Hybrid models for the evaluation of energy sustainability in urban areas

HYBRID MODELS FOR THE EVALUATION OF ENERGY SUSTAINABILITY IN URBAN AREAS

Guglielmina Mutani, Mariapia Martino, Michele Pastorelli[2]

Abstract

Urban population in the world accounts for 54%, with 69% in Italy, and it continues to grow (The United Nations Population Division's World Urbanization Prospects, 2015). In this work, energy sustainability has been analysed in urban contexts with high energy consumptions and low availability of renewable energy sources. The sustainable management of energy is a great opportunity in the complex environments of urban areas where the buildings are always an important contributor. Main results of recent research activities, carried out by the authors, are presented with energy-use models for buildings considering statistical bottom-up and top-down models. These models have been tested on about 50 municipalities in the Metropolitan City of Turin comparing the results of bottom-up models (at building scale) with the top-down model at municipal scale using a GIS tool. Finally, new hybrid models have been integrated to consider urban morphology, solar exposition and microclimatic variables of different urban environments. The use of a GIS tool consents to manage and represent buildings data at urban scale.

1. Introduction

The energy sustainability in urban areas is a critical issue because of complex environments, high population densities, many anthropic activities, high environmental impact, together with high-energy demand, low availability of spaces and of renewable energy sources. A sustainable management of energy could be a great opportunity to be exploited and buildings are always a key-contributor to optimize the use of energy and to reduce greenhouse gases emissions [1].

The aim of this work is to provide a replicable method for future energy self-sufficient districts or cities and to help policy makers to solve the main three energy issues: energy security, energy sustainability and energy equity (Energy Trilemma [2]). In Italy, until now prior actions are energy efficiency and renewable energy sources issues, encouraged also by national and regional subsides [3].

In this work, the models of energy consumption are presented from building to blocks of buildings, district and urban scale, with the aim of identifying a methodology, to optimize the overall energy system - from the demand to the supply - taking into account all the constraints present in real urban environments: territorial, economic and social constrains (i.e. mutual shadowing between buildings, the morphology of built environment, the presence of vegetation, water and historical heritage) as well as the microclimatic variations in the urban settlement [4, 5]. With these models, also the integration of energy harvesting systems, renewable energy technologies and different retrofit solutions of the buildings stock can be investigated at the district or urban scale [6, 7]. Energy models at territorial scale could also help in evaluating the impact of climate change in the energy demand/supply of buildings, as well as the impact of future energy policies.

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The approach of this work is explained in detail in the methodology section (Section 2), while data collection is described in Section 3. The discussion on the results is reported in Section 4 and in the conclusions.

2. Proposed methodology

In an urban environment, the buildings alone could not satisfy all energy needs, then a bigger scale should be used as block of buildings, district, urban, municipal or territorial one. A sustainable city cannot be only a set of sustainable buildings, but it should be considered also the relations between the buildings and the surrounding spaces and the interrelationships between all elements within a city considering also environmental, economic and social aspects.

Precisely, in the building sector, energy consumptions are affected by several factors that can be grouped in three main categories:

- specific characteristic of the building related to the construction;
- specific use of the building and variables related to the people living in the buildings;
- specific characteristic of the analysed territory and spatial organization of the buildings at blocks of buildings, district or territorial level.

The space heating energy consumption of buildings can be divided by two main components [8, 9, 10]: the first related mainly to the building’s use, envelope, systems’ efficiencies, and climate characteristics; the second related to the surrounding environment, open spaces and urban context features, and the locally variations of microclimate. The consumption of buildings can be therefore represented with the following two components:

$$TEC = ECB + ECU \quad (1)$$

where:

TEC is the specific yearly Total Energy Consumption [kWh/m^2]

ECB is the specific yearly Energy Consumption depending from Building, users and climate [kWh/m^2]

ECU is the specific yearly Energy Consumption depending on Urban context [kWh/m^2].

The first component is widely known and it represents the average energy consumption as function of the main characteristics of the building and its users; the second component can differentiate building energy consumptions depending by the characteristics of the surrounding context in which the building is located, taking into account microclimate variations in the built territory; the same building in different parts of the city, can have a different energy-consumption.

Only recently the research is focused on the second component which will have an important role especially for nearly zero energy buildings (nZEBs) with a minimum contribute in energy consumption of the building itself (first component of Eq. 1); then, the role of urban planning will be fundamental for the design of sustainable districts and cities with different urban characteristics. To take into account this new component, the scale of the analysis changes to consider a larger area, at least the one around a group of buildings and then move from the building scale to a larger scale: blocks of buildings, district or urban scale.

Several approaches have been proposed for the energy analysis that can be grouped in three categories: top down models, bottom up models and hybrid models [9, 10, 11].

The first analyses on bottom-up and top-down models were performed by the authors in 2006 within the research project financed by Fondazione C.R.T. [12] and they continued with Cities On Power (www.citiesonpower.eu) and EEB Zero Energy Buildings in Smart Urban District (www.s3lab.polito.it/progetti/progetti_in_corso/eeb).

In this work, the combined use of bottom-up, top-down and hybrid models is presented using a GIS Tool (in Figure 1). This methodology is GIS-based and it applies the simplified bottom-up models to all types of building for the whole city of Torino. Then the overall buildings consumption is compared with the top-down municipal scale data with an iterative procedure as long as the results of bottom-up and top-down models do not match. This methodology was tested on more than 50 municipalities in the Metropolitan City of Turin with different databases and accuracy in the research project Cities On Power [6].

2.1 Bottom-up models

These models operate at building scale, and are usually used to evaluate the energy balance of a single building with high detail. Models at building scale need good knowledge of the building characteristics together with measurement of the energy consumptions for their validation. Usually, from bottom-up models, simplified models can be elaborated using the more energy-correlated variables and defining functions of specific energy consumptions for every group of buildings when the analysis is at urban or territorial scale. Then from data related to specific groups building, the evaluation of energy consumption for block of buildings, district and cities can be carried out with, for example, a GIS tool. To achieve valid and reliable results at district and urban scale, large amount of data must be processed, as more than 2,000 buildings over 2 to 3 heating seasons for the city of Turin [13]. Bottom-up models can also be used for the evaluation of energy savings after buildings retrofits.

2.2 Top-down models

Energy-use data at urban or territorial scale are compared with climate variables, census data and statistical surveys to determine average energy consumption for the existing buildings. These models can compare energy consumptions with different variables (i.e. socio-economic and climate data), evaluate energy consumption trends but cannot distinguish spatial variations in energy consumption on a territory due to different types of buildings or urban contexts. Typical top-down models are used for the Covenant of Mayors action plans (i.e. https://www.covenantofmayors.eu/).

2.3 *Hybrid models*

These models integrate the earlier models with engineering methods based on the building physics, for example, to simulate variations in energy consumption due to conditions other than real ones. In this work, CitySim Pro tool (https://citysim.epfl.ch/) was used to represent energy consumptions and GHG emissions at block of buildings and district scale. In Section 4 an example of different districts for the city of Turin is reported in Figures 12.

The same methodology can be applied also to evaluate the energy savings targets that can be reached on a real building heritage (Figure 2). With this purpose the Energy Certificates database of Piedmont Region, with buildings data and socio-economic variables, was used to evaluate the citizens' participation at the local energy policies, or the feasibility of buildings' retrofits, for the reduction of buildings consumption [6, 14].

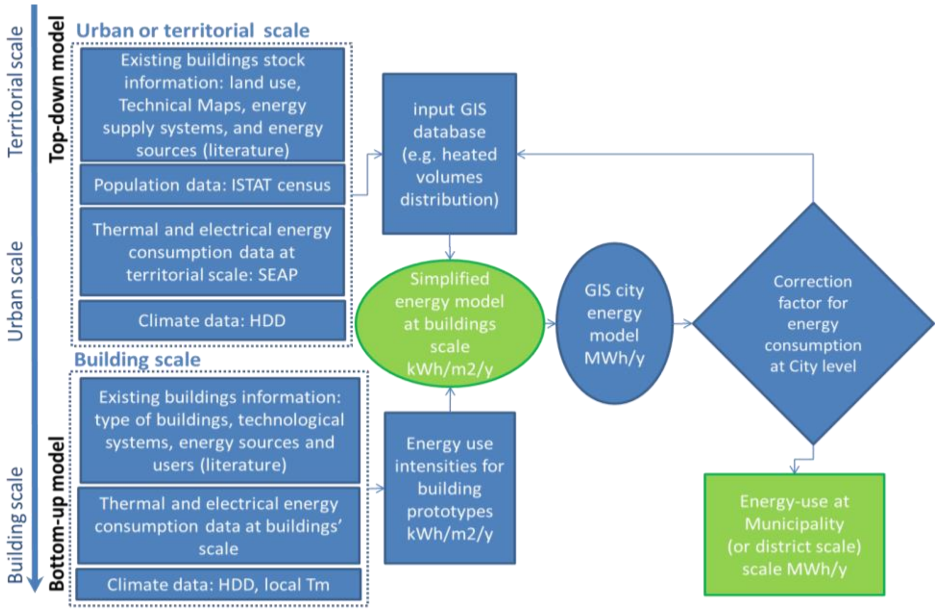


Figure 1: Block representation and comparison between top-down and bottom-up models.

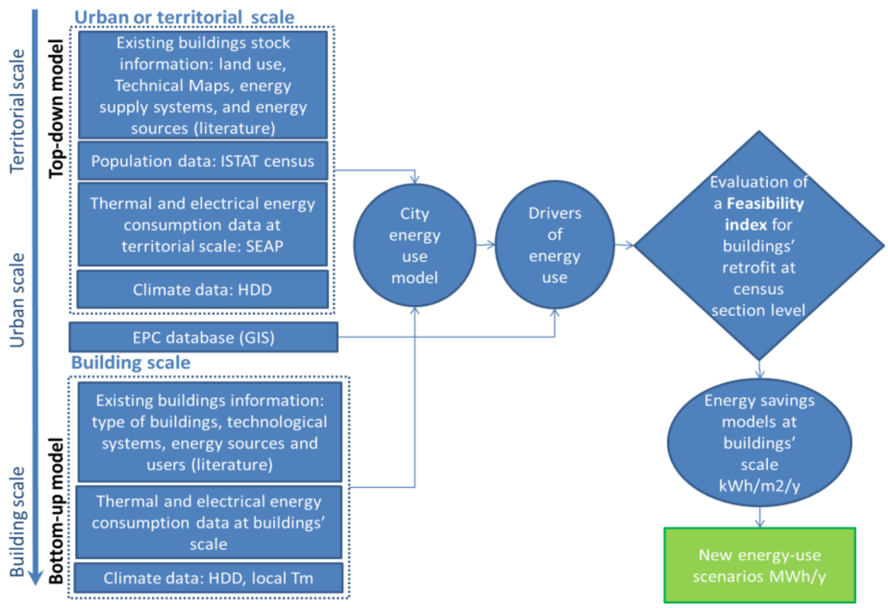


Figure 2: Block scheme for the evaluation of energy savings in a real building heritage.

This procedure is based on average or median values of energy intensities for every type of building and then cannot evaluate how changes in the urban context can influence energy consumptions.

Then, seven typical districts of Torino were identified, four districts built before 1940: Arquata, Crocetta, Raffaello and Sacchi; and three districts built after 1990: Mediterraneo, Spina 3 and Villaggio Olimpico. The use of the software CitySim Pro [15] was integrated in the procedure as engineering tool to evaluate how changes in the urban context can modify the consumption of buildings.

The aim of this work was to define a methodology through a case study. Particularly, the development of a simplified model for the thermal energy-use of different types of building was performed for the city of Turin and the municipalities of the metropolitan area. Beside, an hybrid model was used to consider how the various urban contexts can influence buildings energy consumptions for space heating.

3. Data collection

The availability of reliable data concerning the energy models, mapping and planning of the energy demand and related supply systems is fundamental for the analysis and the development of energy and environmental policies. In Europe there is a lack in harmonisation especially for buildings data and buildings performance certificates. The European community, with the INSPIRE Directive 2007/2/EC, is establishing an infrastructure for spatial information and to data models to support Community policy makers but also to solve the energy trilemma: energy demand/supply optimization, economic competiveness and environmental sustainability considering the specific characteristics of every country, population and building heritage [16].

The necessity of reliable data is also focused in several EU funded projects and in the general objective of the EU Program H2020. The mapping tools must be able to describe the existing area of interest and supply information that help innovative actions. The key factors that make useful and reliable a mapping tool have been identified in the ability to process large and complex data sets to provide a detailed and comprehensive description of the existing energy system and the dynamic development of all relevant supply and demand elements within a given geography.

Specifically, the heating and cooling mapping tool should be capable of modelling flexibility needed for integrating variable renewable energy, and demand response and enable analysing the impact of the increasing number of low energy buildings [17]. Models for the energy demand and supply have the objective to reach more efficient scenarios considering hourly, monthly, seasonal and yearly time periods [18] and the economic impact of new solutions at local, regional and national level.

Data	Database	Scale
Building geometrical and typological characteristics	Technical maps of the City of Torino (CTC, 2015)	building
State of building maintenance	ISTAT 2011 census	block of buildings
Digital surface model	LIDAR ICE data of 2009-2011	grid of 5 m x 5 m
Energy supply system for space heating and hot water production and fuel	ISTAT 2011 census	block of buildings
	District heating company (2010-2016)	building
Energy distribution network	District heating company (2010-2016)	building
Climate data	Regional Agency for the Protection of the Environment (ARPA Piemonte)	weather stations
Energy consumption	District heating company (2/3 heating seasons: 2012-2015)	building
	Sustainable Energy Action Plan, SEAP - Covenant of Mayor (2005)	municipal
Energy Performance Certification of Buildings	Piedmont Region	building
Land use	Technical maps of the City of Torino (CTC, 2015)	building
Population characteristics and distribution	ISTAT 2011 census	block of buildings
Socio-economic variables	ISTAT 2011 census	block of buildings

Table 1: List of database useful to define energy models at territorial scale.

Final users of the data are all the stakeholders involved in the existing power plants and energy infrastructures aimed to make more efficient the energy demand and supply balance at lower costs [19]. Specific final users of the mapping tools are the boards and the Institutions responsible for the promotion and the adoption of actions focused on better energy usage, energy savings plans and integration of heating and cooling plants into spatial policy and urban planning [20, 14]. Modelling tools should be user friendly and open source yet able to model the full energy system, i.e. heating and cooling, electricity and transport.

To create energy model at territorial scale, the databases and their accuracy are essential. In this work, data collection includes the databases reported in Table 1. As it is possible to observe, the different variables are given at different scale, then some reasonings must be done for accurate results (using average, median or prevalent data at building or blocks of buildings scale depending on the variable).

4. Results and discussion

The proposed methodology is a hybrid approach where the simplified building models, derived by the bottom-up approach, match with the energy consumption of a district or a city (top-down approach) but these models can have variations in energy performance due to local changes in urban context and this can be evaluated with an engineering tool.

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 model is an average model and it does not take into account important factors such as the spatial variability in: solar gains, indoor/outdoor air temperatures variations, the utilization of renewable energy sources and, mainly, the level of buildings' retrofit that may have changed the energy consumptions of buildings over the years. 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 of 1.02 as function of the typical built environment analysed (research project: "Cities On Power" http://www.citiesonpower.eu/en/). This value, very closed to the perfect match value (unity value) between building and city energy models, indicated that the databases used are very accurate.

For all the buildings in Torino, the information of heated volumes in the SEAP and in the Technical Maps CTC of the Municipality of Torino were compared; therefore, knowing the overall consumption for the different buildings in the city of Torino, the specific energy-use value was deducted for each type of building. In Figures 3 and 4 the data used for the buildings of Torino are reported with the relative average specific energy-uses for the average heating season 2011-12 (2221 HDD at 20°C).

For residential buildings, the more detailed information about energy-use data, also subdivided by the buildings' period of construction and compactness (with the surface to volume ratio S/V), allows a more accurate model of energy-use with linear regression models of space heating and hot water production (Figure 3 and [13]).

The models reported in Figures 3 and 4 have been calibrated considering the different types of heating system for each census section, knowing the percentage of centralised and individual heating systems using different type of fuels and the presence of the District Heating network (considering the different heating systems efficiencies).

In Figure 5 the energy performance of residential buildings is reported as functions of the compactness, the period of construction, the percentage of occupied building and the closest weather station.

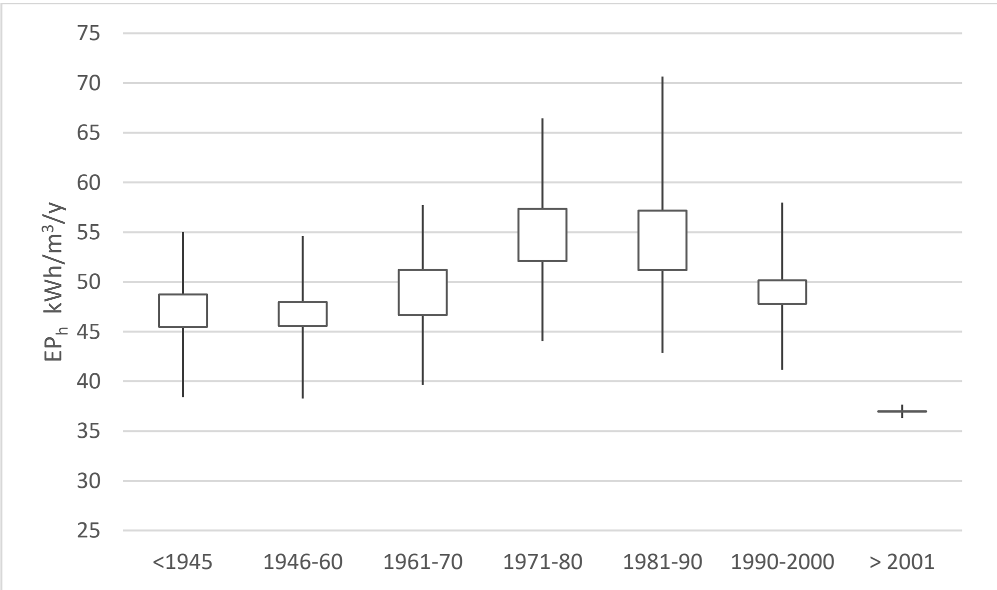


Figure 3: Specific space heating energy consumptions EPh [kWh/m3/y] computed from the heated gross volume, putting in evidence the first quartile, median, average and third quartile values for the heating season 2011-12 (2221 HDD at 20 °C).

In Figure 6 an example of the territorial, technical and economical constrains for the DH network expansion is represented, with respectively: the territorial limits given by the Po river and the hill (in green), the presence of individual heating systems (28.4%), and the high density historical old town in the centre of Torino (in red) and, finally, the economical constrains due to little buildings which will not be connected to the DH network.

With these model, the energy-uses for space heating and hot water production can be represented, as in Figure 7, with the possibility also to correlate these data with the spatial distribution of the CO_2 emission, as described in the QUADRANTE research project for the Italian city of Ivrea (TO) (http://quadrante-livinglab.netsurf.it/index.php, in Italian).

The energy consumption model described in this paragraph was also used to evaluate the potential of solar technologies integrated in the rooftop of existing buildings, as solar renewable energy sources are the most realistic and easy solutions in a high density urban context [6, 13]. A web-interface with an interactive cost-benefit analysis was also developed in the research project “Cities on Power” for all the Metropolitan City of Torino with about fifty municipalities, to evaluate for each building and each Municipality the potential of energy production with roof-integrated solar technologies [21, 22].

Finally, considering the socio-economic variables of the population and buildings (form ISTAT census 2011) with this model was also possible to evaluate the expected energy savings due to future renovation scenarios of buildings. Considering the most influencing socio-economic variables, a feasibility index of future buildings’ renovation was calculated for residential buildings, with a resulting energy saving rate for Torino of 19-27% in the medium and long-term scenarios [8, 14, 22].

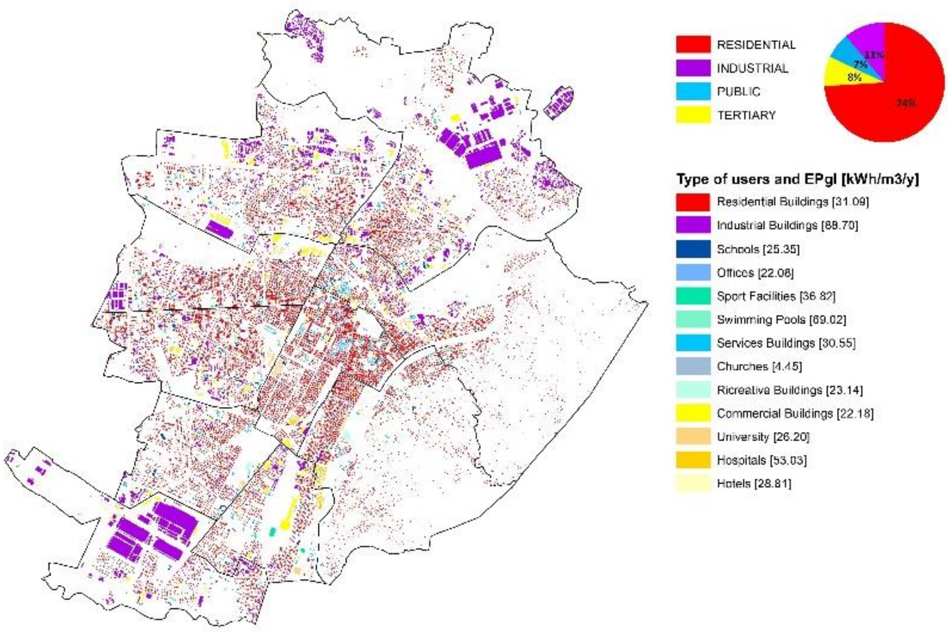


Figure 4: Different type of buildings analysed in Torino with energy consumption EP_{gl} [kWh/m^2/y] for the heating season 2011-12 (2221 HDD at 20 °C).

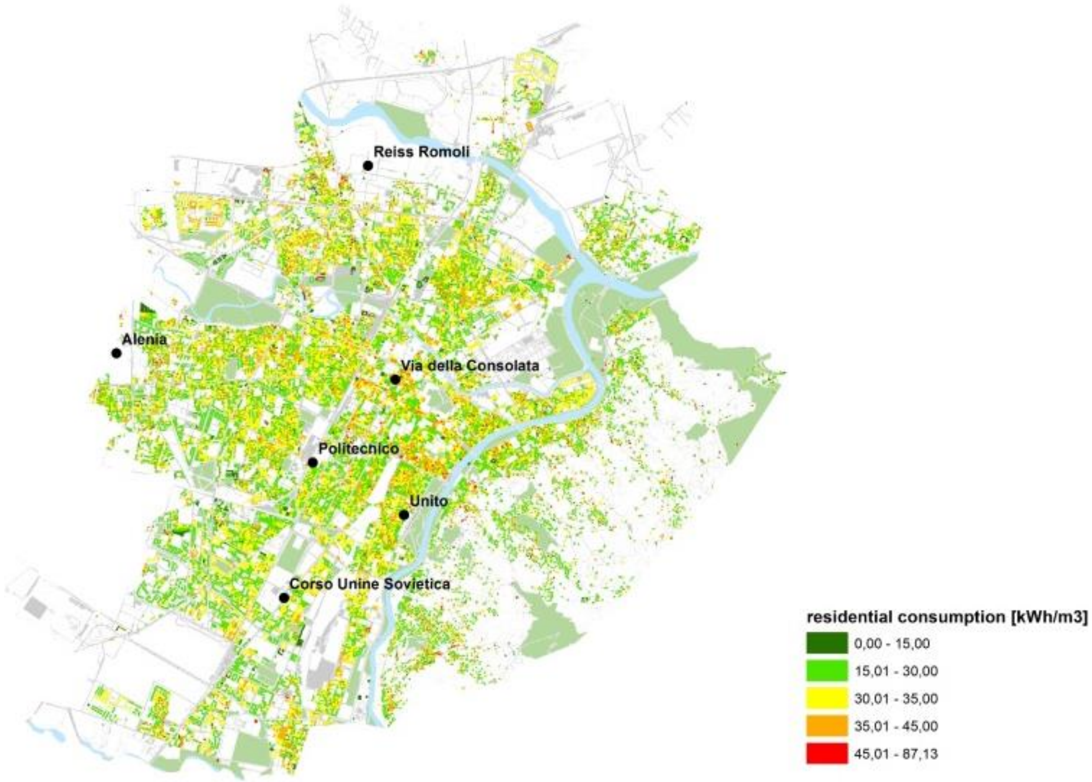


Figure 5: Residential buildings energy performance EP_{gl} [kWh/m^2/y] for the heating season 2011-12 with the location of six weather stations.

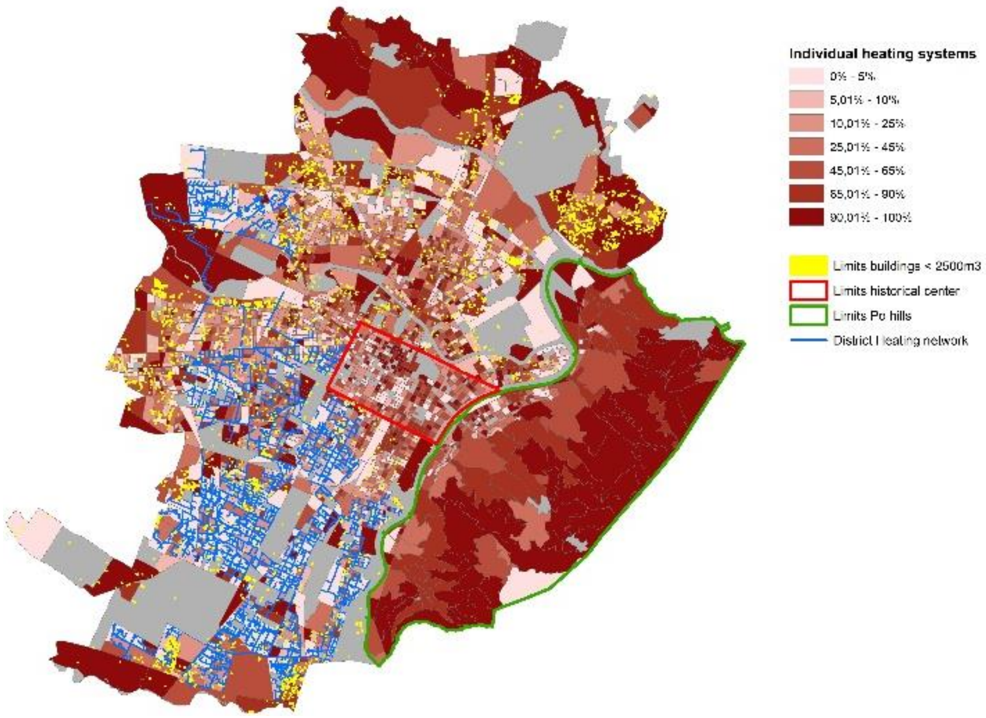


Figure 6: Data about individual heating systems and the territorials and economical constrains for the DH network expansion

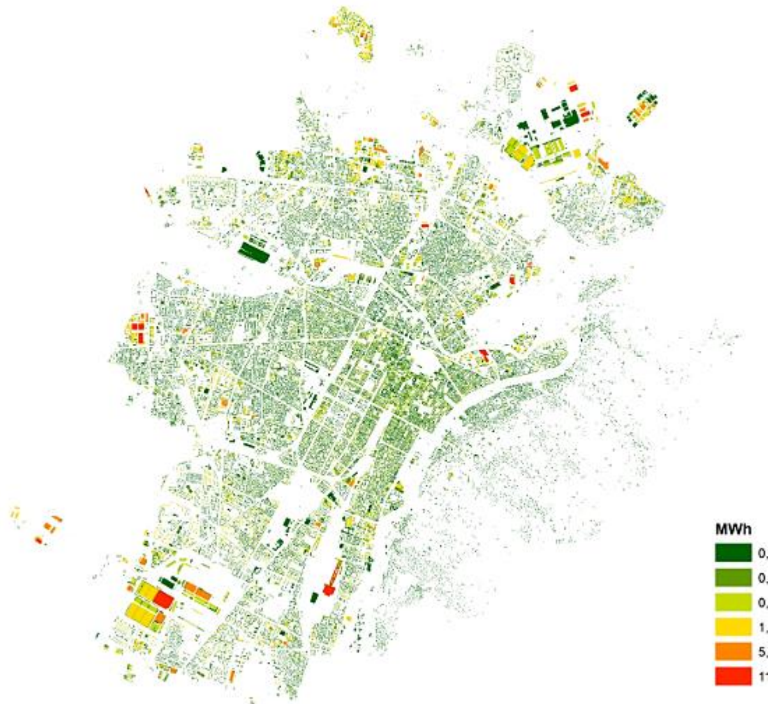


Figure 7: The yearly energy-use for space heating and hot water production (GWh/y) for the heating season 2011-12 (2221 HDD at 20 °C).

The second component of the energy-use for residential buildings in Eq. 1, is related to the surrounding environment, the urban context and the locally variations of microclimate. The same building with different surrounding environments, has different energy consumptions for space heating and cooling. Also the microclimate changes influence energy consumptions of buildings and in Torino the average monthly air temperatures, registered in the different weather stations inside the city, can record differences on the monthly air temperatures of about 3-4 °C, principally during the colder months [23, 24]. Considering the average yearly air temperature in the last 10 years, the coldest areas in Torino are the parks in the periphery, while the warmer ones are in central zones with high building density.

To take into account urban variables in residential energy consumption models, a territorial unit corresponding to the census section was considered with a globally average area of 3.38 ha for the city of Torino and with and average area in the central districts of 1.15-2.12 ha, corresponding to the blocks of buildings area [25]. For each census section, three urban factors have been calculated: the “Urban morphology” factor (U), the “solar exPosure” factor (P) and the albedo coefficient (A).

The “Urban morphology” factor (Eq.2) describes the urban morphology, at block of buildings scale:

$$U = BCR \cdot H/W = BD/W \quad (2)$$

where: BCR [m^2/m^2] describes the relationship between the territorial unit area (census section area) and the buildings’ footprint; the “aspect” or “height to distance” ratio H/W [m/m] represents the canyon effect causing higher air temperatures and lower air velocities in the urban outdoor spaces surrounded by buildings; BD [m^3/m^2] is the building density.The “solar exPosure” (P) is the product of the ratio between the heights of the buildings (H) and the height of the surroundings (H_m) and of the main orientation of the streets (MOS):

$$P = H/H_m \cdot MOS. \quad (3)$$

The main orientation of the streets (MOS) influences the orientation of the buildings, the shadowing on the outdoor spaces and the canyon effect A more detailed descriptions of the urban variables can be found in [9].

Finally, the “albedo” coefficient (A) should normally be considered because it influences the outdoor air temperatures and the canyon effect; it depends on the outdoor surfaces materials as asphalt or concrete streets, green areas, buildings’ facades and roofs. Usually at urban scale, only the albedo characteristics of horizontal surfaces are considered as they can be recorded by satellite sensors; the ASTER images (at 22nd July 2004) were used [23, 24]. In this work, the energy-use for space heating of residential buildings was compared with the average value of each urban variable with global value “G” among each territorial unit. Considering the census section or block of building area as a territorial unit, a correlation between the urban context characteristics (G-UPA) and the average energy consumption data for buildings’ space heating was analysed. In Figures 8, 9, 10 and 11 the urban variables BD, BH, H/W and A are represented for the 3840 census sections of the city of Torino.

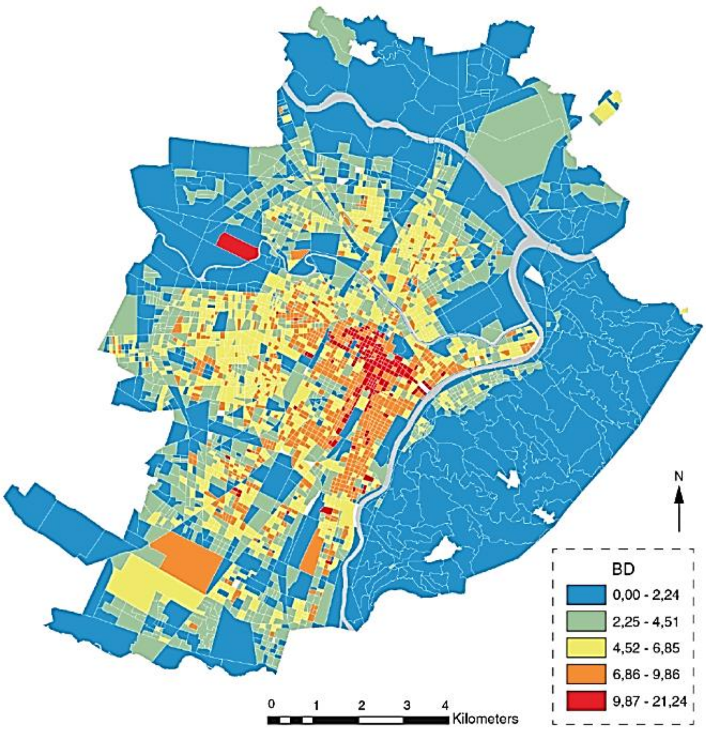


Figure 8: The building density BD [m^3/m^2].

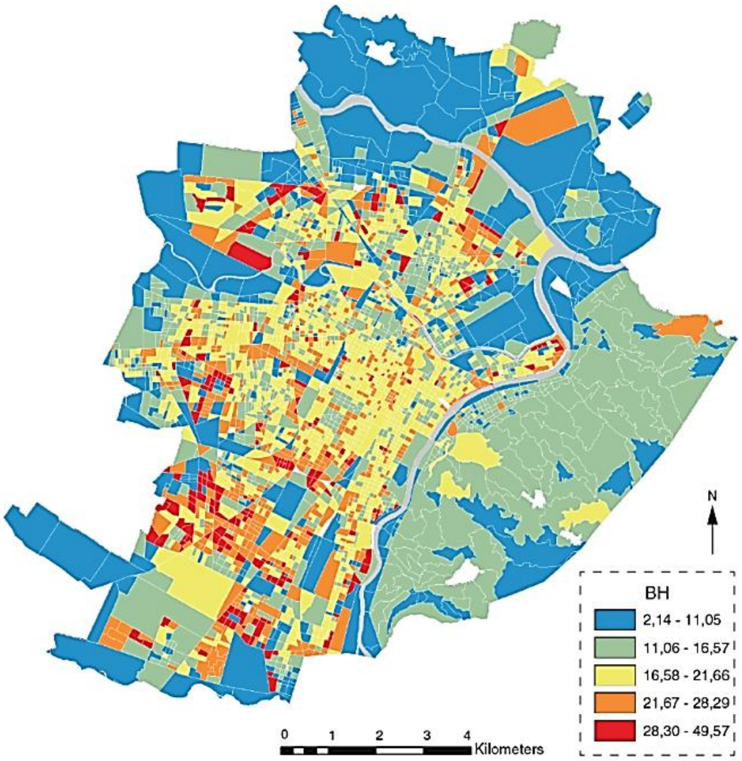


Figure 9: The building height BH [m].

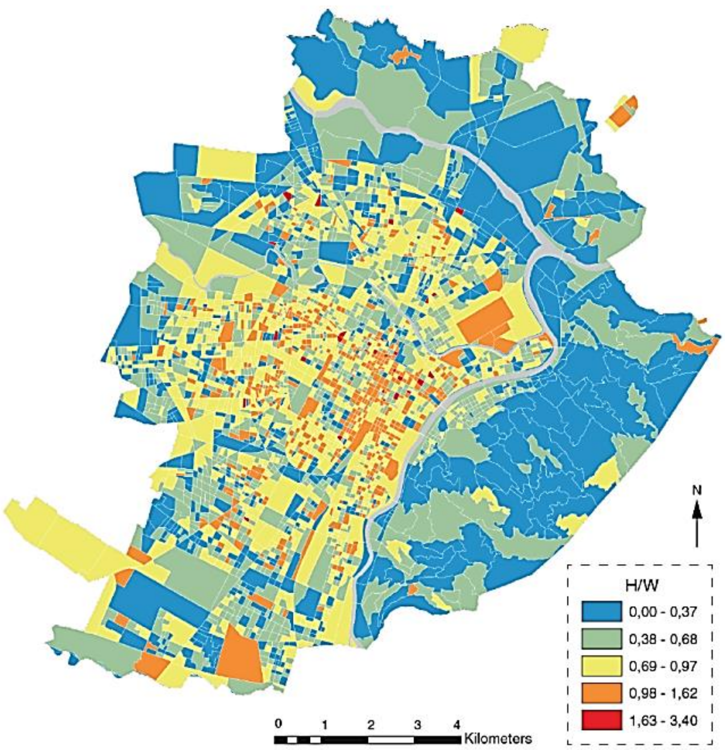


Figure 10: The aspect ratio H/W [m/m].

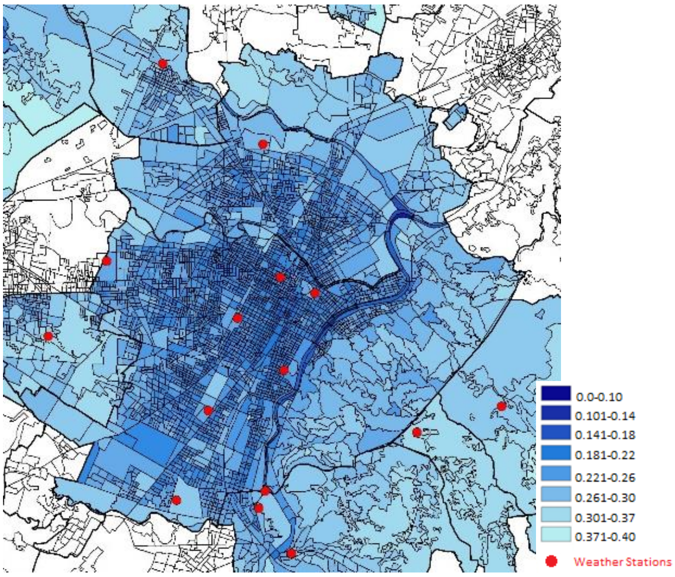


Figure 11: The albedo coefficient A.

To evaluate how urban morphology can influence building energy consumption, the same procedure has been applied to different districts in Torino; the first four districts mainly built before 1945 and the last three ones with newer buildings:

1. Sacchi: 75% of buildings was built before 1945; the 15%, between 1946 and 1980. Its main urban characteristics are: BCR=0.50; BD=8.6 m^3/m^2; BH=19.5 m; H/W=1.2; H/Hm=1.0; MBO=1.1; MOS=0.9; A=0.16.
2. Arquata: 80% of buildings was built before 1945; the 15%, between 1946 and 1980 and 5% after 1992. Its main urban characteristics are: BCR=0.23; BD=4.0 m^3/m^2; BH=19.1 m; H/W=0.4; H/Hm=1.0; MBO=1.0; MOS=0.9; A=0.18.
3. Crocetta: 30% of buildings was built between 1919 and 1945; only 12% after 1981. Its main urban characteristics are: BCR=0.41; BD=6.7 m^3/m^2; BH=20.3 m; H/W=0.9; H/Hm=1.0; MBO=1.1; MOS=1.1; A=0.2.
4. Raffaello: 90% of buildings was built before 1970 with the 67% built before 1960. Its main urban characteristics are: BCR=0.48; BD=8.2 m^3/m^2; BH=20.0 m; H/W=0.9; H/Hm=1.0; MBO=1.0; MOS=1.0; A=0.16.
5. Mediterraneo: 65% of buildings was built between 1946 and 1980; only 5% after 2000. Its main urban characteristics are: BCR=0.27; BD=6.7 m^3/m^2; BH=27.5 m; H/W=0.9; H/Hm=1.0; MBO=1.1; MOS=0.9; A=0.17.
6. Spina 3: all buildings were built after 1990. Its main urban characteristics are: BCR=0.22; BD=3.1 m^3/m^2; BH=21.3 m; H/W=0.7; H/Hm=1.0; MBO=1.1; MOS=1.3; A=0.23.
7. Villaggio Olimpico: 70% of buildings was built after 2000; the 20%, between 1980 and 1990. Its main urban characteristics are: BCR=0.20; BD=4.1 m^3/m^2; BH=21.4 m; H/W=0.4; H/Hm=0.9; MBO=0.9; MOS=1.3; A=0.19.

In Figure 12 are represented the districts: Arquata (a), Crocetta (b), Villaggio Olimpico (c) and Spina 3 (d). As it is possible to observe, Crocetta has higher buildings density and aspect ratio H/W typical of cities centres. Conversely, the newer districts Spina 3 and Villaggio Olimpico have lower building densities, buildings coverage ratio and aspect ratios.

For this study, the typologies of buildings were grouped with similar characteristics, so the variation in energy consumptions was caused only to the urban context differences (second component in Eq.1). Then, to have more differences on the urban context, the tool CitySim Pro was also used to change the urban layout creating new configurations; the validation of the models was made with the real urban configurations comparing the space heating measurements and the results of the CitySim Pro simulation on at least two heating seasons.

Combining the energy-use data with the results of the different urban layouts and associating two different class of solar exPosure factor (P < 1.15 non-optimal and P ≥ 1.15 optimal), different trends of heating energy consumptions can be observed (in Figure 13): two parabolas with the lowest energy consumption in correspondence of the "optimal" classes of U and P factors.

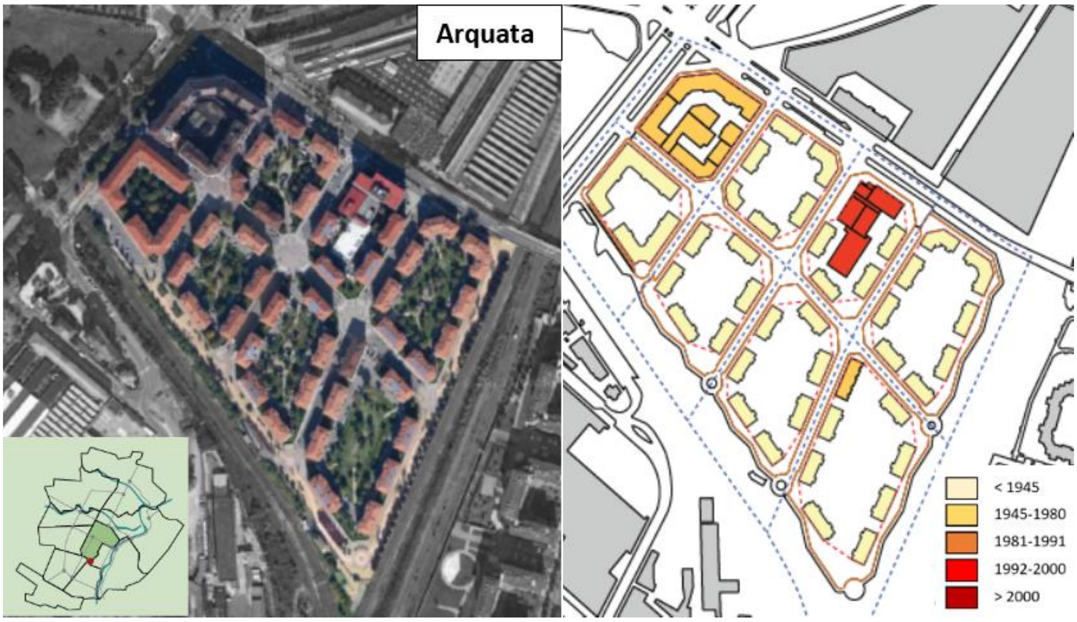


Figure 12(a): Urban configurations of Arquata district with buildings' period of construction.

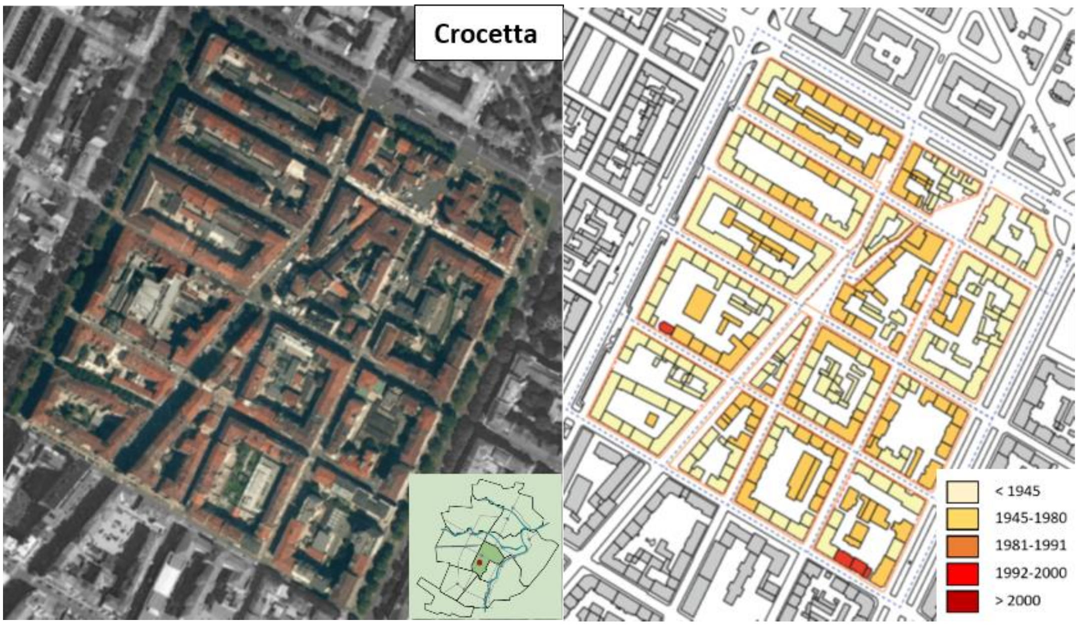


Figure 12(b): Urban configurations of Crocetta district with buildings' period of construction.

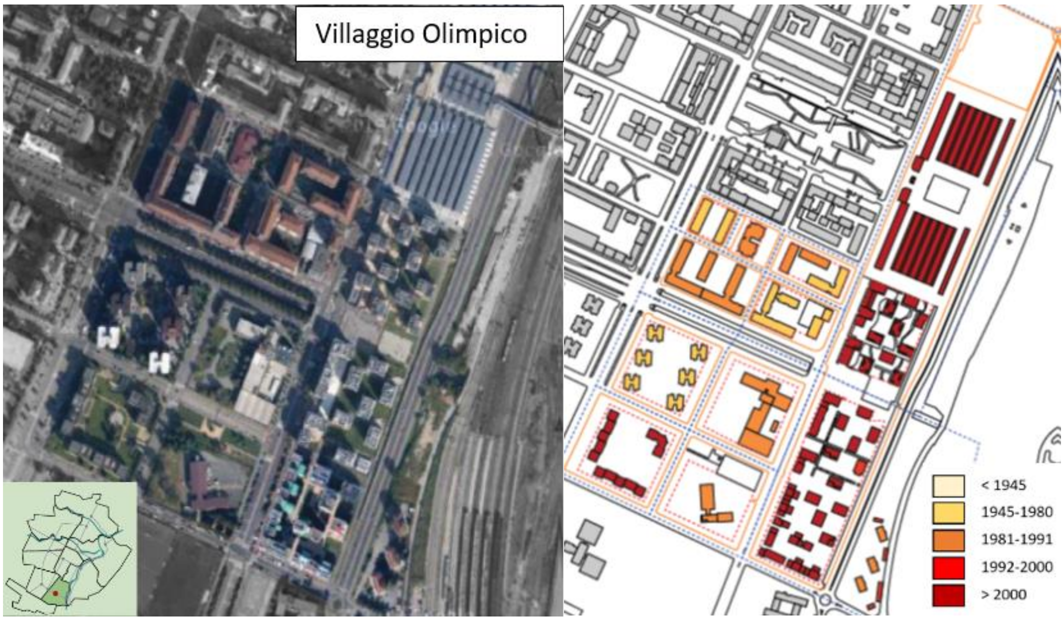


Figure 12(c): Urban configurations of Villaggio Olimpico district with buildings' period of construction.

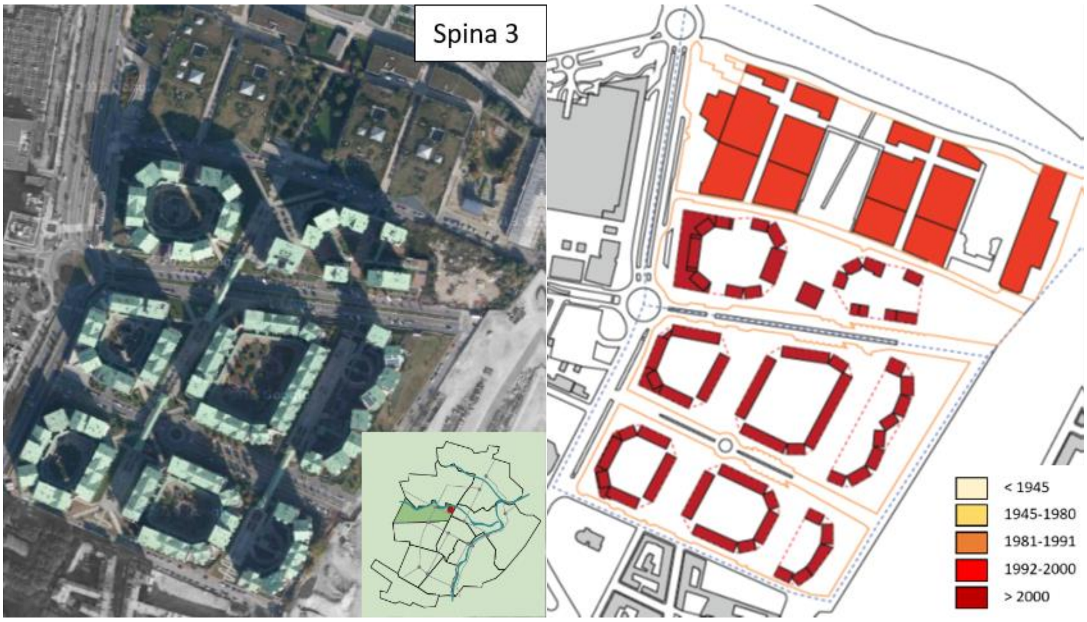


Figure 12(d): Urban configurations of Spina 3 district with buildings' period of construction.

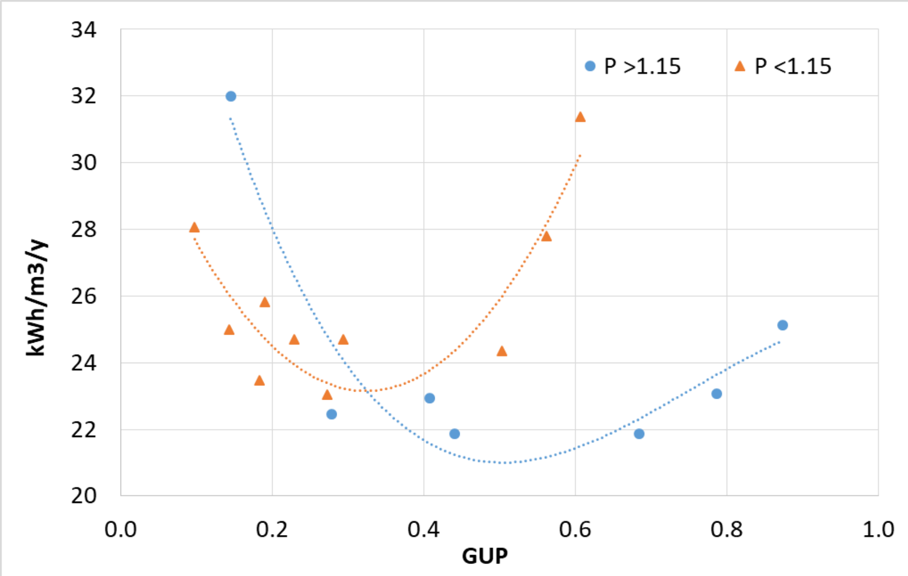


Figure 13: Heating energy consumptions and GUP values as a function of the solar exposure factor P classes (P<1.15 non-optimal and P≥1.15 optimal) for a central district in Torino.

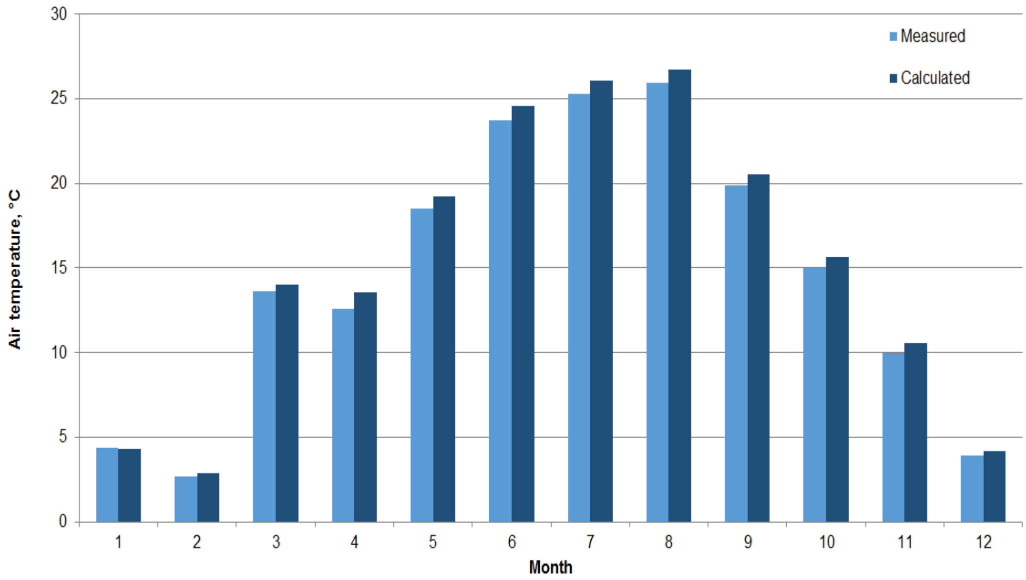
In Figure 13 it is possible to note that for low buildings densities (lower GUP values), energy consumption increases independently by the solar exPosure factor P; as for low-density urban layouts with low aspect ratio H/W no canyon effect can be exploit with a resulting higher heating energy-uses [9]. Otherwise, with higher buildings densities and aspect ratios, consequently higher GUP values, there is a different trend of increasing consumptions depending by the solar exPosure factor P. With a low solar exposition, the energy consumption increases rapidly, while with a better solar exposition this effect is smoothly with a larger range of the optimal GUP values with low energy consumptions.

Finally, from a comparison of the outside air temperatures recorded by eight weather stations in the city of Torino some correlations have been founded as function of the urban characteristics [23, 24]. In particular, considering the 2012 as an average reference year, the following correlation for the average monthly air temperature has been obtained for every census section (and represented in Figure 14):

$$T_{air,m} = (23.84\ G_{T,m}) + (1.4\ BCR) + (0.34\ H/W) + (0.39\ MOS) + (0.26\ H/H/) + (1.06\ MBO) + (-1.06\ A) + (-1.43\ H_2O) + (-0.32\ V) \quad (4)$$

where:

$G_{T,m}$ is the gradient of monthly air temperature varying on the annual period from 0 to 1, and H_2O and V represent respectively the presence of water and green surfaces (presence=1, absence=0).



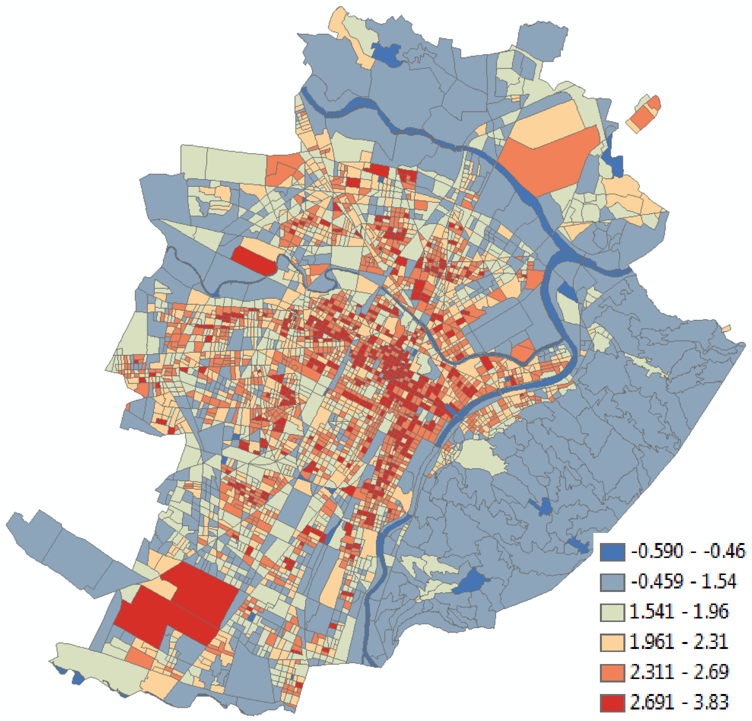


Figure 14: Monthly outside air temperatures measured and calculated (Eq. 4) for "via della Consolata" weather station and outside air temperature calculated with Eq. 4 for the coldest month of February 2012 for the city of Torino.

(1) Conclusions

The sustainability of urban environments should be analysed on multiple dimensions considering also socio-economic elements, varying from city to city and then no "one-solution" strategy can be proposed. The optimization of energy demand and supply of buildings and the exploitation of renewable energy sources at urban level could be a good compromise to the need of a sustainable environment and the high energy consumption for the anthropic activity, especially in urban contexts.

Main studies demonstrated also the influence of urban morphology on energy consumptions and moreover a correlation between energy consumptions and the microclimate variation in an urban environment. Therefore, simplified hybrid models based on Geographical Information System (GIS) tools could be an interesting solution to manage big data coming from different sources to design more sustainable and liveable cities. The research group is working on the demonstration of the validity of the proposed models to a wider geographical area, with different climatic conditions and building heritage. The study will cover not only the Italian territory, but also other countries such as the developing countries.

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