AMONGST DIFFERENT URBAN FEATURES

Using a holistic approach (as previously described in Section 2), the conceptual framework proposed above does not provide a comprehensive picture of the complexity of the relationship between cities and energy consumption. Indeed, another group of interaction exists and significantly contributes to such complex relationship. This group includes the interactions amongst the four different types of urban features (physical, functional, geographical, and socio-economic). Differently from the relationships described in the previous paragraphs, these interactions indirectly affect energy consumption. Nevertheless, these indirect effects can be significant and should not be ignored.

However, only a small part of the literature reviewed in this paper considers these secondary interactions, which are synthetize in Figure 3. In particular, Holden and Norland (2005) are the first to find a significant interaction between two physical features, i.e. house typology and house age. They find that the difference in energy consumption between single-family housing, row houses and multifamily housing is lower when considering housing units built after 1980. In other words, the energy efficiency of multifamily housing compared to single-family housing has decreased in recent years. This means that the direct effect of house typology on residential energy consumption becomes weaker when the indirect effect of house age is considered.

Similarly, Chen et al. (2008) find a positive interaction between population density and density of facilities (land use mix), which means that densely populated cities in China also have higher concentrations of activities. On the same page, Brownstone and Golob (2008) find that population density is negatively associated with car ownership, income and the number of family components, and that "households which are solely Black, solely Asian, solely Hispanic, or mixed White and Hispanic, all tend to reside in higher-density areas". Population (weighted) density is also found to be inversely association with housing type (calculated as an ordinal variable: 0 = multi-family, 1 = single attached, and 2 = single detached) and housing size (using the number of rooms as proxy), according to the results obtained by Lee and Lee (2014) using a multilevel structural equation model (MSEM), which means that in denser populated areas there is a higher concentration of multi-family houses with a lower number of rooms.

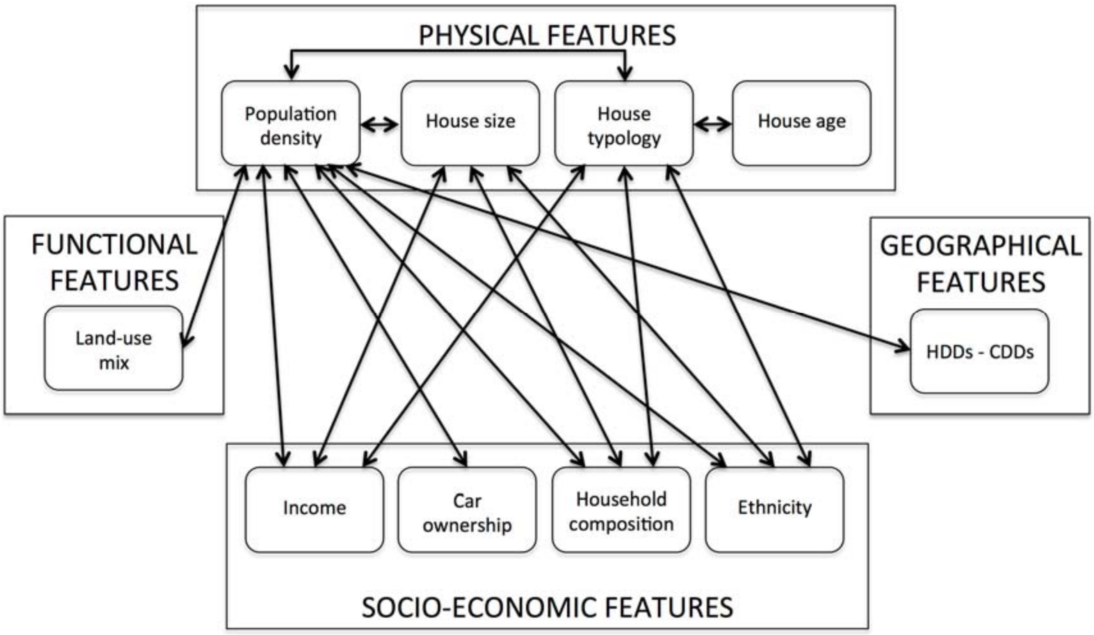


Figure 3. Key relationships amongst the four groups of urban features

Finally, Ewing & Rong (2008) devote much effort to analyze the way urban form can indirectly affect residential energy consumption through the housing stock and the formations of urban heat islands (UHIs). By using a hierarchical modeling, the authors find that house typology and house size are significantly associated with several socio-economic features. In particular, as the number of family members and income increase, both house size and the odds that the household will choose a single-family detached house increase. Analogously, also ethnicity is found to significantly affect the choice of both house typology and house size: White households are more likely to choose bigger single-detached homes than Black, Hispanic and Asian ones. Furthermore, Ewing and Rong also find that multifamily houses are associated with denser urban areas and that houses are significantly larger in sprawling counties than in compact ones. In addition to these results, the study shows that the effect of the urban heat island (UHI) is greater in compact developments, which implies that in denser areas "temperatures are higher that they would be otherwise".

Considered together, these results suggest that the indirect effects of these secondary interactions between physical, functional, geographical and socio-economic factors can significantly contribute to the increase and/or decrease of transport and residential energy consumption at urban scale. In other words, the correlations between different urban features and energy consumption found by the literature so far (and described in Section 3) cannot prove a causal relationship. Indeed, they may partially be the effect of secondary interactions between other variables. For example, a strong positive correlation between housing size and residential energy consumption may not be exclusively due to a direct link between these two variables, but it may also include the indirect effects of other physical (e.g. population density) and socio-economic (e.g. income and ethnicity) variables. However, it is very difficult to identify and untangle all the direct and indirect effects from different urban features on transport and residential energy consumption. Therefore, the task of establishing independent links between cities' characteristics and their energy and carbon footprint remains very challenging (Rickwood et al., 2008) and requires further investigation.

5 DISCUSSION AND CONCLUSIONS

This paper puts together and compares the relevant literature on the relationship between cities and energy consumption over the last twenty years. Two main energy sectors have attracted the interest of the scientific community – transportation and residential sectors – and a large number of urban features have been analyzed. In particular, as we have distinguished between four different categories of urban features (physical, functional, geographical, and socio-economic), the review shows that a great body of the literature has focused on the relationship between urban form (i.e. physical features) and energy consumption, while fewer researches have also investigated the effects on energy use and CO_2 emissions of other urban characteristics, such as those describing the functional, geographical and socio-economic aspects of a city.

Despite the great interest of the literature on this topic, a consistent number of interactions between urban features and energy use at urban scale still lacks of consensus. One of the main open questions is about the relationship between population density and energy consumption.

While it is widely argued that density is negatively correlated with both transport and residential energy use, there is less agreement about the scale (and significance) of this correlation and whether this inverse association can be generalized or whether it exists only for particular density ranges and specific clusters of cities. In addition to this open debate, the impact of social factors on energy use still requires further investigation. In particular, the effect of some social factors such as the level of education or the ethnicity on households' travel behavior and residential energy use.

Furthermore, several studies previously reviewed (Baur et al., 2013; Creutzig et al., 2014; Mindali et al., 2004) show the importance of sample clustering when different cities from around the world are considered together: some urban features, such as house typology, travel behavior and ethnicity, indeed, can significantly differ between countries, due to different historical background and socio-economic development; therefore, the impacts of such urban characteristics on energy consumption can hardly be generalized. Overall, three main limitations to the studies included in this review have emerged. The first issue concerns the approach used to analyze the relationship between cities and energy consumption. Many studies employ a sectorial approach rather than a holistic one. Consequently, they only consider direct effects of a number of urban factors on energy consumption or CO_2 emissions, without taking into consideration the possible indirect effects associated with the interactions that may exist amongst the different urban factors. As previously mentioned, these indirect effects may be significant and cannot be ignored if we want to explore the relationship between cities and energy consumption in its complexity and multidimensionality.

The second limitation concerns the methodology used by the different researches reported here and is strongly related to the first limitation previously described. The most frequent statistical techniques employed to study the type and significance of relationship between different urban features and energy consumption/CO_2 emissions are two: the analysis of correlation and the multiple regression analysis. Both methods 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.

Finally, the third issue concerns the limited data availability. As highlighted in many of the reviewed studies, the lack of a comprehensive dataset about cities’ energy consumption and CO_2 emissions by sector represents a significant limitation, which has been overcome by merging different data sources or by collecting data using questionnaires, whose reliability could be questionable. Similarly, many of the described researches report as a limit that they have considered just a restricted number of urban variables while others, which may be equally important, could not have been captured.

Given the findings of the studies presented above and taking into consideration the limitations previously described, this review proposes a conceptual framework to guide future research on the relationship between cities and energy consumption. The proposed framework presents the main urban factors influencing the energy and carbon footprint of a city and illustrates clearly the key relationships between these features and both transport and residential energy consumption, highlighting those relationships that are not straightforward and require therefore further research (Figure 2). Most importantly, this framework also illustrates a second group of relationships – i.e. those amongst the four categories of urban features (Figure 3) – which may significantly affect energy consumption but are often ignored by the scientific literature, thus providing a more comprehensive picture of the complex and interconnected interactions between cities and energy consumption. This wider picture could represent a new starting point for future research on this topic. Indeed, further research is needed in order to evaluate the extent to which urban characteristics influence transportation and residential energy consumption. Only if these impacts are clearly understood, urban planning policies can effectively improve energy saving in cities and reduce urban emissions.

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Fig. 1,2,3: created by the authors

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