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Characterization of building thermal energy consumption at the urban scale

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Abstract

The ongoing urban transition toward decarbonized energy systems has raised the attention on local energy planning practices. Besides the multiple actors involved in the planning process, the complexity of the urban energy systems requires the elaboration of heterogeneous data. In such contest, the paper introduces and compares two GIS-based methodologies for supporting the spatial characterization of the local residential built environment in terms of building distribution and space heating energy consumption. Starting from the assessment of residential consumption, a third method for the characterization of non-residential building thermal energy consumption is proposed. From a bottom-up perspective, in both residential models all the buildings are geo-referenced and clustered according to their thermo-physical characteristics. From a top-down perspective, energy balance data are used to calibrate the bottom-up results and to match the total building loads. The procedure, tested on the city of Turin as case study, allows assessing the energy use of buildings and to create urban energy maps.
The energy spatial characterization of a territory is the basis for performing short and long-term scenarios analysis. Results of this method can be useful to: i. decision maker to understand the current state of the territorial energy consumption to identify critical energy intense areas; ii. citizens for visualising their energy consumption and iii. researchers for setting up the basis of further urban analysis.

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Keywords: building stock; urban; energy modeling; GIS; space heating

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1. Introduction

Energy conservation in buildings is considered one of the key priorities for European low carbon transition. Many recent researches are focused on the investigation of procedures for assessing buildings energy consumption at different scales from single buildings to the whole building stock. Methodologies for the evaluation of energy consumption at single building level are currently well known and widely adopted by both architects and engineers [1]. The challenge is to improve the reliability of models results through occupant behavior analyses [2, 3]. On the contrary, the definition of standardized modeling procedures for the estimation of the energy consumption at the building stock level is still a challenging topic [4]. The large number of necessary information and data may lead to very time consuming and complex evaluations. Nevertheless, many studies have tried to define a procedure for large buildings stock energy consumption evaluations, mainly referred to the residential sector. First efforts used top-down data (e.g. energy statics) and current Standards and regulations for analytically defining the building distribution considering their primary energy consumption [5; 6]. By coupling building energy audit together with energy simulation, [7] proposed a methodology for classifying residential buildings according to the climatic zone, the construction period and the size. Moreover, the EPBD [8] required all the Member States to identify a set of reference buildings in order to create a common base for assessing the energy savings potential from building retrofitting at national or regional scale. The idea of Reference Buildings set has been thus created for defining representative buildings for modeling, in simplified way, existing and future performances of groups of buildings through buildings simulation [9; 10]. Starting from national/regional statistics and from building sample, the TABULA project [11] had the goal of creating a European common structure of building typologies and representative buildings. By this project, a preliminary evaluation of current energy consumption of the national building stock has been provided. Together with the development of computational tools, Geographic Information Systems (GIS) tools have supported local building stock analyses. A GIS- based procedure has been proposed and applied on the city of Milan by [4]: the approach uses statistical available data to evaluate the city buildings' energy performance and to define several scenarios for decreasing the energy consumption. By simplifying the methodology of the European Standard EN ISO 13790, urban energy maps have been created by [12] for historical centre of the city of Benevento, Italy. Mattinent et al. [13] proposed a calculation and visualization approach for energy use and greenhouse gas emissions estimation at the district level. Sample buildings and energy audits have been integrated with statistical data by [14] for assessing the energy performances of buildings of the Lombardia region (Italy). In the city of Ferrara (Italy), Fabbri et al. [15] highlighted how the creation of a GIS database of energy performance certificates may provide useful information about the building heritage and may support the identification of energy related indicators. In the city of New York, [16] estimated the building sector energy end-use intensity per unit of floor area for the different end-use services (space heating, space cooling, domestic hot water and electricity). They considered energy end-uses dependent on building destination function (office, residential etc.) and not from construction type and age of buildings. From all previous studies it results that a spatial explicit energy characterization of the stock represents a useful tool for the assessing cost-effective energy efficiency policies.

The choice of the approach it's clearly dependent on input data's availability and on the desired resolution of results. In this paper, a methodology for the assessment of urban residential space heating consumptions is proposed. The methodology allows choosing between two bottom-up GIS-based models that are proposed and compared. One model is related to the reference-building concept (Section 2.1) while the other assigns specific energy intensity to each building according to its compactness and construction period (Section 2.2). A last model, derived from non-residential building distribution and energy balance data is proposed for the characterization of non-residential buildings (Section 2.3). All the models are applied and validated on the city of Turin, Italy. Moreover, through top-down data (census data, energy statistics, Covenant of Major's data [17]) the urban non-residential building energy consumption is estimated and spatially distributed through the different census sections.

As a result, a methodological framework for comprehensively characterize the space heating energy profile of a city is provided.

2. Methodology

The procedure proposed in Section 2 aims at supporting the characterization of urban building stocks from the perspective of buildings (residential and not) distribution and space heating energy consumption. In particular two methodologies are proposed, applied and compared for residential buildings (Model 1 and Model 2 of Fig.1). Starting from the residential assessment, a third method for evaluating non-residential buildings' features and consumption is offered. The schematic of the process is summarized in Fig. 1. Main steps are: i. the creation of a GIS database and map for evaluating and containing the buildings geometrical and typological characteristics; ii. the creation of bottom-up urban space heating energy models for the assessment of thermal consumption in residential buildings; iii. the validation and correction of urban energy models with top-down data; iv. the creation of non-residential energy models starting from results of point iii. and by using top-down data.

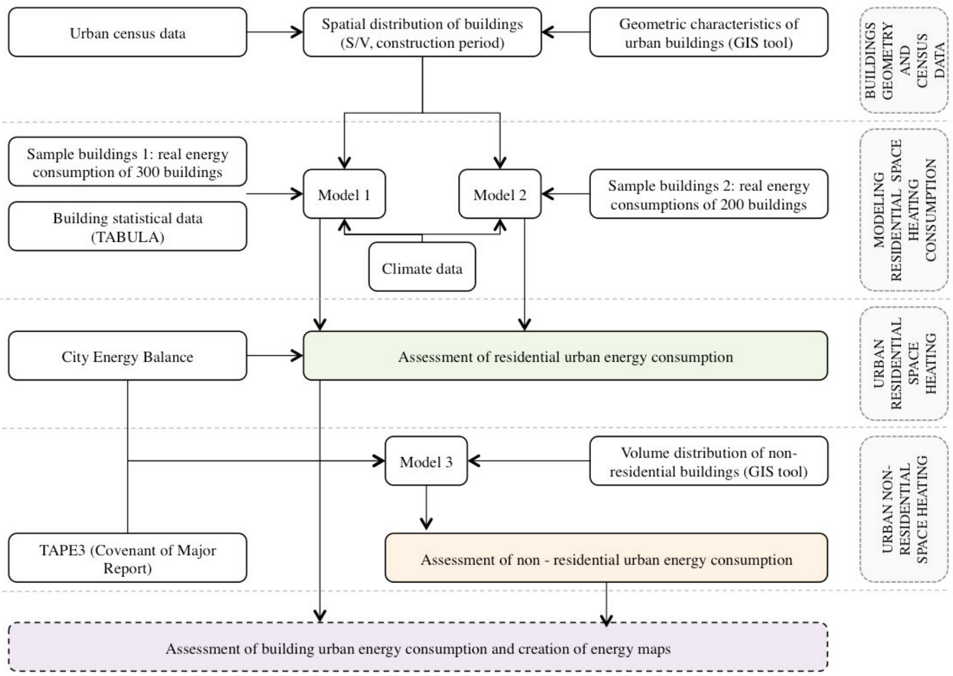

Fig. 1. Schematic of the methodological procedure

The analysis conducted in this work on residential buildings starts from the results of the research project "Cities on Power" - focused on the promotion of energy savings solutions and renewable energy sources in urban contexts [19,20] - and on the European TABULA project [11]. A common framework in the proposed methodologies consists in the use of GIS open source tools for identifying building characteristics and their distribution in the urban contest. Buildings are classified according to main factors affecting the energy consumption (e.g. space heating consumption in this research). Space heating energy consumption is mainly driven by the climate, the thermo-physical characteristics of the envelope (affected by the period of construction traditions and energy regulation), and the compactness [18]. In this research, as commonly performed in the Italian contest [11, 18, 20], residential buildings are classified according to their volume, construction period (materials, structural characteristics and building standards) and to the surface to volume ratio (to evaluate the compactness). Non-residential buildings are instead categorized considering their destination use and volume (offices, schools, commercial buildings etc.).

From the Municipality of Turin [21], chosen as case study, it is possible to derive information about the number of floors and the construction period of all the residential buildings sited in the urban boundaries. These data can be matched to the city base map (available at the technical department of Municipalities) for the calculation of all the required geometric and dimensional characteristics of buildings: perimeter, base surface, building heights, gross and net volume, external surface. For non-residential buildings, information about the volume only has been collected. In Table 1, main data referred to the distribution of building volume in Turin obtained by GIS evaluation can be observed.

Table 1. Buildings' data obtained by GIS in the Municipality of Turin

Residential		Non residential	
Heated volume of buildings – Mm^3	138.9	Schools Mm^3	5.9
Average surface of the apartments – m^2	75.3	Gyms, swimming pools and sports facilities Mm^3	0.617
Average height of a floor – m	3.5	Offices Mm^3	4.2
		Commercial (little activities) Mm^3	0.22
		Industrial activities Mm^3	24.67
		Churches Mm^3	0.517

Once all the dimensional and structural characteristics have been defined, the second step of the procedure consists in the association of a space heating energy consumption value to the buildings. Residential building models (Model 1 and Model 2) in Fig. 1 are based on a bottom-up approach and they are used to represent the energy consumption of residential buildings through a detailed spatial representation considering their percentage of heated volume, period of construction, and compactness. Subsequently, data of the Turin Action Plane Energy (TAPE) [17] were used to correct the buildings' models taking into account the spatial variability of the urban contest. TAPE data are referred to the year 2005, all the energy consumption data are thus normalized to 2005 climatic conditions (2703 Heating Degree Days) and all the buildings built after 2006 have been added in the evaluations after the validation of the modeling procedure at 2005. For data about buildings' use, heating volumes and buildings' geometry, the Technical Map and the Land Use of the Metropolitan City of Torino [22], and the 2011 ISTAT census [23] have been used.

2.1. Model for characterizing residential space heating energy consumption using reference building: Model 1

The first proposed approach consists in clustering the buildings into reference building classes [9; 10] and in associating to each class a reference energy performance value. In this study, reference buildings are identified considering the available data derived from GIS calculations together with the ones provided by Italian/local statistics. They are thus classified into 36 combinations of: i. four classes of compactness: single families (SF) – detached single buildings ($S/V > 0.8\ m^{-1}$); terraced housed (TH) – lined townhouses ($0.6 < S/V <= 0.8\ m^{-1}$); multifamily (MF) – low-storey buildings ($0.4 < S/V <= 0.6$ m-1); apartment blocks (AB) are tower blocks of buildings ($S/V <= 0.4\ m^{-1}$) [11]; ii. nine classes of construction periods C1=1900-1918; C2= 1919-1945; C3= 1946-1960; C4 = 1961-1970; C5= 1971-1980; C6= 1981 -1990; C7= 1981-2000; C8= 2001-2005; C9= 2006-ongoing [19]. Each class is then characterized by the materials typical of their construction periods and the geometrical characteristics equal to the weighted average size resulting from GIS calculations. The energy performance value referred to each building class should be statically representative of the energy behaviour of these building archetypes. Space heating energy consumption values can be derived through the energy audit of existing representative buildings or through energy simulation (e.g. TRNSYS) or existing literature considerations. In this research, both real data provided by the local district heating utility and simulation data from previous literature [11] have been used. The use of real data, when the sample is statically representative, can lead to more accurate results reducing the gap between simulation results and real energy behaviour of buildings. In this study, real space heating energy consumption data (with monthly detail for three consecutive heating seasons: 2011/2012, 2012/2013 and 2013/2014) of a sample of 300 representative residential buildings have been used, together with building simulation, for the association of space heating consumption to each reference building. All sample buildings data have been normalized to 2005 climatic conditions, clustered accordingly to the buildings classes and statically analysed. A normal distribution is applied to each cluster of sample buildings for two reasons: i. eliminating buildings with atypical behaviour from the analysis and ii. evaluating an average value of energy consumption. For all post-2006 buildings, TABULA data [11] as well as building energy regulations have been considered [24].

2.2. Model for characterizing residential space heating energy consumption at single building level: Model 2

Considering the spatial database available for the residential buildings of Turin, as well as for Model 1, the main energy-influencing variables were selected: the heated volume or surface, the compactness (with the surface to volume ratio) and the period of construction [20]. The 2011 ISTAT census data were also used to improve the models considering the average percentage of the heated volume, systems' efficiency, and the number of inhabitants on census section scale. Linear regression models have been chosen to evaluate the specific energy-use for space heating (kWh/m^2/K) as a function of the surface to volume ratio for the different periods of construction (the energy-uses for the domestic hot water and for cooking have not be taken into account) [18; 20].

The resulting simplified models of space heating energy-use do not take into account important factors such as the spatial variability in: solar gains, indoor/outdoor air temperatures and, mainly, the retrofit of buildings that may have changed their energy consumptions over the years. To consider these variables and to adapt the model to real energy consumption data [17], the model of the specific energy-use of buildings was multiplied by a correction factor equal to 1.24 as function of a typical built environment of the City of Turin. In Table 2 details on the developed linear model for calculating space heating energy-use can be observed.

Table 2. Linear models for specific space heating (kWh/m^2/K) as a function of the surface to volume ratio S/V (2703 HDD). Space heated volume: 71.3%, correction factor 1.24

Period of construction	< 1919	1919-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-2005	>2005
Slope	143.42	132.99	100.40	97.98	98.95	86.91	76.69	141.11
Constant	110.39	107.29	104.61	103.85	103.85	77.28	77.73	1.22

2.3. Models for characterizing non-residential space heating energy consumption at census section level: Model 3

From the city energy balance [17], the total energy consumption associated to non-residential buildings is available. Moreover, by GIS evaluations, the volume distribution for the building by destination use for each census section can be estimated. By combining such precious information and by applying several statistical analyses, it is consequently possible to calculate the average urban energy intensity of non-residential buildings classified for their destination use (Table 3).

Table 3. Linear models for specific space heating (kWh/m^3) as a function of the heated volume (2703 HDD)

Non residential buildings	Schools	Gyms, swimming pools and sports facilities	Offices	Commercial (little activities)	Industrial activities	Churches
Heated volume m^3	5,926,337	616,896	4,267,591	222,578	24,677,166	517,667
kWh/m^3	31	42.81	25.71	10.41	129.98	3.37

3. Results

The whole procedure has been applied to the city of Turin, North-West of Italy considering the 2005 energy balance data for validation (2703 HDD at 20°C). The building spatial characterization can allow multi-scale considerations (Fig. 2): i. at the buildings level: destination use, the position, the construction period and all the geometrical-dimensional characteristics; ii. at the census section level, the district level and the urban level: the number of residential and non-residential buildings, the gross total and effectively occupied volume (by matching the base map and census information), the volume distribution in terms of building type and construction period.

From Fig.2 can be observed that the occupied volume built before 2006 in Turin is about 139 Mm^3 (177 total Mm^3) of which more than 75% is characterized by high compactness (AB) and more than 90% has been built before the ‘80s. The volume built after 2006 is equal to 0.3 Mm^3 (2011 census data). Non-residential buildings occupy a total volume of about 36.23 Mm^3 of which 68.1% used for industrial activities, 16.4% for education, 11.8% are office buildings, 1.7% for sport activities, 1.4% are churches and 0.6% for little commercial activities.

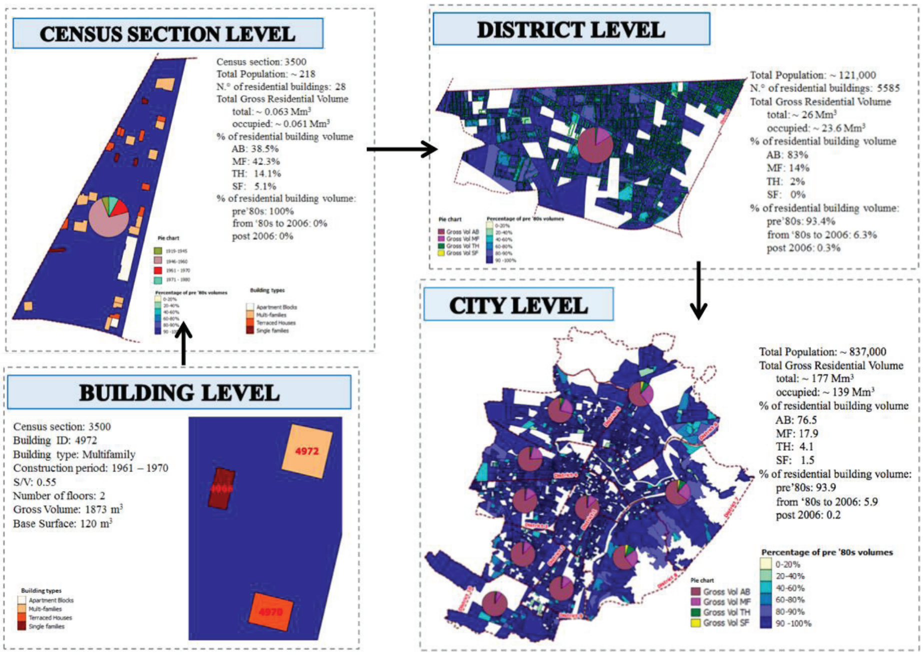

Fig. 2. Multi-scale distribution of residential buildings at the city level

Model 1 and Model 2 have thus been applied to the calculated urban volume distribution (pre 2006 built environment) for the estimation of urban space heating energy consumption. By applying Model 1, urban space heating consumption results equal to 6.39 TWh while applying Model 2 equal to 5.96 TWh. A relative difference of about 7% is observed between the two modeling approaches. The energy balance [17] for residential buildings is 6.84 TWh, including cooking and hot water end-uses. From current literature and statistics [25] hot water and cooking services account for about 14% of residential thermal energy consumptions and space heating for 86%. Considering the energy balance, it can thus be assessed that 5.88 TWh represents the space heating energy consumption of pre-2006 buildings of the city of Turin (Fig. 4b). With respect to balance data, Model 1 overestimate the official consumption of about 8% while Model 2 (already calibrated with a 1.24 correction factor) of about 1.3% leading to very accurate results. Both models can be further calibrated in order to be consistent with the energy balance data. A separate evaluation has been performed for residential buildings built after 2006 and considering 2011 volume (consumption associated to 0.3 Mm^3 of 4.2 GWh). By applying model 3, it results that non-residential buildings consume 3.6 TWh for space heating. Totally, the built environment of the city of Turin consumes 9.49 TWh/yr for space heating at 2703 HDD. Considering normative HDD (2617 HDD at 20°C) urban reference consumption can be set as 9.19 TWh of which 62% residential consumption and 38% non-residential. The heat densities per census section can be observed in Fig. 3a and Fig. 3b. As expected, the higher heat densities (Fig.4) as well as higher space heating consumption (Fig. 4b) can be detected in the areas close to the city center, while higher energy intensities in the areas where the compactness of buildings is lower (Fig. 3a).

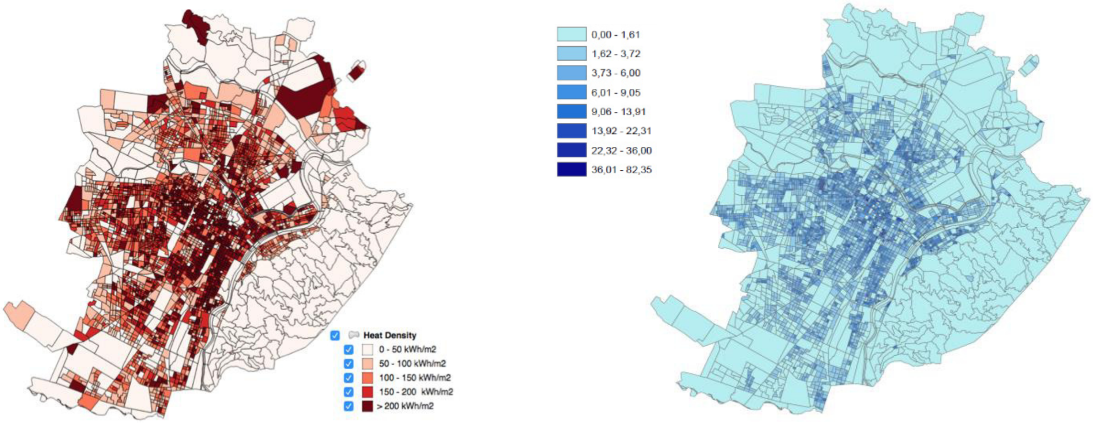

Fig. 3. (a) Heat density per unit of census sections' surface kWh/m^2 (b) Heat density per unit of building volume and census sections' surface kWh/m^2/m^3

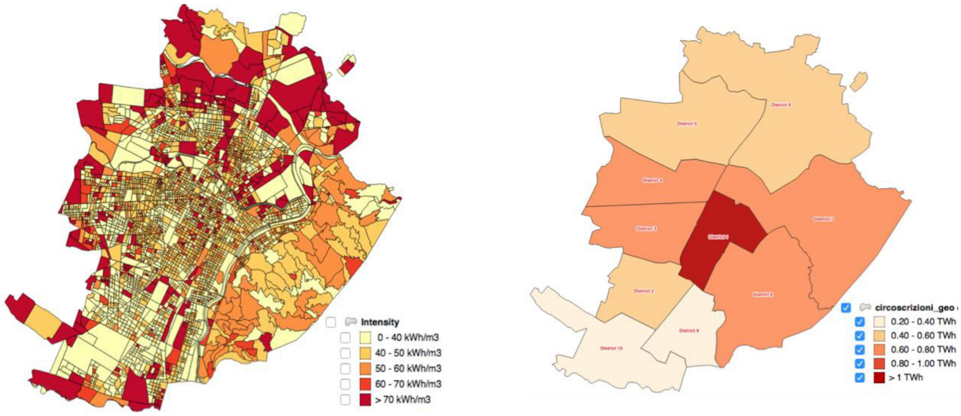

Fig. 4. (a) Distribution of space heating intensity kWh/m^3 (b) Distribution of space heating consumption TWh

4. Conclusion

In this paper, a GIS-based procedure for the spatial characterization of the urban built environment in terms of both volume distribution and space heating energy consumption has been proposed. Two bottom-up models for residential buildings and a model for non-residential buildings, based on top-down data, have been developed and successfully applied to the city of Turin. The GIS-based methodologies for supporting the spatial characterization of the local building distribution and space heating energy consumption are the starting point for performing short and long-term scenario analysis of the urban energy system. In particular, they set the base for further analyzing in a comprehensive way, the competition between different energy conservation measures (e.g. between district heating solutions, individual boilers or heat pumps and retrofit measures by building types). In fact, spatial analyses can be used to build full-integrated energy models of urban system including demand and supply side of the energy chain. This approach fits well with recent European projects on smart cities, in particular, with integrated planning framework for the development of sustainable and resilient cities, as done in the case of the EU FP7 InSmart project (http://www.insmartenergy.com). The smart city as well low carbon city approach aims at analyzing on the short and long-term different possible scenarios through and integrated methodology. The proposed procedure for the spatial characterization of the buildings stock could therefore evolve by integrating several tools (e.g. energy system models, multi-criteria methodologies etc) in order to support the development of medium-term Strategic Sustainable Energy Plans with regards to economic, environmental and social criteria and paving the way towards actual implementation of priority actions.

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