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Abstract. The energy consumption of buildings is related to several factors, such as the construction and geometric characteristics, occupancy, climate and microclimate conditions, solar exposure, and urban morphology. However, the interaction between buildings and the surrounding urban context should also be taken into consideration in energy consumption models. The aim of this work has been to create a bottom-up model in order to evaluate the energy balance of residential buildings at an urban scale, starting from the hourly energy consumption data. This modeling approach considers the building characteristics together with urban variables to describe the energy balance of the built environment; it can therefore be used to manage heterogeneous types of data at different scales and it can offer accurate spatial-temporal information on the energy performance of buildings. Detailed heat balance methods can be used at a building scale to estimate heating loads, but this urban-scale simplified model can also be used as a decision tool to support urban design explorations and for policy purposes. This urban energy consumption model was verified for a case study of a district in Turin, Italy, with the support of a GIS tool, considering hourly energy consumption data of about 50 residential users for two or three consecutive heating seasons. The results show that a simplified model, based on low quality and quantity data, which are typical of an urban scale, can be a powerful tool for the evaluation and spatial representation of the energy needs of buildings at an urban scale.

1. Introduction

The global CO_2 emissions from energy and industry increased in 2017, following a three-year period of stabilization. The building sector accounted for about 28% of the total energy-related CO_2 emissions, and buildings should therefore play a central role in the transition to clean energy [1]. The energy consumption of buildings in high-density urban contexts significantly influences urban sustainability, and built-up areas can represent a context where energy efficiency improvements can be introduced and greenhouse gases (GHG) can be mitigated [2,3]. Two necessary actions have been identified to achieve energy sustainability in an urban context: the improvement of energy efficiency and the exploitation of the available renewable energy sources [4].

The development of Urban-Scale Energy Modeling (USEM) at a district or city level is currently the goal of many research groups, as a result of the increased interest in evaluating the impact of energy efficiency and low-carbon measures on urban environments [5]. These models are useful to explore energy efficiency solutions at an urban or district scale and to quantitatively assess retrofitting strategies and energy supply options, which in turn can lead to more effective policies and an effective management of the energy demand [6]. Since the relationship between urban form and buildings affects the energy performances of such buildings, it is possible to obtain a lower energy demand through the use of USEMs by improving the morphology of the built environment [7]. The energy consumption of

the building stock in urban contexts is affected by several factors and, in order to create these models, it is necessary to process data at different scales, to identify indicators that can be used to accurately describe these environments. The main parameters that should be considered are the design of the built environment, the relationship between the buildings and open spaces, the type of materials used on the external surfaces, the type of solar obstructions and the local climate and microclimate conditions [8]. The canyon effect, for example, is known to influence the energy consumptions of buildings, and to cause an increment in the absorption quota of solar irradiation and a lower wind speed in the outdoor environment, with a consequent increase in the surrounding air temperature and poorer air quality [9].
In this work, a bottom-up, hourly, district-scale energy balance model is presented. Urban parameters were added to the energy balance fluxes of the built environment to evaluate how the urban form effects the space heating energy consumption of buildings: the canyon effect, which was quantified using the "height-to-width" ratio (H/W), in order to describe the typical urban microclimate around the buildings; obstructions, and the solar exposition and heat flow due to thermal radiation to the sky from the built environment were also evaluated with the Sky View Factor (SVF) to measure the visible portion of the sky from a given location [10]. Moreover, the climatic and microclimatic conditions were considered by analysing data from different weather stations.
This paper has been divided into four parts. This first part (section 1) deals with the description of the energy models and the importance of the use of USEMs to improve the sustainable energy development of high-density urban areas; the second part (section 2) describes the innovative methodology, the data and the application of the method to a case study; in the third part (section 3) the results of an hourly energy balance model of residential buildings are presented and discussed; and, finally, the last part (section 4) defines the contribution and the importance of this work and future research.

2. Materials and Method

The basic approach of urban building energy models that adopt a 'bottom-up' approach is to apply physical models of the heat and mass flows in and around the buildings in order to predict the thermal energy-use and the indoor and outdoor environmental conditions of the buildings stock. The methodology used to assess the energy performance of a building, as described in the UNI EN ISO 52016-1:2018 and UNI EN ISO 52017-1:2018 standards, has been considered in this work. This methodology involves using the transient heat and mass transfer equations between the building and outdoor environment through the opaque and transparent elements of the building envelope, mainly as a function of the internal and external air temperatures and solar irradiation conditions. In a previous work [11], an engineering bottom-up energy model was designed and applied to 50 residential buildings located in a district of the city of Turin. These first results have been used to improve and optimize the hourly model previously presented. Other variables have been introduced including the thermal capacity of the building and the number of air changes per hour depending mainly on the period of construction of the buildings. In addition, some applications of the model to assess energy supply and demand have been analyzed to exploit the solar energy. In particular, this work presents a method that can be used to calculate the energy consumption time series for the space heating of residential buildings at district scale, with an hourly time interval. The energy consumption for space heating of residential buildings was obtained from the sensible heat flow balance equations (1, 2), assuming the following efficiency of the heating system:

$$\phi_H + \phi_{\text{int}} + \phi_{sol} - (\phi_T + \phi_V + \phi_{extra}) = C_b \cdot \frac{dT_{i,b}}{dt} \tag{1}$$

$$\phi_H = \sum b \cdot U \cdot A \cdot (T_e - T_{i,a}) + \sum b \cdot \rho_a \cdot c_a \cdot \frac{ach \cdot V}{3600} \cdot (T_e - T_{i,a}) - (\phi_{\text{int}} + \alpha_{sol} \cdot A_{op,sol} \cdot I + g_w \cdot A_{w,sol} \cdot I) + \\ + SVF \cdot \left(\frac{1-\cos\gamma}{2}\right) \cdot R_{se} \cdot U_{op} \cdot A_{op} \cdot h_r \cdot (T_e - T_{sky}) - C_b \cdot \frac{(T_{i,b} - T_{i,b-1})}{3600} \tag{2}$$

$$\xi = \begin{cases} \frac{\tan(\beta)}{H/W} & if \quad \beta < \arctan(H/W) \\ 1 & if \quad \beta \geq \arctan(H/W) \end{cases} \qquad A_{sol} = \xi \cdot A \tag{3}$$

where:

- ϕ_H is the *heat flow released by the heating system* to the confined environments in order to guarantee a comfortable air temperature (i.e. 20 ± 2 °C in the heating season), and it was calculated by multiplying the energy supplied to the heating system by its efficiency (η_H);
- ϕ_T is the *heat flow rate by transmission,* and it was calculated considering the thermal transmittances (U), and the heat dispersant areas (A);
- ϕ_V is the *heat flow rate by ventilation,* and it was calculated using the heat capacity of the air per volume ($\rho_a \cdot c_a \cong$ 1,247 J/m^3/K) and the hourly volumes exchanges by infiltrations ($ach \cdot V$); the number of air changes per hour *ach* varies between 0.3 and 0.5 depending on the period of construction and the maintenance level of the building.
- ϕ_{extra} is the *extra heat flow rate by thermal radiation to the sky,* and it was calculated with the view factor between the built environment and the sky –that is the shading reduction factor considered for obstructions calculated measuring the *SVF* at the ground level (SVF_g) and the average *SVF* of the buildings– the solar height (β), the urban canyon angle, *arctan(H/W)*, the external thermal surface resistance (R_{se}), the radiative heat transfer coefficient (h_r), the thermal transmittance of an opaque envelope (U_{op}) and its area (A_{op}), and the sky temperatures (T_{sky});
- ϕ_{int} is the *heat flow rate due to internal heat sources,* and it was calculated as a function of the type of buildings using the floor area of residential buildings and the average floor area per dwelling, while the internal heat gains were calculated using the hourly profiles of the internal heat gains from occupants and equipment in residential buildings;
- ϕ_{sol} is the *heat flow rate due to solar heat gains,* and it was calculated considering the absorption coefficient of the opaque envelope ($\alpha_{sol,\mathrm{op}}$ assumed equal to 0.6 considering an average color of the building walls), the area of the opaque envelope (A_{op}), the effective glazing area (A_w), the solar energy transmittance of the glasses (g_w), the percentage of sunny surfaces (ξ), and the incident solar irradiance (I), which was calculated considering the orientation and inclination of building envelope surfaces;
- C_b is the *internal effective heat capacity of the buildings*, and it was calculated according to UNI/TS 11300-1:2014 equal to 95-165 kJ/m^2/K (per envelope area) depending on the period of construction of the buildings;
- $T_{i,a}$ the internal air temperature and $T_{i,b}$ the building temperature were considered equal and are variables from 18 to 22 ° C during daytime and decrease up to 16 °C during the night;
- I is the incident solar irradiance, and in was calculated considering the percentage of sunny surfaces (ξ) as a function of the height of the sun (β) and of the 'height-to-width' ratio (H/W). When the solar height, β, is less than the urban canyon angle, *arctan(H/W)*, the shadow quota is equal to the *tan(β)* and *H/W* ratio; when the solar height, β, is greater than *arctan(H/W)*, there is no shadow on the building walls (equation 3 in Figure 1).

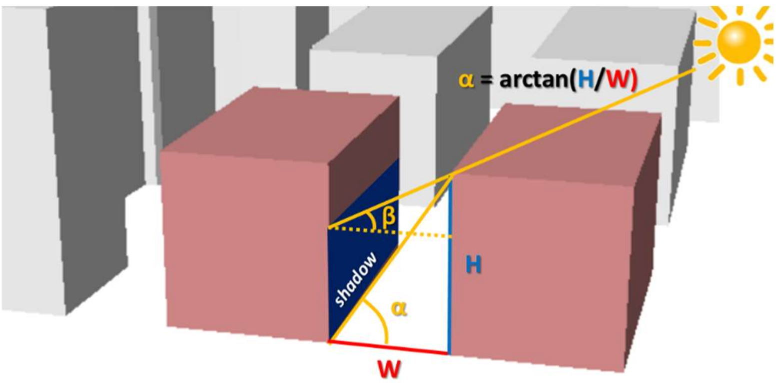

Table 1. Climate variables for the 2012/2013 heating season in Turin (0ct-15th to Apr-15th).

Month	*T* [°C]	I_{hor} [Wh/m^2]
10-2012	15.5	3.2
11-2012	10.6	2.2
12-2012	4.6	1.8
01-2013	5.0	1.9
02-2013	4.3	3.0
03-2013	8.2	3.7
04-2013	13.9	4.8

Figure 1. Scheme used to describe the solar height, β, and the urban canyon angle α=*arctan(H/W)*.

2.1. Case study

The city of Turin is located in the North-Western part of Italy and it has a continental temperate climate. There are about 60,000 heated buildings in Turin of which 75% is from the residential sector. The residential sector in Turin is mainly made up of large and compact condominiums, and 80% of the buildings were built before 1970 (before the first Italian Law on energy savings in buildings was introduced).

This study analyzes residential buildings that are connected to the district heating network (DHN) in Turin. The annual space heating consumption of about 90 buildings in a central district in Turin and the climate data of the Politecnico di Torino weather station (WS) were known [10,11,12]. The hourly consumption data of 50 of these residential buildings were available for three consecutive heating seasons. These residential buildings, which were built before 1980, are large condominiums with an average surface-to-volume ratio (*S/V*) of 0.30 m^{-1}. Seventeen of the considered buildings were built between 1919 and 1945, 20 between 1946 and 1960, 11 between 1961 and 1970 and only 2 between 1971 and 1980.

A 3D model was created for this area using the Municipal Technical Map of Turin (2015), the BDTRE of Turin (2018) and a Digital Surface Model (DSM) with a precision of 5 meters. A 3D dataset sample, with an accuracy equal to LOD1 (OGC® Standards), was created with a GIS tool. Although the 3D precision is not so high, and certain information, such as the type of roof, is unknown, this accuracy level is acceptable for this area since the hourly energy model, presented in this work, is at an urban scale.

2.2. Input data

The main data used to create the 3D model in this work were georeferenced, and the following database was produced with the support of a GIS tool (ArcGIS 10.6):

- The hourly thermal consumption of 50 residential buildings and the annual thermal consumption of 90 buildings for at least two consecutive heating seasons (2012-13, 2013-14 and 2014-15) [10,11,12];
- The hourly climate data of the Politecnico WS: air temperature and sky temperature, relative humidity and solar irradiance on the horizontal plane (I_{hor}). The climatic characteristics of Turin, as recorded at the Politecnico WS, are indicated in Table 1: the average values of the external air temperature (T) and the average daily solar irradiance on the horizontal plane (I_{hor}) are indicated for each month considering the heating seasons investigated; climate data of the other ARPA Piemonte WSs in Turin are also indicated (https://www.arpa.piemonte.gov.it/);
- The urban context characteristics: the SVF of the built environment was obtained using the Relief Visualization Toolbox and the DSM of Turin; the *H/W* ratio was used to evaluate the extent of the shadows between and on the buildings;
- The quota of sunny surfaces at different hours of the day, considering a typical monthly day as a reference; this quota was calculated using the hourly variations of the shadow percentage for each building (equation 3) considering: the height of the sun β (solar position), the shadow created by the different buildings, which is influenced by the height of the buildings, H, and by the distance between buildings, W;
- The construction characteristics of the buildings, such as the period of construction and the type of users, as well as the geometric characteristics of the buildings, such as the height, perimeter, net/gross floor surface and net/gross volume, *S/V* ratio;
- The thermal characteristics of the buildings: the U values, distinguished according to the period of construction of the buildings, the g_w of the transparent envelope, the α_{sol} of the opaque envelope components, the emissivity (ε) of the envelope, and the heat capacity C_b (UNI/TS 11300-1:2014, UNI EN ISO 52016-1:2018, UNI-TR 11552:2014);
- The census database: occupancy, percentage of heated volume, level of maintenance of the buildings, the type of energy vectors, that is, individual or central heating systems (census data: ISTAT 2011).

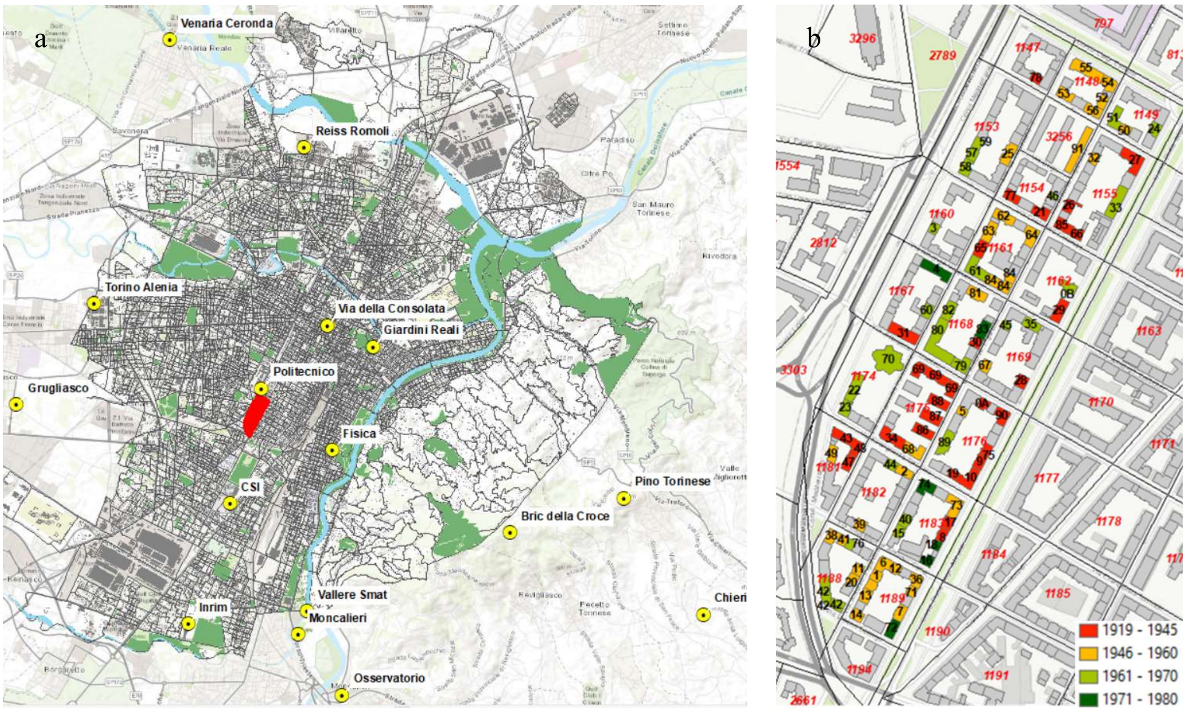

Figure 2. a) The City of Turin with its 16 weather stations and (in red) **b)** the central district of Turin (Italy): buildings (ID_b) with the period of construction and ID_{cs} of the census sections in red.

Table 2. Characteristics of the selected buildings: building orientation (BO), period of construction, net heated volume V_n, surface-to-volume ratio *S/V*, height *H*, average distance between buildings *W*, canyon effect *H/W*, sky view factor (SVF_g), thermal transmittance of the opaque envelope (U_{op}), heat capacity of the building (*C*), space heating consumption (EP_H), and average monthly absolute relative error ($|E_r|$).

ID_b	BO	Period	*Vn* [m³]	*S/V* [m⁻¹]	*H* [m]	*W* [m]	*H/W* [-]	SVF_g [-]	U_{op} [Wm⁻²K⁻¹]	*C* [kJm⁻²K⁻¹]	EP_H [kWh/m³/y]	$\|E_r\|$ [%]
47	S/E	1919-45	2728	0.42	18.4	28.12	0.503	0.484	0.99	165	41.41	6.1
30	S/E	1919-45	2195	0.39	18.5	26.46	0.500	0.242			30.60	7.5
88	S/O	1919-45	3147	0.41	14.7	23.69	0.538	0.282			34.23	19.1
77	S/O	1919-45	5105	0.34	22.1	22.77	0.589	0.253			43.24	4.5
87	S/O	1919-45	3118	0.40	15.1	23.69	0.538	0.282			30.80	7.3
20	S/E	1946-60	2800	0.36	22.8	28.25	0.550	0.396	1.04	155	31.68	9.7
37	S/E	1946-60	2280	0.38	19.5	24.07	0.522	0.301			39.76	18.8
5	S/E	1946-60	2010	0.38	25.0	22.63	0.493	0.251			51.73	13.6
13	S/E	1946-60	3232	0.35	19.6	24.07	0.522	0.301			25.82	21.0
62	S/O	1946-60	6525	0.34	21.9	21.71	0.569	0.243			39.01	9.5
41	S/O	1946-60	2265	0.41	23.7	28.25	0.550	0.396			34.68	22.0
46	S/E	1961-70	3100	0.56	20.2	22.77	0.589	0.253	1.04	145	23.42	9.5
79	S/E	1961-70	4542	0.34	18.7	26.46	0.500	0.242			29.37	46.2
61	S/O	1961-70	9957	0.32	22.5	21.71	0.569	0.243			36.86	8.7
44	S/O	1961-70	2405	0.38	18.9	17.51	0.568	0.253			35.88	18.1
76	S/O	1961-70	2049	0.37	23.0	28.25	0.550	0.396			38.46	9.4

Figure 2a shows the city of Turin and indicates the 16 WSs in different urban areas. The nearest WS (Politecnico) was selected for this work, but the availability of climatic data that refer to different morphological contexts of the city allowed an assessment to be made of the microclimate characteristics in relation to the thermal consumption of the buildings. Figure 2b shows the case study area, in which the 50 analyzed residential buildings are located. It is possible to observe that the morphological characteristics of the block of buildings are very similar, that is, with the typical regular orthogonal grid of Roman cities. Sixteen buildings were selected in a previous research [11] on the basis of their period

of construction, the orientation, the characteristics of the urban context and the type of adjacent street; the buildings located in front of large tree-lined avenues were not selected because the space heating energy consumptions could be influenced by the presence of the trees.
Table 2 shows the main characteristics of the 16 residential buildings that were selected. The shapes of these buildings are similar, the height is between 15 and 25 meters and the *H/W* factor is close to 0.5. The SVF_g at the ground level is the most variable, with values varying from 0.24 to 0.48; an *SVF* was calculated for each building as the average between SVF_g and the value at the roof level, which was considered equal to 1. Most buildings were constructed before 1970, and therefore have higher thermal transmittance values of the opaque envelope (U_{op}) than newer buildings; the thermal transmittance window value (U_w) is between 3.0 and 5.9 $Wm^{-2}K^{-1}$; and the annual space heating consumptions (EP_H) for the 2012-13 season have been indicated. The last column shows the results of the application of the model, and the average monthly absolute relative error ($|E_r|$).

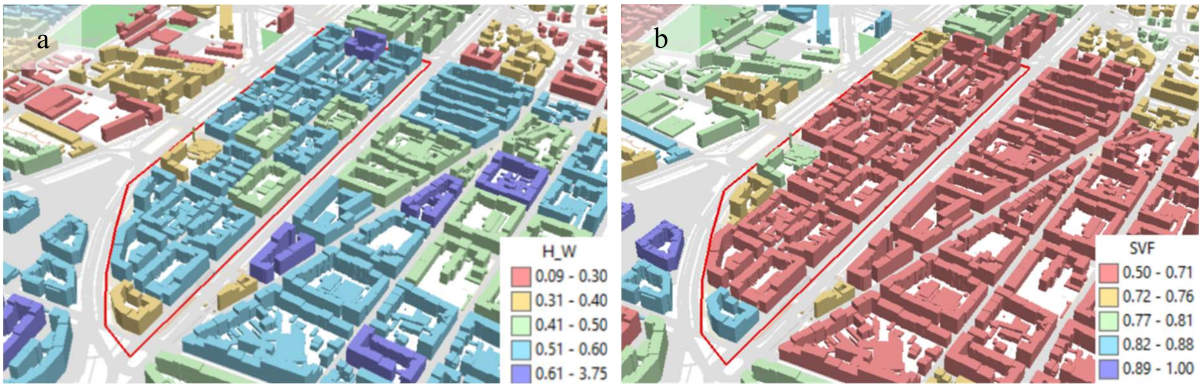

Figure 3. Distribution of the urban variables in a district in Turin: **a)** urban canyon height-to-distance ratio (*H/W*); and **b)** sky view factor (*SVF*). The red line outlines the case study area.

As mentioned before, the urban variables affect the thermal energy consumption of the buildings. The building coverage ratio (*BCR*) values are between 0.4 and 0.5 for the 9 census sections in which the 16 selected buildings are located, except for the "1181" section (where the *BCR* is 0.25); the building density (*BD*) is more variable, since it depends on the height of the building, but the values are very similar and close to the average value (BD_{avg} of 6.84 m^3/m^2) in the 9 selected census sections. The canyon height-to-width (*H/W*) ratio varies slightly for the selected census sections, with values close to 0.5 (see Figure 3a), and the main orientation of the streets is mainly East to South (typical of Turin) with a MOS_{avg} value of 0.6, except for the "1154" section (*MOS* = 1 for the East-West axis and MOS = 0 for the North-South axis). The *SVF* is quite variable (see Figure 3b), and the lack of vegetation (NDVI) influences the low reflectance of the outdoor surfaces, which is uniform and typical of an urban built environment.

3. Results and Discussion

This work presents a bottom-up modeling approach based on an hourly energy balance of residential buildings in a central district of Turin. The geometrical, morphological and microclimate characteristics throughout the area are very similar (Table 2). Future research will be devoted to applying the model to different urban contexts. In this case, the only variables that change are the *SVF* and the solar exposition of the building blocks. The *SVF* was calculated for each block of buildings with a percentage of solar exposition between the SVF_g and the unitary value, considered on the roof.
A few examples of hourly data pertaining to buildings (ID_b) '47', '62' and '44' are presented in Figure 4a; the average hourly values of certain typical days (14th November 2012, 10th December 2012, 17th January 2013, 16th February 2013, 16th March 2013) during the heating season 2012-13 (dotted line) and the hourly values for 10th December 2012 (continuous line). The bottom-up-model was obtained using a spreadsheet in Excel® considering an average monthly value of the heating system efficiency (an annual value of about 0.8 for buildings connected to the DHN). Figure 4b shows a comparison of the measured and calculated monthly thermal consumptions of buildings (ID_b) '47', '62' and '44'. Excluding the months

of October and April, when switching the system on and off can cause anomalies in the consumption data, the monthly results of the energy consumption show a lower percentage error than 15% and an annual percentage error of less than 6%.

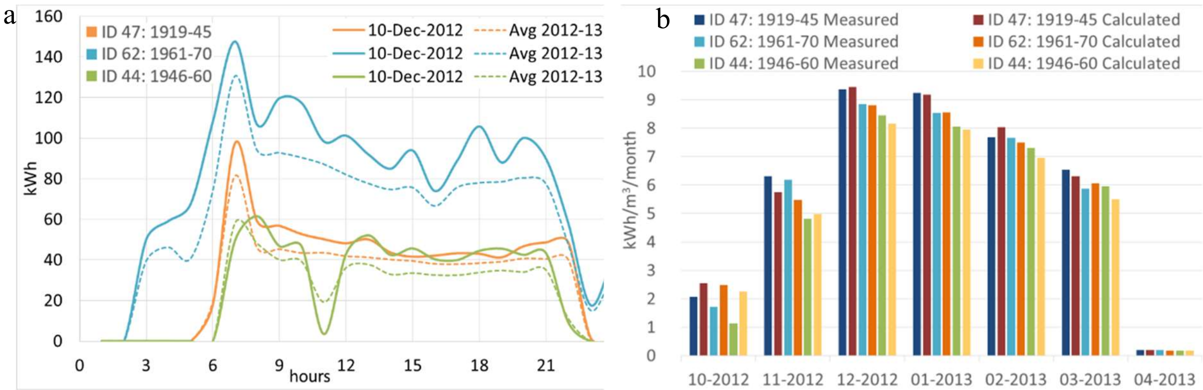

Figure 4. Buildings: ID_b 47 (period 1919-45), ID_b 62 (period 1946-60), ID_b 44 (period 1961-70). **a)** Measured hourly energy consumption for space heating; **b)** Measured and calculated monthly thermal consumptions (2012-13); the heating system was only turned on one day in April.

Figures 5a, 5b, and 5c show the results of building (ID_b) '47'. Figure 5a describes the daily trends for the 2012-13 season of the measured and calculated consumptions and the daily relative error (E_r). The average daily value of E_r is -3% (with an absolute relative error of 14%). Figure 5b shows the cumulative frequency, and it is possible to observe that the model is quite accurate (the greatest inaccuracy occurs for the months of October and April, due to the imprecision of the measured data).

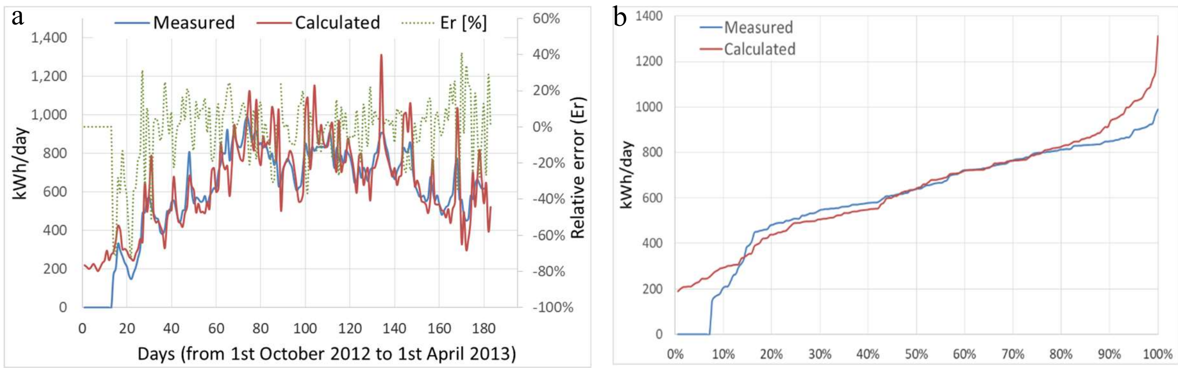

Figure 5. ID_b: 47: **a)** Daily consumption and relative error (E_r); **b)** Cumulative curves;

In this analysis, the sun and sky models were elaborated with the support of the 'Area solar radiation' GIS tool, using the DSM of Turin, a Municipal Technical Map and BDTRE, the monthly data of atmosphere transparency (τ) and the ratio of the diffuse radiation (H_{dh}) to the global radiation (diffuse radiation H_{dh} plus direct radiation H_{bh}) from 'Photovoltaic Geographical Information System - PVGIS' of JRC (Table 3). The simulation takes into account the monthly shadows of all the obstructions on the territory, and Figure 6a shows the annual solar radiation values (Wh/m^2/y) on horizontal surfaces in the district. The hypothesized ST area was assessed considering the roof area of the analyzed buildings most exposed to solar irradiation. The solar thermal collectors had an average efficiency of 70% and a system performance ratio of 75%. The potential thermal production from solar thermal collectors was quantified for each month. Table 3 shows the percentage of energy covered by the solar thermal production for the three buildings (ID_b), that is, '47', '62' and '44'.
Figure 6b shows an evaluation of the potential of solar thermal (ST) collectors integrated with photovoltaic modules on the roof. USEM models are in fact important to assess the renewable energy sources that are compatible with the energy demand during the day. The thermal consumptions for the

2012-13 season are compared with the potential ST production; the hypothesized ST area was dimensioned in order to avoid a monthly overproduction of thermal energy.

Table 3. Monthly atmospheric data used to evaluate the solar radiation and the results of the ST potential.

Month	$H_{dh}/(H_{bh}+H_{dh})$	τ	ST/Consumption [%]		
			ID_b:47	ID_b:62	ID_b:44
10-2012	0.51	0.56	197	95	333
11-2012	0.52	0.46	36	15	46
12-2012	0.51	0.42	10	4	11
01-2013	0.51	0.46	10	4	11
02-2013	0.42	0.58	39	16	39
03-2013	0.43	0.64	100	44	100

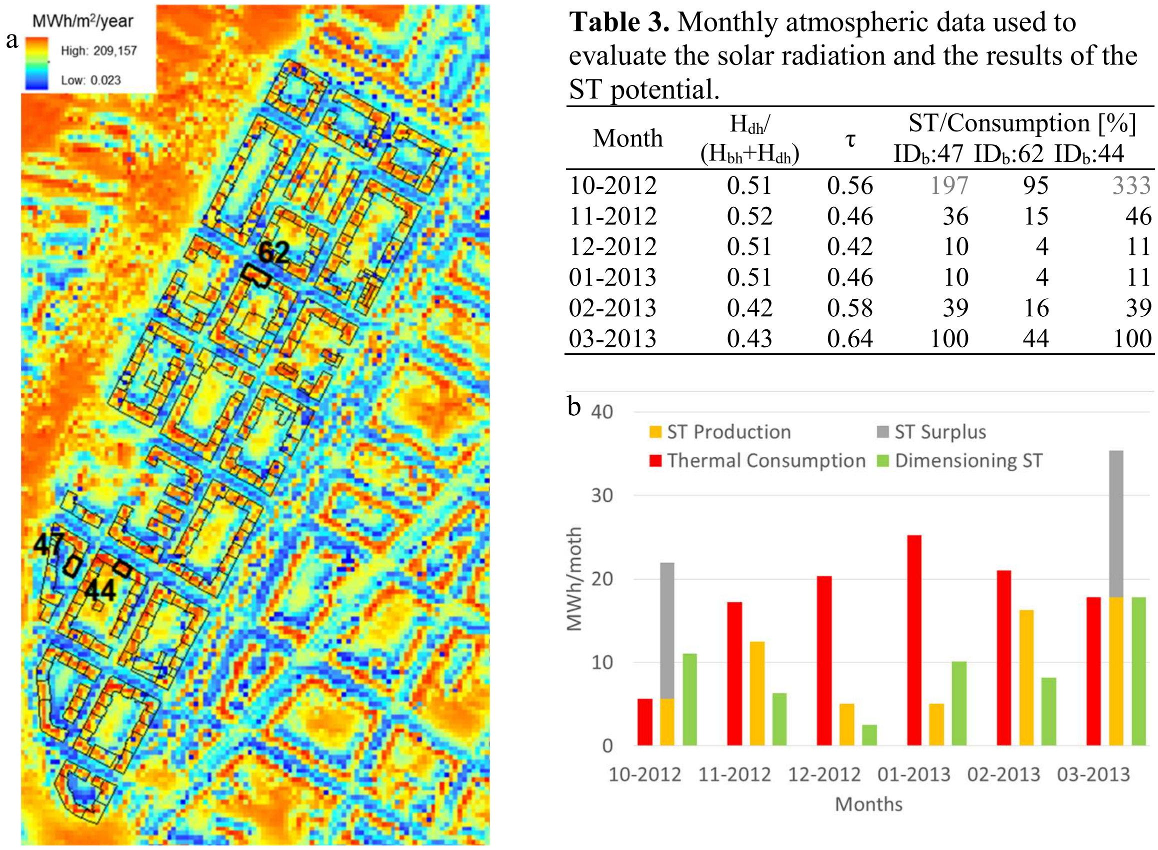

Figure 6. a) annual Solar Radiation evaluated with the GIS tool using a DSM of Turin (with a precision of 5 meters). **b)** Energy consumptions, ST production, ST surplus and dimensioning ST.

4. Conclusion

Urban-Scale Energy Modeling can play a key role in managing building space heating consumptions in order to reduce GHG emissions in a high-density urban context. The main urban parameters that affect the thermal energy consumptions of buildings are: the building coverage ratio (*BCR*); the building density (*BD*); the canyon effect (*H/W*); the main orientation of the streets (*MOS*); the normalized difference vegetation index (*NDVI*); the relative buildings height (H/H_{avg}); the sky view factor (*SVF*); the urban heat island (*UHI*) effect and the albedo (a_{NIR}).

The novelty of the presented model is that a few urban variables (*SVF* and *H/W*) have been introduced to apply an hourly space heating energy model at a territorial scale, with the support of a GIS tool. With these urban parameters it was possible to take into account the solar exposure and the heat exchanges with the external environment that significantly influence the energy consumption. In fact, from this work it is emerged that in favourable conditions with high values of *SVF* and good orientation, energy consumption is lower than in unfavourable conditions. Moreover, the shape of the building, the built environment compactness, and the type of the surrounding open spaces –described with the *H/W* ratio and the *SVF*– are fundamental in its heat exchange.

This paper is a first step toward the simplification of heat flux analysis at an urban scale with the purpose of attaining energy savings and sustainable urban planning in the future. Data retrieval work is already underway to further optimize the hourly energy consumption model at an urban scale. Moreover, it will above all be necessary to test the model in different urban contexts, in consideration of the fact that the case study area was very homogeneous, in terms of buildings' type and shape, of the presence of greenery and of the type of roads; 15 different areas have already been selected in Turin for the future work.

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