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Original Citation:

Mutani, Guglielmina; Todeschi, Valeria (2017). *Space heating models at urban scale for buildings in the city of Turin (Italy).* In: CISBAT 2017 International Conference - Future Buildings & Districts - Energy Efficiency from Nano to Urban Scale, CISBAT 2017, Lausanne, Switzerland, 6 -8 September 2017. pp. 841-846

Publisher:

Elsevier

Published version:

DOI:10.1016/j.egypro.2017.07.445

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 122 (2017) 841–846

Energy Procedia

www.elsevier.com/locate/procedia

CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland

Space heating models at urban scale for buildings in the city of Turin (Italy)

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Abstract

Today 54 % of the world's population resides in urban areas and in 2050 the projections are for 66 %. Therefore, the issue of city sustainability becomes increasingly important. This paper analyzes city energy sustainability with consideration to the complex built environment, high population densities, anthropogenic activities, energy demands, environmental impacts, as well as limits on both space availability and renewable energy sources. The evaluation considers models of thermal energy consumption for both residential and non-residential buildings based on a GIS tool. The thermal energy-use models consider established statistical methods as well as the introduction of energy-dependent urban-scale variables.

Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale

Keywords: space heating energy-use; buildings; statistical model; urban scale; GIS

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1. Introduction

In Italy, 68.2% of people live in urban areas, and this percentage is expected to rise in the future [1]. Urban areas possess complicated built environments with high concentration of human activities, high environmental impacts and low natural resources. Policy makers and urban planners can achieve recognizable success by improving the thermal efficiency and livability of these complex urban areas. A more sustainable energy management plan for urban areas will reduce environmental pollution and promote energy savings and more efficient energy

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Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale
10.1016/j.egypro.2017.07.445

technologies. While the transportation and industrial activities can differ among cities, buildings are a common and key-contributor to reducing emissions and promoting a more sustainable use of energy [2]. The purpose of this work is therefore to analyze building energy-use and to define models at urban scale. Particularly, this study focuses on space-heating energy consumptions for buildings in the city of Turin (located in northwestern Italy).

This work evaluates a model for thermal energy consumption of residential and non-residential buildings. Knowing the statistical distribution of energy consumption allows planners to better implement retrofit interventions and optimize the energy supply. Previous studies have reported buildings' urban-scale thermal energy-models based on statistical analysis of existing buildings data [2, 3]. This work adds to the statistical analysis, considering main energy-dependent variables, such as: building envelope, utility systems' efficiencies and microclimate variations around buildings [4, 5, 6]. These main energy-dependent variables are obtained through sampling more than 2,000 buildings over 2 to 3 heating seasons in the city of Turin.

The accuracy of urban models for energy consumption depends on the reliability of the databases and the amount of missing data. Space heating models have been developed for homogenous groups of buildings with a statistical approach; normal distribution, average and variance of energy consumptions were used to discard anomalous data. This paper describes an iterative methodology, based on a GIS tool, that considers a hybrid model which considers both bottom-up (building scale) and top-down (municipal scale) approach.

The described methodology can be used to manage and represent buildings' energy consumptions at a scale from individual buildings to an entire municipality. Knowing with more accuracy, the energy distribution and the main energy dependent variables allows the buildings sector to contribute more towards improving city sustainability and livability with smart policies.

2. Case study

In this work the thermal-energy consumption for building space-heating and water-heating are analyzed. Consider that Turin, located in northwest Italy, enjoys a temperate climate.

For the energy-use model and its representation at urban scale, the following databases were utilized: the Municipal Technical Map of the City of Torino (CTC, 2015), the 2011 ISTAT census database on population, buildings and heating systems, the Digital Terrain Model (DTM, every 10 m), building information (e.g. height, surface to volume ratio, roof type [obtained from Lidar], etc.), and climate characteristics (e.g. outdoor air temperatures, heating degree days HDD for six weather stations in different parts of the built environment in Turin).

Comparing the results of the bottom-up approach at buildings scale and top-down approach at municipal scale, a correction factor was determined as the bottom-up models are simplified average models and do not take into account important factors such as the spatial variability in: solar gains, indoor/outdoor air temperatures, uses of renewable energy sources and, mainly, the level of buildings' retrofit that changes building energy consumption. To consider these variables and to adapt the model to real energy consumption data at building and municipal scales, the model of bottom-up approach multiplied buildings energy-use by a correction factor. The correction factor accounted for the type of environment the building was in, so it is typical of Turin.

3. Methodology

The energy-use model at urban scale for space heating and hot water production of the buildings in the City of Turin was evaluated considering a hybrid approach matching bottom-up and top-down models [7-11]:

- Bottom-up model: single building (about 2,000 residential buildings and 130 schools and public buildings connected with the district heating network) sampled for energy consumption considering the main energy-use related variables; for residential buildings: volume, period of construction, compactness (or the surface to volume ratio) and volume percentage of heated space [2]; for non-residential buildings: user, volume and volume percentage of heated space [9].
- Top-down model: from the Sustainable Energy Action Plan (SEAP - Covenant of Mayor), the energy consumptions of the City of Turin were analyzed for all sectors at the municipal scale (for the year 2005).

Combining these models, a statistical model at urban scale of individual building energy consumptions was developed using a Geographical Information System (GIS) tool. Subsequently, other elements influencing the energy-use were considered such as the spatial distribution of buildings, the main energy-dependent characteristics of buildings (i.e. types of building, heating system), some socio-economic variables, the buildings' retrofit level.

For the development of the bottom-up models, the annual heating consumption of 2,092 buildings in Turin were georeferenced with the support of a GIS tool. These data were normalized on the 2011-12 heating season (with a relative deviation of 1.5% on the medium value of HDD in the last 10 years) considering six weather stations in the city (see Fig.1a). Homogeneous groups of buildings taking into account the types of user, the period of construction (subdivided in 9 classes from ISTAT 2011 census data) and the surface to volume ratio were identified; most of the analyzed data were about old residential buildings (87.5%) constructed before the first Italian law on energy savings in buildings L. 373/1976), with low surface to volume ratios. These S/V ratios were due to the prevalence of big condominiums connected to the district heating network.

3.1. Statistical analysis

The different types of buildings were subdivided into homogeneous groups by typology of use and characteristics. For every homogeneous group, a statistical analysis was performed in order to evaluate the normal distribution of energy consumption data. This allowed us to neglect anomalous data that differed too much from the average consumption (e.g. Fig. 1b; in green the selected buildings). After analyzing the trend of the consumptions for each homogeneous group, an average value of energy consumption and its standard deviation were determined. In Table 1 the homogeneous groups of buildings subdivided by type, period of construction and surface to volume ratio, are reported. The analyzed residential buildings have the same distribution in the city of Turin, with the most numerous classes for the buildings built in 1946-60 (29%), in 1918-1945 (20%) and in 1961-1970 (20%).

Table 1. The homogeneous groups of buildings for the energy-use models, considering: type of building, period of construction and S/V.

Use	Period of construction	Classes of period of construction	Classes of S/V [m^{-1}]					N. buildings analyzed	N. buildings selected
			1	2	3	4	5		
Residential buildings	<1918 & 1818-1945	(1-2)	<0.32	0.32-0.41	>0.41-0.59	>0.59-0.78	>0.78	409	325
	1946-1960	(3)	<0.38	0.38-0.58	>0.58-0.68	>0.68		366	288
	1961-1970	(4)	<0.32	0.32-0.38	>0.38-0.50	>0.50		553	433
	1971-1980	(5)	<0.37	0.37-0.57	>0.57			238	187
	1981-1990	(6)	<0.33	0.33-0.36	>0.36			41	33
	1991-2001	(7)	<0.30	0.30-0.40	>0.40-0.82	>0.82		12	10
	2001-2005 & >2005	(8-9)	<0.40					2	2
Schools	nurseries & kindergartens							41	28
	primary & secondary schools							46	30
	grammar schools or lyceums							22	20
	technical institutes							33	31
Offices								39	27

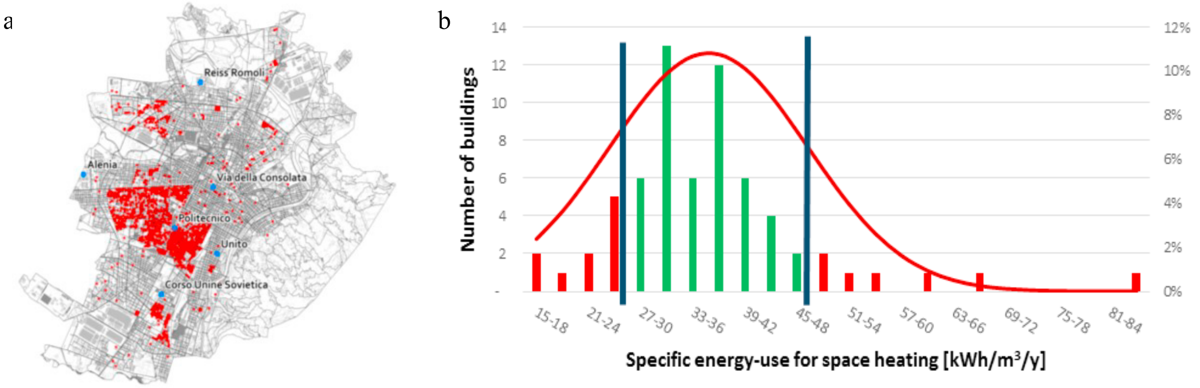

Figure 1. (a) The data sample of 2,092 buildings with space heating energy consumptions in red and the considered 6 weather stations in blue; (b) Normal distribution of specific space heating energy consumption (considering the heating season 2011-12 with about 2221 HDD at 20°C for "via della Consolata" weather station) of residential buildings with "S/V < 0.32 m^{-1}" and period of construction "< 1945". In green the 68% of the selected data and in red the anomalous data with consumptions lower or higher than the average energy-use ± its standard deviation.

4. Results and discussion

In this paragraph, the results of the statistical analysis on the energy consumption of residential and non-residential buildings are reported. The analyzed residential buildings are mainly compact and big condominiums with low S/V ($S/V_{avg} = 0.38\ m^{-1}$; the average value for the buildings in Turin is of $0.6\ m^{-1}$, with $0.5\ m^{-1}$ in the center) because the sample, used in this analysis, was created with buildings connected to the DH network. For each period of construction, the analysis was conducted on different classes of compactness (i.e. S/V), as reported in Table 1.

In Fig. 2a the average and standard deviation (with the vertical line) values of space heating consumption (EP_h) are represented for each period of construction. For the period of construction from 1961 to 1990, buildings consumed more energy for space heating than old and recent ones probably due to the thinner structures of building envelopes built during the economic boom after the end of the Second World War. After 1991, the average energy consumption decreased thanks to the consequences of the Italian Laws on building energy savings (L. 373/76 and L. 10/91). The differences in energy consumption, represented by the standard deviation, are mainly due to the compactness of the envelope, the heating system efficiency, the solar exposition and other variables of the buildings. These variations were mainly constant while the trend of energy consumptions increased after 1960 and decreased after 1991. For a higher robustness of the statistical analysis more data on energy consumptions are needed, especially for recent buildings built after 2001 (as can be observed by the number of buildings in Table 1).

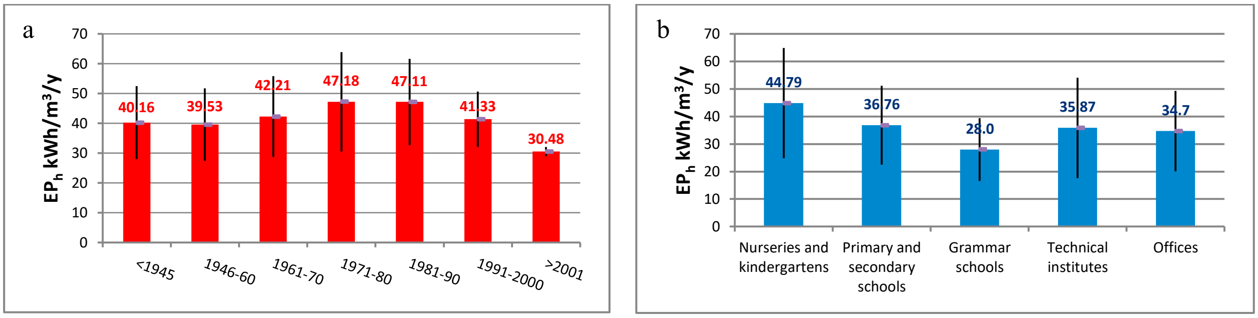

Figure 2. Specific space heating consumptions average values EP_h and the standard deviations (vertical lines) for the heating season 2011-12; (a) residential buildings by period of construction and (b) non-residential buildings by types of users.

For public buildings, consumption data of 233 buildings were collected; most of them are schools (142; 61%) and only for this type of public building only, some distinctions have been made between the different types of school. Particularly in Fig. 2b, it can be observed that: nursery and kindergarten buildings consumed more energy, as they require warmer environments than primary and secondary schools; high schools were divided into grammar schools and technical institutes because they have different timetables and various types of laboratories and activities with consequently different energy demands.

In Fig. 3a the average energy consumption for space heating of residential buildings, subdivided in the selected homogeneous groups by periods of construction and S/Vs, is represented. Space heating consumptions increased with S/V and this increase was based on the period of construction. As already observed in Fig. 2b, the older buildings had similar consumptions to more recent buildings; thus some different clusters have been assumed. As seen in Fig. 3b, the buildings constructed before 1970 and from 1991 to 2001 have been grouped together, as for the buildings built from 1971 to 1990. Lower energy consumptions can be noted for newer buildings (after 2001) and also similar values of energy consumptions can be observed for buildings with high values of S/V.

The information of heated volumes in the SEAP and in the technical map of the Municipality of Turin were compared for all the buildings; therefore, the average specific energy-use value was deducted from the overall consumption for the different types of building. In Table 2 the average consumptions data used for the buildings of Turin are reported; in brackets, the corrected heated volumes and the relative specific energy-uses data.

In Table 3, the statistical comparison between bottom-up and top-down models using the GIS tool are reported. The described energy consumption bottom-up models, for residential and non-residential buildings in Turin, were applied with a correction factor of 1.02 to match the result of statistical models of buildings consumption and the SEAP municipal energy consumption reported for the year 2005. This value shows the good quality and accuracy of buildings database. The correction factor considered the: different types of heating systems across the city's different neighborhoods, percentage of centralized vs individual systems, presence of the District Heating network, and different level of buildings retrofit [12].

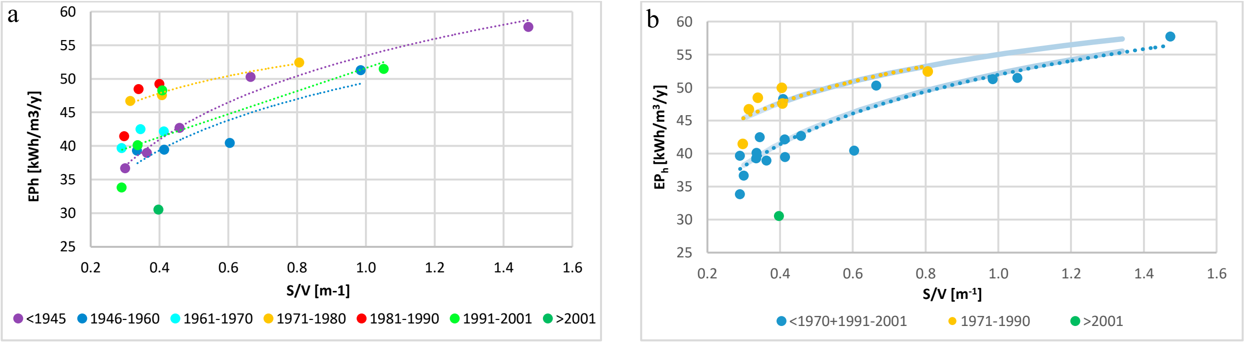

Figure 3. (a) Specific space heating consumptions EP_h of residential buildings according to the S/V and period of construction; (b) EP_h of residential buildings according to the S/V, divided into 3 homogeneous classes for different period of construction.

Table 2. Gross heated volumes of buildings (in brackets the used heated volumes comparing GIS tool and SEAP databases) and the relative specific energy-uses for space heating and hot water production considering the reference heating season of 2011-12 with 2221 HDD at 20 °C.

Types of building	Number of buildings in Turin	Volume (at 2005) km^3	EPgl (at 2011-12) $kWh/m^3/y$
Churches	306	25.52 (510.41)	27.73 (4.45)
Commercial buildings	2,818	11,691.18 (8,993.22)	17.06 (22.18)
Hospitals	606	2,508.01	53.03
Hotels	260	849.21 (424.60)	57.62 (28.81)
Industrial buildings	4,519	29,713.93	88.70
Offices	918	3,232.15	22.08
Residential buildings	44,803	160,548.12	31.09
Recreational buildings	108	593.94	23.14
Schools	1,754	5,340.73	25.35
Services buildings	1,985	5,315.57	30.55
Sport facilities	397	512,415.11	36.82
Swimming pools	93	271.89	69.02
Universities	403	2,147.47 (3,376.43)	41.20 (26.20)

Table 3. Gross heated volume of residential buildings, HDD, percentage of space heated and the correction factor applied to Turin.

City	Volume of residential buildings in 2005 (km^3)	Volume of residential buildings in 2015 (km^3)	Standard HDD at 20°C UNI 10349-3: 2016	HDD at 20°C year 2005	HDD at 20°C for last 10 years (last 5 years)	Thermal energy-use at 2005 (MWh/y)	Thermal energy-use from District Heating at 2005 (MWh/y)	% of heated volumes ISTAT 2011 (-)	Correction factor (-)
Turin	160,548.12	163,361.84	2648	2703	2449 (2150)	5,846,863	1,000,104	0.845	1.02

With these models, the energy-consumption for space heating and hot water production can be represented, as in Fig. 4a, with the possibility also to correlate these data with the spatial distribution of buildings CO_2 emissions.

Finally, in Fig. 4b the average specific energy-consumption is represented for the different districts of Turin with the vertical bar chart (scaled on the value of 42 $kWh/m^3/y$ for the tertiary sector in yellow). Figure 4b shows how specific energy-use (EP_{gl}) depends upon neighborhood as outdoor air temperature may be influenced by the Urban Heat Island (UHI) effect, in addition to other microclimate variations. Notably, lower values of EP_{gl} are observed in the city center (where there is more UHI) regardless of whether the neighborhood is residential, public or tertiary.

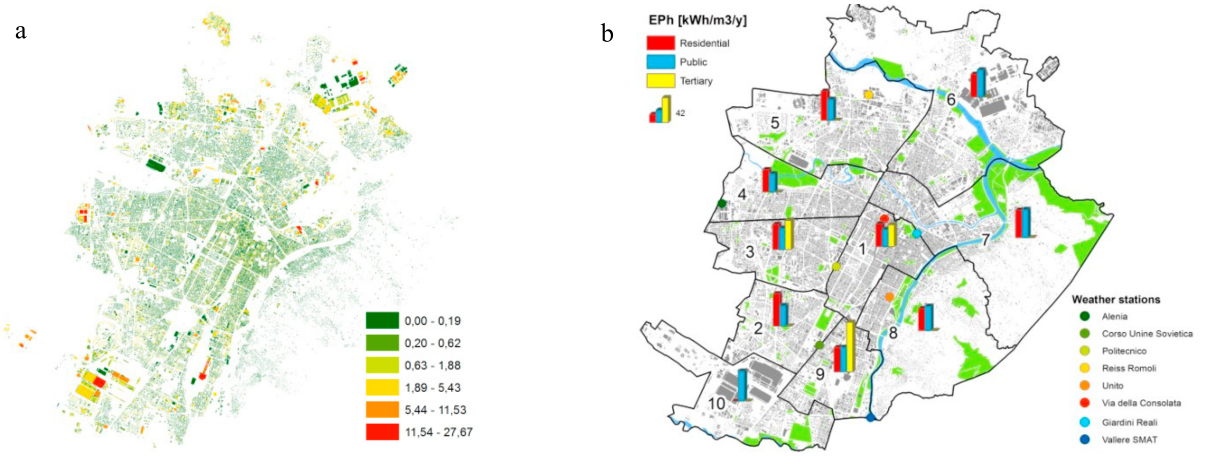

Figure 4. (a) The yearly energy-use for space heating and hot water production for the heating season 2011-12 (GWh/y); (b) The 10 districts in Turin with the considered weather stations and the average specific energy-use EP_{gl} (the scale can be observed in the legend for tertiary sector).

5. Conclusion

The sustainability of urban environments can be analyzed on multiple dimensions including: human activities and neighborhood use, energy-consumption, socio-economic level, air quality, types of outdoor space and the UHI effect. Clearly these will vary from city to city, and as such, a “one-size fits all” strategy would fail to capture these nuances. Optimization of energy demand and supply of buildings at urban level could be a good compromise to the need of a sustainable environment and the high-energy demand due to the various human activities especially in urban context. The simplified bottom-up building energy-consumption models, shows consumption is log-normally and gamma distributed for homogeneous groups of buildings, suggesting the use of this models together with a GIS tool for the promotion within big data analyses of similar sample domains; more work is still needed to conferm these conclusions. The results of such big data analyses can help optimize energy demand subject to the limited energy sources, help identify where government incentives could best smooth peak energy demands, and identify the most ripe areas for application of renewable energy sources. Thus, the adopted methodology can help policy makers better execute an urban plan maximizing our goals of improved sustainability and livability, for our cities.

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