GIS-Based Energy Consumption Model at the Urban Scale for the Building Stock

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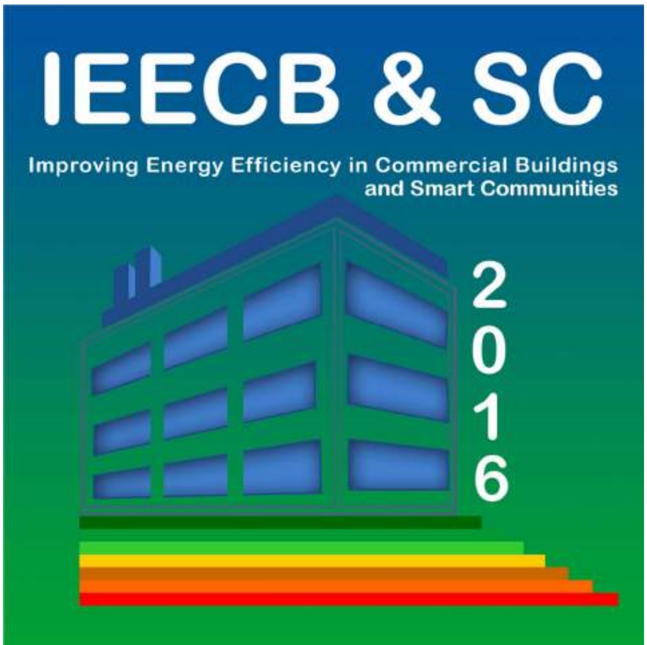

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GIS-Based Energy Consumption Model at the Urban Scale for the Building Stock

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Abstract

Energy efficient buildings' issue integrated into the district and CO_2 emission reduction strategies and policies is one of the main concerns in the European Union (EU). In order to achieve an effective impact, instead of just concentrating on the improvement in terms of energy efficiency to one particular building, this approach requires challenges to be solved in an entire municipality or an entire district. Accordingly, it is significant understanding the comprehensive residential building stock models in the urban environment able to promote a sustainable energy planning. In this paper we describe a new methodology based on two different modelling approaches top-down and bottom-up with the aim to evaluate the buildings energy consumption model of a municipality. This methodology is mainly based on information that is already available on building stock from the literature and data collection (i.e., technical department of municipality, web, energy auditors and others) which is later transferred into the Geographic information system (GIS). Into this in future studies GIS platform provides the information on energy performance in the whole city as well as creating the urban energy maps for assessing retrofitting scenarios and support decision making for policy implementation to achieve sustainable urban planning. This study is part of an ongoing Smart City research study, national cluster project named Zero Energy Buildings in Smart Urban Districts (EEB) and is tested in a medium sized town in the Piedmont region (Italy), and the results are discussed.

Keyword: Geographic Information System (GIS), Thermal Energy Consumption Model, Building Stock, Urban Scale

Introduction

Nowadays, there is an immense impact on energy demand and consequently GHG emissions due to the way that cities are acting and growing [1]. In Italy, the energy balance in 2013 has demonstrated a further reduction of the energy demand for about -1.9% compared to 2012 level. This trend is happening not just due to the economic crisis, but also to the result of the successful implementation of energy efficiency policies. Indeed, the end users of energy accounted for about 126.6 (Mtoe) with a reduction of 1% compared to 2012. It is noteworthy that only sector where the energy consumption has increased is the construction one (+ 5.6%) [2].

Particularly in the building sector, energy consumption is influenced by the spatial organization. Therefore, where the purpose is the assessment of globally achievable energy savings and the greenhouse gases reduced emissions, it is crucial to broaden the focus on the building stock at urban scale [3]. Accordingly, many different approaches and tools are developed for the spatial representation of energy demand, production and CO2 emissions such as a Geographical Information Systems (GIS). The implementation of spatial analysis through GIS tools can be important to manage, archive, analysis, and geo-referenced visualization of the energy data and to optimize the energy sources available on the territory [4].

It is required to understand the building energy performance in an entire district or municipality to achieve a sustainable energy planning strategies that speed up the energy renovation and energy efficiency procedure in needed existing buildings [6]. In fact, the Sustainable Energy Action Plan (SEAP) promoted by the European Commission brings up the strategies for realizing the greenhouse gas reductions required by 2020 for municipalities that have joined the Covenant of Mayors [5]. There are numerous approaches that have been conducted to evaluate the energy consumption model for a large building stock (i.e. Real monitored data [7] considering a cadastre found out from a big number of individual certifications [8] or Census data [9]). Accordingly, with the aim of the energy consumption reduction, many building energy regulations are approved (e.g. codes, standards, etc.) in most of the developed countries [10]. Several types of research have been carried out primarily in order to investigate the methodologies for single building's energy performance [11], [12] or for building stock [13]. In this study, the attention is focused on the residential building stock at urban scale.

There are two general methodologies to modelling energy use that are used for building sector: 'top-down' and 'bottom-up' methods. The top-down approach uses historic aggregate energy values reported by energy suppliers and estimates the energy consumption of housing stock as a function of top-level variables. These variables comprise macroeconomic indicators (e.g. unemployment, inflation and gross domestic product), energy price, and general climate. As this model is based on historical information, therefore, it is not adequate for the evaluating the impact of new technologies on energy consumption. The residential energy demand system for Spain [14] is an example of this kind of model. The bottom-up method accounts for the estimated or simulated energy consumption for a specific individual or group of houses. This approach involves two categories: the statistical method and the engineering method. The adaptive neural network technique that [15] applied to a building in Montreal and the conditional demand analysis model used by [16] for San Diego are two examples of statistical bottom-up models.

This work is focusing on a method for evaluating the thermal energy consumption of residential building stock in one of the municipality in Piedmont (Italy) "Settimo Torinese" which is, representing approximately 46875 inhabitants [21] based on GIS for mapping energy consumption profile. The main goal of this work is to show that the energy-efficient strategy for a Smart City of the future should start on its existing building stock.

Methodology

The methodology used in this study is based on the literature that is partly mentioned in the previous section where the models used for the energy assessment of existing residential buildings can be divided into two categories [17]:

- Top-Down models: energy-use data at urban scale are compared with climate variables, census results, and statistical surveys to determine average energy consumption for existing buildings. These models can compare different variables, but cannot distinguish spatial variations in energy consumption of a Municipality or a territory.

- Bottom-Up models: these models, at building scale, are used to evaluate the energy balance of a single building with high detail; together, a set of energy consumption models, can be combined to evaluate the energy consumption of blocks of buildings, districts or cities; to achieve a valid and high quality results at urban scale a large number of data which is explained in the next section related to the buildings is required. These models can be also used to evaluate energy savings model after building retrofits.

In this case, it has been implemented a hybrid approach where the single building models, derived by the bottom-up approach, were used to represent the energy consumption of residential buildings in a district or a city through a detailed spatial representation considering the heated volume, the period of construction, and the compactness of residential buildings. While the statistical models at urban scale, derived by the top-down approach, were used to validate the above energy buildings' models taking into account the spatial variability of the urban context, the socio-economic level, the type of users, the buildings' retrofit level and other important factors influencing the energy-use of buildings.

In the following paragraph the description of the data used for the bottom-up and top-down approaches is described. Particularly, the calibration of the two models has been made, introducing correction coefficients in the bottom-up approach at buildings scale to get the overall consumptions at Municipal scale as reported in the SEAP. These correction coefficients take into account the characteristics of the built heritage and the typical users influencing the energy consumptions (e.g. the buildings' retrofit level and the users' behavior).

Evaluation of thermal energy of residential buildings in large urban context

For the evaluation of Space heating energy consumption of residential buildings, it can be considered some advantageous indicators as a period of construction, compactness and density of the buildings [3], [18]. In this work has been considered the climate with the Heating Degree Days (HDD), the compactness of buildings with the surface to volume ratio (S/V) and the period of construction with different levels of the envelopes' thermal insulation and systems' efficiencies to calculate the energy consumption on existing buildings [19]. The sources of data needed are essential:

i) Energy-use data: Sustainable Energy Action Plan (SEAP), considering 2009 as a reference year for the case study [5]; ii) Buildings use, Heating Volume, Building Geometry: The Database Spatial Reference Entities (BDTRE) Piedmont, other information as the height of the buildings and the type of roof obtained from Lidar datasets, Digital Terrain Model of Piedmont Region (DTM) [20]; iii) Demographic data: The 2011 ISTAT at census section scale [21]; iv) Climate data: outdoor air temperature and the Heating Degree Days (HDD) by climatic ARPA database [22]. As the energy consumption considered in the "Action Plan for sustainable energy" referred to the year 2009, the model was taken into account the HDD for that year. It was considered the climatic data recorded at the Brandizzo Malone weather station, as the closest station in terms of geographical coordinates (45°10′37″ N, 7°50′08″ E, 192 (m s.l.m.) to Settimo Torinese (45°08′26″ N, 7°45′49″ E, 212 m s.l.m.).

For this research, the ArcGIS 10.2 is used to analysis energy consumption [25]. Considering the spatial distribution of the heated volumes, for residential buildings with different characteristics, the energy-use of the single buildings' models was applied on an urban scale. The 2011 ISTAT census data were also used to improve the models considering the average percentage of the heated volume, the type of buildings' envelope, systems' efficiency, the period of construction, and the number of inhabitants on census section scale. The proposed methodology can be divided into following steps:

1. The residential building stock has extracted from the Database Spatial Reference Entities (BDTRE) Piedmont [20];

2. The surface to volume ratio S/V_{real} has calculated (Figure 1(a)). This ratio is classified as Detached House S/V ≥ 0,72; Terrace house 0,57 ≤ S/V ≤ 0,71; Row house 0,46 ≤S/V ≤0,56; Tower S/V ≤ 0,45 [23], [24];

3. The construction period has attributed for every residential building (Figure 1(b)), where is classified as <1919; 1919-1945; 1946-1960; 1961-1970; 1971-1980; 1981-1990; 1991-2000; 2001-2005; >2005 [21];

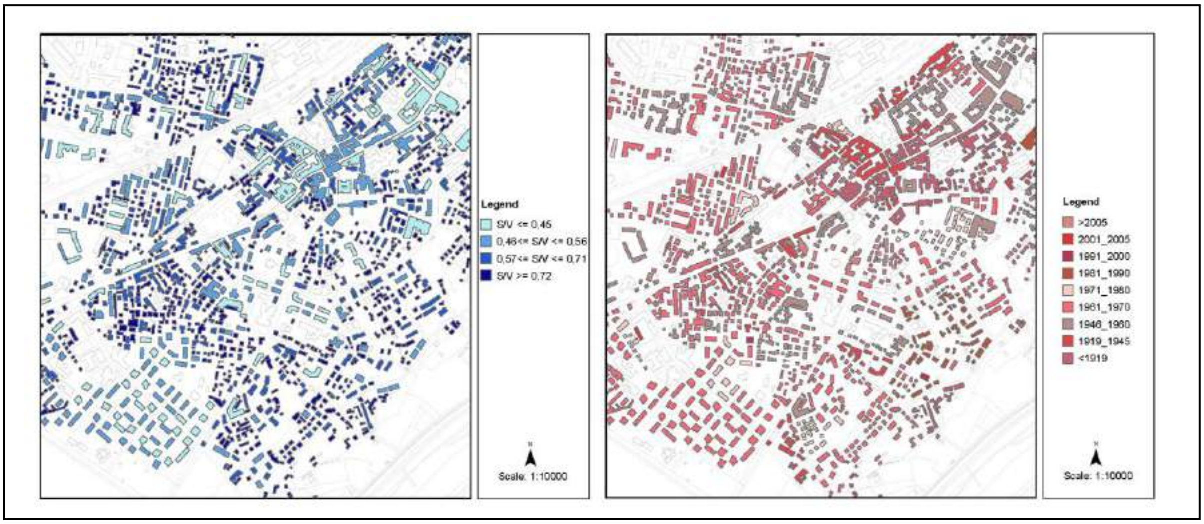

Figure 1, (a) surface to volume ratio S/V calculated for residential buildings and (b) the building construction period attributed for case study (elaborated by authors)

4. The energy demand has calculated using the model started from the model of Torino [24].

Comparing the bottom-up and top-down results, correction factors can be determined to calibrate the bottom up results to achieve good results at Municipal scale. The simplified models of space heating energy-use developed in the bottom-up approach do not take into account significant factors such as solar gains, indoor/outdoor air temperatures and, specially, the refurbishment of buildings. To consider these variables and to adapt the model to real energy consumption data, the model of the specific energy-use of buildings was multiplied by a correction factor and the demographic aspect [23].
For the city of Settimo Torinese, the energy consumption correlations have been defined starting from the model of Torino [24] corrected by the HDD (normalized on the average value of the Heating Degree Days of the last 10 years). These linear correlations used to simulate the energy-use EPgl (for space heating and domestic hot water production) as a function of the surface e to volume ratio S/V for Settimo Torinese are shown in Figure 2, where;

EPgl (kWh/m^2/y) = Slope (kWh/m/y). S/V (m^{-1}) + Constant (kWh/m^2/y)

The models consider the statistical percentage of the real heated volumes, the existence of uninhabited dwellings (the average value for Settimo Torinese is 0.83; from the census) and the correction factor = 1.19 depending on the different use and type of buildings while these values for Torino are respectively 0.94 and 1.04. The correction factors are average values for each city depending by the different territory, residential users, and buildings characteristics.

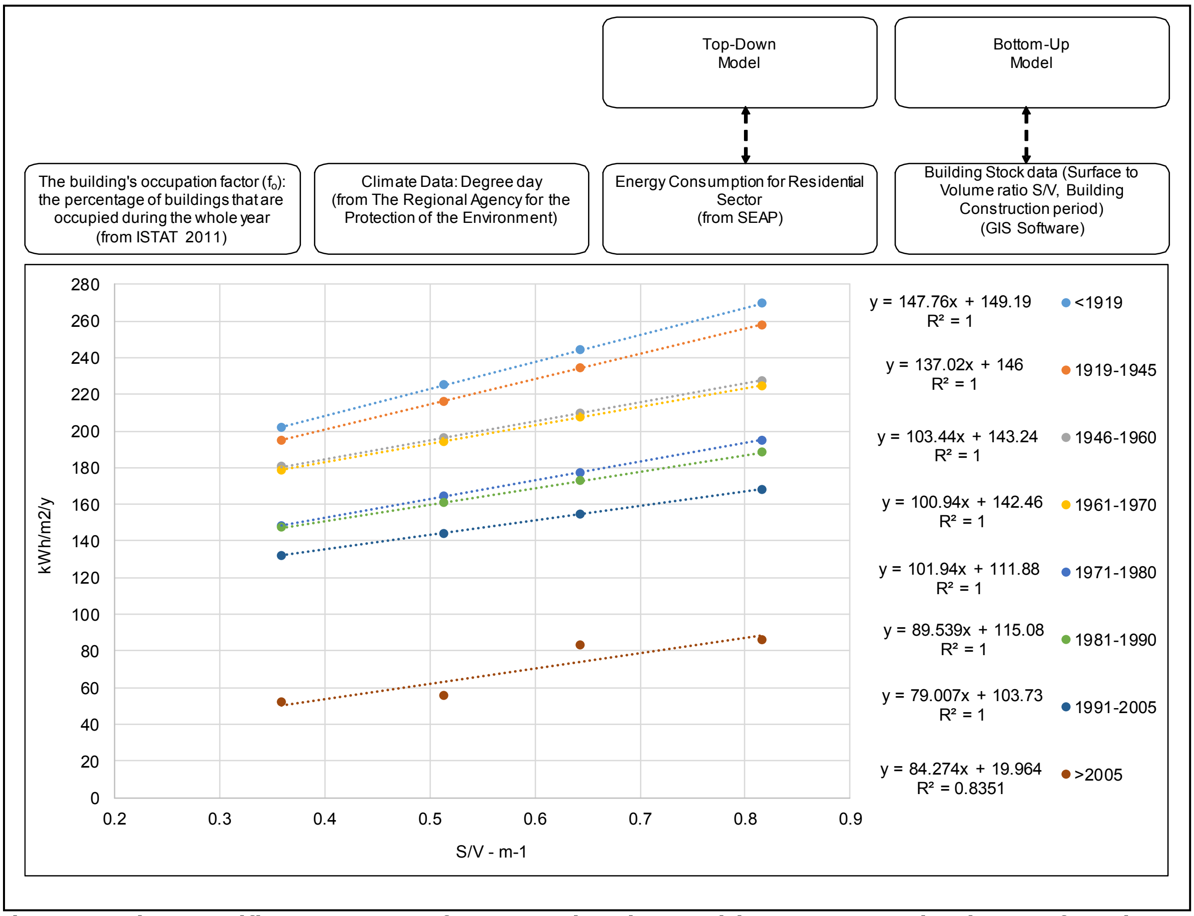

Figure 2. The specific energy-use for space heating and hot water production as function of the building construction period and the surface to volume ratio S/V for residential buildings for Settimo Torinese.

The specific energy-use EPgl for space heating and hot water production's model have a coefficient of determination R^2 =1 except in the case of construction period after 2005 (R^2 =0.8351), showing that the variation of energy-use can be explained as a function of the surface to volume ratio S/V for each period of construction. R^2 indicates how well the statistical model fits the data and, since the Torino model has been used [19], the coefficient of correlation for Settimo Torinese is equal to 1 by meaning that the regression line perfectly fits the data. The simplified linear equation models used to simulate the energy-use for the cities of Torino and Settimo torinese are defined in Table 1.

Table 1, Linear model of specific energy-use (kWh/m^2/y) for space heating and hot water production as function of surface to volume ratio S/V and period of construction for residential buildings in Torino and Settimo Torinese.

Buildings' construction period	Torino (2462 HDD)		Settimo Torinese (2926 HDD)	
	Slope kWh/m/y	Constant kWh/m^2/y	Slope kWh/m/y	Constant kWh/m^2/y
<1919	130.82	140.75	147.76	149.19
1919-1945	121.31	137.93	137.02	146
1946-1960	91.58	135.49	103.44	143.24
1961-1970	89.37	134.80	100.94	142.46
1971-1980	90.26	107.72	101.94	111.88
1981-1990	79.27	110.56	89.539	115.08
1991-2005	69.95	97.61	79.007	103.73
>2005	100.84	22.02	84.274	19.964

Results

Integrating the Top-down and Bottom-up models, it is obtained the average annual energy-use for space heating and hot water production equal to 218 kWh/m^2/y. In Figure 3 is shown the energy classes of the Piedmont Region [26] and the number of buildings belonging to those classes. The building more energy efficient is located in class B ($EP_{gl,\ average}$ = 68.25 kWh/m^2/y) with the construction period after year 2006 and the surface to volume ratio $S/V_{average}$ = 0.57 m^{-1}. While the building with less efficient class G ($EP_{gl,average}$ = 324.04 kWh/m²/y) are mostly belong to the construction period year <1919 and $S/V_{average}$ =1.33 m^{-1} with 1 floor.

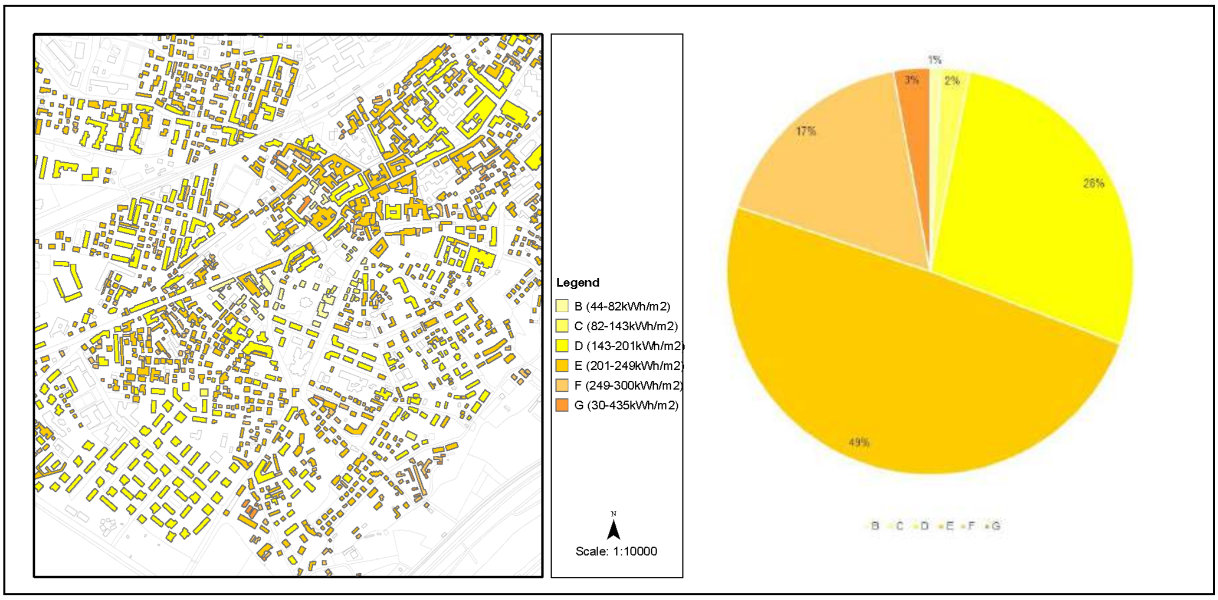

Figure 3, Energy efficiency classes kWh/m^2/y and the percentage number of buildings belonging to those classes.

As shown in Table 2, the number of buildings for different periods of construction and for energy certification classes (space heating and domestic hot water production), the more recent buildings belong to the better energy classes rather than older. It is happening due to the effective implementation of the energy efficiency policies and laws.

Table 2, Number of buildings for different periods of construction and for energy classes.

Energy efficiency classes $kWh/m^2/y$	Construction period									Tot.
	< 1919	1919 - 1945	1946 - 1960	1961 - 1970	1971 - 1980	1981 - 1990	1991 - 2000	2001 - 2005	> 2006	
A+ < 27	-	-	-	-	-	-	-	-	-	-
A 27-43	-	-	-	-	-	-	-	-	-	-
B 44-81	-	-	-	-	-	-	-	-	25	25
C 82-142	-	-	-	-	-	-	20	8	38	66
D 143-200	1	2	68	240	181	149	103	59	1	804
E 201-248	36	66	332	816	125	51	2	5	-	1433
F 249-299	65	99	115	208	5	-	-	-	-	492
G 300-435	31	38	11	5	-	-	-	-	-	85
N.C. > 435	-	-	-	-	-	-	-	-	-	-
Tot.	133	205	526	1269	311	200	125	72	64	2905

Conclusion and future study

The European Directives, including the Energy Efficiency Directive 2012/27/EU [28], emphasize that big effort must be made by a Member States to optimize the use of energy sources. This can be achieved through an energy efficiency plan, setting several policy targets as reduction in EU greenhouse gas emissions, raising the share of EU energy consumption produced from renewable resources and energy efficiency improvement. Despite the great energy efficiency improvements in buildings, recent energy consumption data analyses show that these targets will unlikely is reached [27].

Therefore, the assessment of the residential building energy consumption at city/municipal scale is significant to achieve the energy efficiency goals in EU. The importance of the period of construction and shape factor of buildings is discussed, where more recent buildings belong to the greater energy classes due to the current effective implementation of the energy efficiency regulations. On the other hand, it can be obtained the same conclusion for the surface to volume ratio S/V: the single-family houses belong to the low energy classes, rather than the compact buildings, as towers.

Therefore, it is crucial to define a comprehensive profile model to understand the current state of the energy consumption for building stock. This paper began by calculating the energy consumption profile at the City Scale with the use of geographic information systems (GIS) that can significantly help in the planning of actions. The estimation of energy-use for each residential building of the case study was calculated through the methodology described. For the future study, it will compare the bottom-up measured energy consumption and the calculate one. Afterward, it will calculate the renovation rate for residential building stock, taking into account the social variables. Particularly, a multi-criteria decision-making will be applied to achieve a sustainable and smart energy planning as a method, which has fascinated the decision makers' attention for a long time [29].

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