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A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale

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ABSTRACT

The paper presents a spatially explicit and "bottom-up" methodology for the building stock analysis of the residential sector. It integrates different input data in a Geographical Information System (GIS), without using the "archetypes approach" and simulation tools. In particular, the energy balance at the building level (BL) for the whole Valle d'Aosta region (Italy) is addressed, using the Italian Ministerial Decree 26/06/2009 and the UNI/TS 11300-1:2014 standard. Main outputs are the estimation of the geo-referenced heating demand of the residential buildings for the case study area (almost 42,000 buildings), and the development of a methodology that can be applied at different scales. The application of the methodology to the case study slightly overestimates the total thermal demand of the residential building stock, especially referring to the more energy demanding buildings. However, being the method influenced by data availability, the quality is expected to improve with newly available data. The proposed GIS-based methodology is designed to be part of a broader Spatial Decision Support System (SDSS) for sustainable energy plans that integrate renewable sources in the building stock energy renovation.

1. Introduction

In European households, heating and domestic hot water alone account for almost 80% of the total final energy use, and only 16% of the heating and cooling (H&C) consumption is covered by renewable energy sources (RESs) [1]. Given the relevance of spatial patterns of energy demand and supply, the analysis of low carbon energy transition increasingly requires the application of a geographical dimension perspective and reliable information at a suitable spatial resolution [2,3]. According to [4], there are two main approaches to building stock analysis (BSA): (i) "top-down" and (ii) "bottom-up". The first is based on the analysis of the impacts of energy measures often with regard to economic indicators; an example of these studies can be found in [5]. Instead in bottom-up models, the energy performance of the building stock is typically calculated based on the assessment of reference buildings (often called "archetypes" [6]). Examples of bottom-up application can be found in [7]. For an exhaustive description of these models see [8]. Concerning the archetype approach, the question on what makes a building representative, and the definition of the correct number of archetypes has been rarely addressed, as pointed out by [9].

In the proposed method, a BSA based on a spatially explicit bottom-up approach for the residential sector (almost 42,000 buildings) allowed us to consider the specificities of each building without forcing it in a building category. The procedure has been tested mainly using open datasets. Considering the state-of-the-art methodologies (e.g., "TABULA/episcope" approaches [10,11]), the aim of this work is to find synergies among different approaches. Indeed, the novelty of the approach is the estimation of the space heating demand of a residential building stock, avoiding its categorization in typologies (i.e. archetypes), and the possibility of application in different contexts through the nowadays capability of GIS tools in harmonizing different input datasets (see Section 2). However, due to data unavailability, the single building results were aggregated to carry out the only possible validation (see Section 3).

In the selected case study, the Italian region of Valle d'Aosta (VdA – NW of Italy), the residential sector was chosen for the availability of data from different sources and for its more uniform distribution over the area. A building level (BL) detail has been applied in order to integrate various spatial information and to aggregate the output at different scales (see Section 3), making

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the methodology suitable for regional planning purposes that is the final objective of the proposed study. The BL has been chosen as the smallest unit of analysis also to better characterise the thermal energy demand. Indeed, the aim is not to propose alternative analysis at BL, rather than describe a methodology aimed at reaching a trade-off between the number of input data and the detail level that gives more flexibility to the decision-makers in developing sustainable energy strategies at different scales. In the case of data unavailability, the knowledge gap has been filled using aggregated census tract data. In addition, given the size of the study area (a whole region with more than 40,000 residential buildings), some working hypotheses were necessary to apply the method on a large scale (see Section 2).

To the best knowledge of the authors, this is not the first GIS-based BSA at the BL. Recently, [12] proposed a thermal demand estimation for the historical buildings of Antwerp district (Belgium), starting form cartographic data and degree-day values. However, the presented methodology depicts the possibility to achieve a BL spatial estimation of space heating demand for a whole region, avoiding dynamic simulation tools, which are more commonly used in scientific research and less often for informing policy-making processes [13].

Lastly, the proposed methodology has been performed within the Interreg Alpine Space project GRETA (Near-surface Geothermal REsources in the Territory of the Alpine space) and has been applied in three different pilot areas. This work presents the application in one of these, the VdA region.

2. Materials and methods

2.1. Building geometry and data sources

The geometrical features of the buildings are estimated applying the following procedure and computations:

- Building footprint is assumed as the gross surface per floor ($S_{j,\,g}$) of the buildings;
- $S_{j,\,g}$ is multiplied by 0.83 [24] to account the walls and obtain the net surface per floor ($S_{j,\,n}$);
- Gross volume ($V_{j,\,g}$) is obtained as $S_{j,\,g}$ per $\overline{H_j}$;
- $S_{j,\,n}$ and $V_{j,\,g}$ are further multiplied by 0.75 [24] to estimate the heated surface per floor and the heated volume ($S_{j,\,h}$ and $V_{j,\,h}$);
- Average height ($\overline{H_j}$) is estimated from the height difference between DSM and DTM, following the approach of [23];
- Number of floors is calculated dividing $\overline{H_j}$ per 2.7 m (the minimum floor height according to Italian regulations);
- Total heated surface ($S_{j,\,T}$) is calculated as $S_{j,\,h}$ per number of floors (buildings with $S_{j,\,T}$ smaller than 25 m^2 are then excluded from the analysis in the case study since considered too small);
- Dispersing surface ($S_{j,\,d}$) is computed as perimeter per $\overline{H_j}$ plus twice $S_{j,\,g}$;
- S/V ratio is computed as the ratio between $S_{j,\,d}$ and $V_{j,\,g}$.

For the VdA case study, the proposed methodology calculates the space heating demand of buildings using the following data, also overcoming its inhomogeneous granularity (further information on data, sources, and scale can be found in the Table S1 – suppl. material): (a) Digital Surface Model (DSM) and Digital Terrain Model (DTM), civil (i.e. not industrial) buildings (polygons), historic centres (points), tourist and tertiary buildings (polygons) of VdA (from regional GeoBrowser [17] and OpenStreetMap project [18] – OSM); (b) Buildings Energy Performance Certificates (EPCs) collected in the Lombardia region (adjacent to VdA – CENED+2.0 dataset [19]) including age, energy performance parameters and geometrical features. EPCs of Lombardia region are used as ancillary data due to the unavailability of this information for VdA region; (c) Number of residential buildings, total heated surface, and number of permanently occupied and total flats per age at census tract level in VdA (from last Italian Census on population and buildings performed in 2011 [20]); (d) Mean energy demand per age of the buildings for each municipality of VdA [21]; (e) Total energy consumption of residential sector per fuel for each union of municipalities of VdA [21]; (f) Temporally resolved dataset of temperatures from 75 official weather stations in VdA [22].

2.2. Energy balance of residential buildings

The proposed spatial evaluation of heating demand applies, for all the j-th buildings of the building stock, a simplified energy balance that takes into account the envelope transmission ($H_{j,\,t}$) and ventilation ($H_{j,\,v}$) energy losses, on one hand, and the solar ($Q_{j,\,s}$) and internal ($Q_{j,\,i}$) energy gains, on the other hand (Eq. (1)).

$$Q_{j,h} = \left(\frac{\left(H_{j,t} + H_{j,v}\right) * HDD_j}{1000} - f_x * \left(Q_{j,s} + \ Q_{j,i}\right) \right) [\text{kWh}] \tag{1}$$

where $Q_{j,\,h}$ is the space heating demand of the whole building (kWh), HDD_j are the heating degree days (°C), and f_x is a free gains reduction coefficient (fixed value of 0.95 according to [14]). The result of Eq. (1) was then modified to consider the possible presence of partially heated buildings within the analysed VdA building stock (Eq. (2)).

$$Q_{j,h}^{mod} = f_{j,occ} * f_{j,avg} * Q_{j,h} \, [\text{kWh}] \tag{2}$$

where $Q_{j,\,h}$ is the “balance-based” heating demand computed with (Eq. (1)), $f_{j,\,occ}$ and $f_{j,\,avg}$ are the correction coefficients calculated from the information available on the buildings' occupation (point c) of Section 2.1) and from the mean thermal demand per building age and municipality (point d) of Section 2.1), respectively. $f_{j,\,occ}$ was statistically derived to reflect the percentage of permanently occupied flats on total ones, in each census tract per period of building construction [20].

In the case study, the space heating demand ($Q_{j,\,h}$) was multiplied by this occupation percentage inside each census tract. $f_{j,\,avg}$ was introduced to take advantage of the average values, per age of the building and municipality, derived from several EPCs provided by the VdA Energy Agency (point d) of Section 2.1). In this case, the estimated heating demand ($Q_{j,\,h}$) was multiplied by a factor defined as $f_{j,\ avg} = \frac{\bar{Q}^{CENED}_{m,\ p,\ h}}{\bar{Q}^{EPC}_{m,\ p,\ h}}$. Where $\bar{Q}^{CENED}_{m,p,h}$ is the average heating demand ($\bar{Q}_h$) per the m-th municipality and the p-th period of construction estimated using the CENED dataset, and $\bar{Q}^{EPC}_{m,\ p,\ h}$ is the average heating demand using the EPC dataset, only available to the authors in this aggregated form. For the case study, only the heating demand has been estimated because, given the position in the Alps, the cooling demand has been considered negligible [16]. Fig. 1 provides a final overview of the methodology, which was developed and applied to the VdA case study.

2.3. Adaptation of the methodology to data availability

Datasets containing the annual space heating demand per square meter (kWh/m^2) and measured energy consumption data were not available at the BL in VdA. To overcome this issue, the global thermal transmittance value ($U_{j,\,m}$) of buildings was calculated starting from EPCs of the Lombardia region [19], applying the inverse formulas present in [14], and examining only the certificates for whole buildings (not flats) located in the climatic zone F. It was assumed that similar residential buildings in Lombardia and VdA have similar thermal characteristics, as they are located

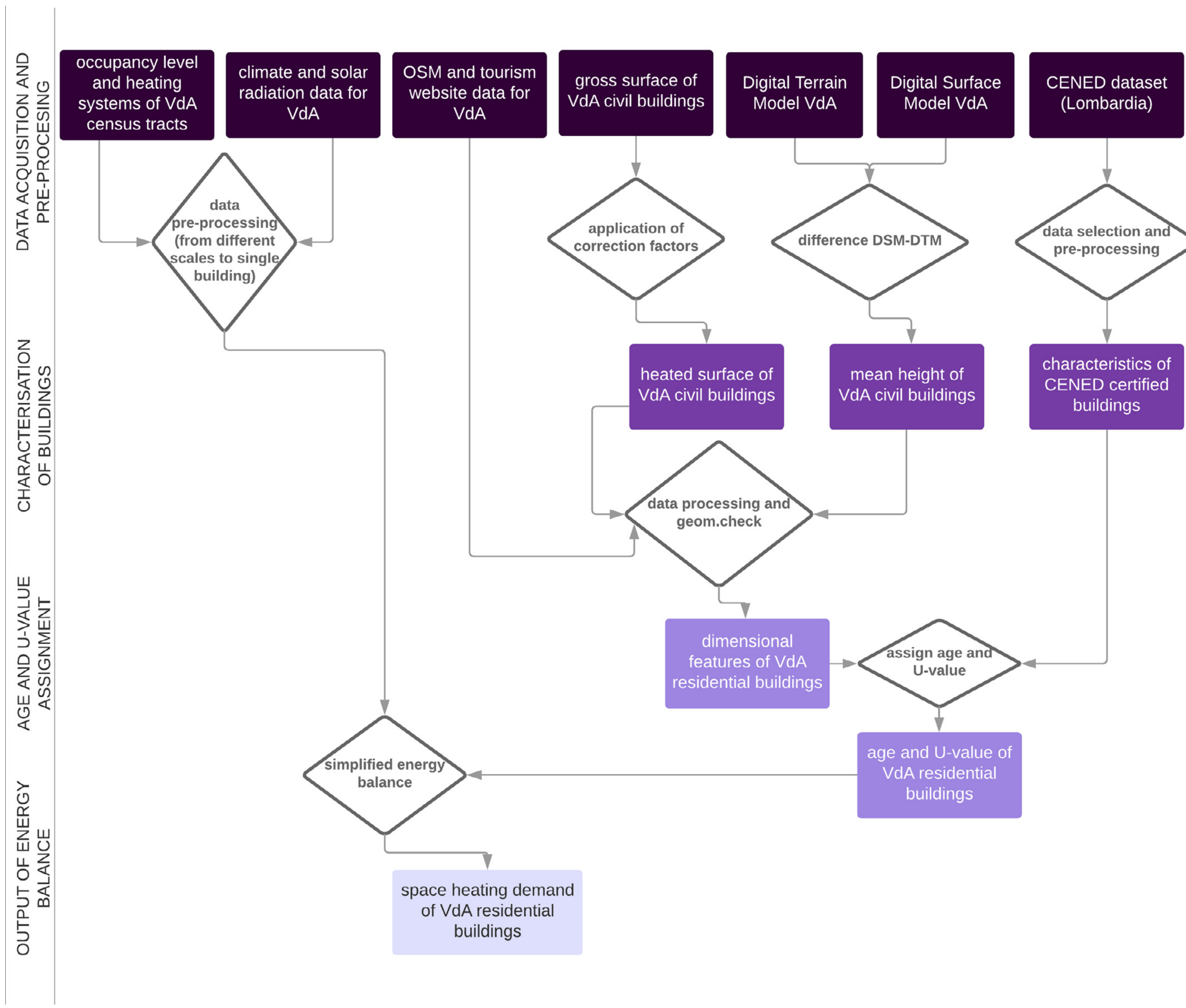

Fig. 1. Conceptual flowchart of the methodology developed for the spatial estimation of space heating demand of residential buildings in VdA.

in the same climatic zone of Italy. Indeed, more than 70% of VdA municipalities are located in the climatic zone *F*, in which the heating season starts the 5th of October and ends the 22nd of April (according to Italian regulation [15]).

Before the assignment of the $U_{j,\ m}$ to the j-th building, the following conditions were applied: (i) CENED buildings (point b) of Section 2.1) with S/V ratio and efficiency of the heating system lower than the 2° and higher than the 98° percentile were considered outliers and excluded from the analysis; (ii) VdA buildings within a circular buffer of 50 m around the historical centre of towns and villages (from GeoBrowser [17]) were included in the oldest period of construction.

Building age was collected at the census tract level, from the last Italian Census [20], as the number of residential buildings per period of construction. Then, in the case study, the Euclidean distance [25] of the known parameters $S_{j,\ T}$, S/V ratio, and age standard scores (mean = 0 and std = 1) was used as similarity criteria to assign the $U_{j,\ m}$ to VdA buildings.

Seventy-five VdA weather stations have been selected from [22] to retrieve hourly data for air temperature required to calculate the HDD and thus the building heat losses due to both transmission ($H_{j,\ t}$) and ventilation ($H_{j,\ v}$), as in Eq. (1). In particular, $H_{j,\ t}$ was calculated from $U_{j,\ m}$ values and $S_{j,\ d}$, whereas $H_{j,\ v}$ was calculated starting from $V_{j,\ h}$ and the number of air exchanges (0.3), according to [14]. Further details on $H_{j,\ t}$, $H_{j,\ v}$, $Q_{j,\ s}$ and $Q_{j,\ i}$, including the implemented equations in the case study, can be found in [14,15]. HDD in (Eq. (1)) were estimated using 20 °C as base temperature; HDD values range from 1000 over 5000. As in [26], the average temperatures are interpolated using the elevation as an independent variable with a linear regression model. To further reduce the error on HDD values, a multivariate linear interpolation was performed using the following independent variables: weather station elevation, mean solar irradiation, slope orientation, sky-view factor, number of shadow hours, to obtain HDD values for each buildings' position. The variables have been selected, through a feature selection, seeking the highest correlation of HDD with other raster data (e.g., slope, land use, other geomorphological features). $Q_{j,\ s}$ was calculated using monthly irradiation on the vertical walls (estimated with r.sun GRASS GIS module [27]) and assuming a window area equal to ⅛ of $S_{j,\ T}$ [28]. $Q_{j,\ i}$ was instead estimated starting from $S_{j,\ T}$ and the length of the heating season, according to [15].

The validation of the proposed methodology at the BL was not possible in the case study due to the lack of measured data. Therefore, the results of (Eq. (2)) were compared with the only available aggregated information at supra-municipal scale (point e) of Section 2.1). In order to compare these two datasets, the thermal energy consumption of VdA buildings was calculated based on the estimated demand, applying a mean efficiency factor ranging between 0.8 and 0.9. Buildings used as holiday houses have not been explicitly surveyed in the Census nor was the data available at regional scale. Thus, it is important to note that the proposed methodology was not designed to deal with mixed-use buildings (e.g., residential and office/commercial activities in the same building).

3. Results

The presented methodology provides as the main output the spatial evaluation of the space heating demand ($\frac{Q_{j,h}^{mod}}{S_{j,T}}$ expressed in kWh/m^2) for each residential building for the whole VdA region. However to validate the methodology, single building results have been aggregated and compared with the space heating demand at supra-local level, which was the only data available for the validation process. The map of the whole area can be accessed on the GRETA project WebGIS (thermal demand map) and it is available in Figure S1 as supplementary material.

The percentage of buildings attributed to different energy classes of estimated space heating demand has been compared with the percentage of buildings belonging to the same energy classes, according to the data by EPCs of the VdA region (point d) of Section 2), as shown in Fig. 2. The calculated total thermal demand of the residential building stock was slightly overestimated compared to the available aggregated data (point e) of Section 2), as detailed at the end of this section. Indeed, the results show an overestimation of the number of buildings especially attributed to the energy classes between 100 and 250 and above 500 kWh/m^2 per year and a not negligible underestimation of the number of buildings in the three more efficient classes (below 100 kWh/m^2 per year).

It is assumed that this difference occurred mainly because of two sources of uncertainty: (1) the information on real buildings' occupation was not available at the BL (see Section 2.3); (2) the lack of information about the mixed use of buildings (residential, commercial, offices, etc.), especially common in the historical centre of towns and villages. For the latter, they were accounted as entirely residential, according to the working hypothesis of no mixed buildings. In addition, the available data on the buildings' footprint refers to 2005, Census data on the number of buildings per period of construction applies to 2011, while the aggregated data used for the comparison (Fig. 2) relates to 2015 as the most recent reference year. As such, the last dataset likely includes a higher number of recently constructed buildings, assumed to have higher energy efficiency, and this may also justify the underestimated number of more efficient buildings.

The comparison between the estimated thermal consumption of buildings and the aggregated information at supra-municipal scale confirmed the overestimation of estimated values in a range from around 9% to 23% (see Table S2 – suppl. material). This may be also due to other sources of uncertainties, e.g., the different ways of heating system utilization. Indeed, the methodology did not consider both the operation schedule of the heating plants and the possibility of partially heated buildings along the year. Recently [8] reported on the so-called performance gap, which occurs when there is a large difference between the predicted theoretical energy demand and the actual consumption. In the authors' opinion, this difference can be ascribed to: (i) the users' behaviour inside the building, (ii) the lack of information about the energy performance of the heating systems or (iii) the “rebound effect”, where technical innovations do not lead to a decrease in energy consumption since the increment of efficiency tends to be balanced out by growing consumption [29].

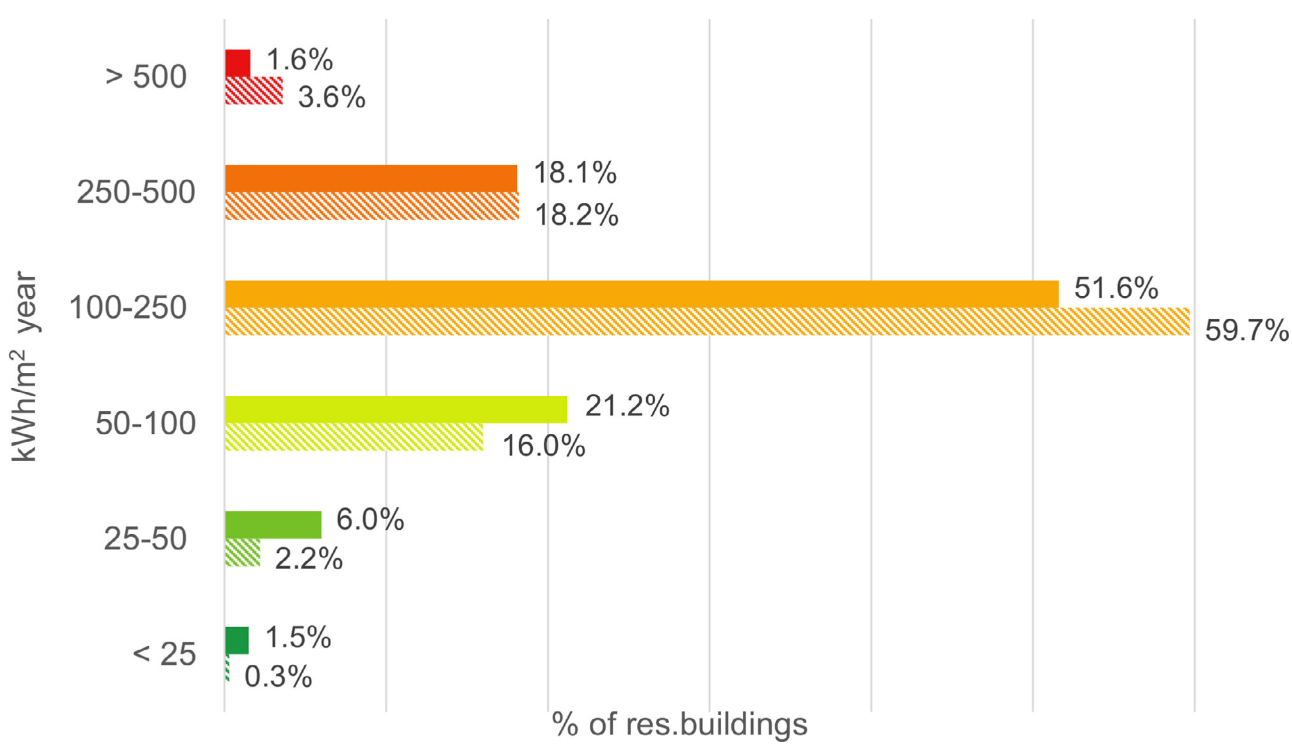

Fig. 2. Comparison between estimated values (pattern fill) and aggregated data (solid fill) of thermal consumption of the analysed VdA buildings.

4. Discussion and conclusion

The main objective of this study is providing support for sustainable energy planning processes, offering a basis for further GIS-based analysis rather than for energy simulations. The described methodology aims to be included in a Spatial Decision Support System for energy decision-makers; it will help to identify focus areas for interventions of energy refurbishment, by integrating already available data. The methodology also offers the possibility to aggregate the results at different scales, given that the outputs are provided at the BL. This makes it more suitable to be used in administrative and decision-making processes, as well as in a spatial multi-criteria analysis (e.g., involving socio-economic and behavioural parameters, physical variables, etc.). Largely depending on data availability rather than on geographic position, it can be potentially applied in different contexts and, due to the methodology's flexibility, the quality of outputs improves with an increased level of information detail. Recently [30] criticised the use of GIS-based approaches to energy demand assessments at district and city level, due to the generalization of the building models. However, this does not depend on the use of GIS software but on the approach used in the study. In this work, a trade-off was sought between the degree of generalisation of BSA and the willingness to consider the specificities of each building. Even though this is not the first BSA carried out with a spatial-based approach (see for instance the cited work of [12]), the presented spatial estimation of space heating demand was done for each building of an entire region without using simulation tools. Within the GRETA project, the methodology has been applied to other two pilot areas; for further information see [31].

The main limitation of the presented methodology concerns the lack of homogeneity and data availability. For instance, Census data are available at the census tract level, while geometrical and energy features have been estimated for each building. This combination of diverse scales of analysis is a complex issue and requires several approximations in the calculation process (making difficult the assessment of the results through sensitivity analysis). The working hypotheses made for the application of the method on a large scale are a consequence of this lack of detailed data. In addition, the acquisition of measured data on building energy consumption at the BL is crucial in order to better validate the estimated values of energy demand and to better assess the potential impact of incentives and policies on the territory under analysis. Information on the actual occupancy and use of buildings would also allow a better characterisation of the building stock. Unfortunately, this data is often difficult to gather at the BL because of privacy issues or because it is not collected at the same level of detail and in a systematic way by different public entities (statistics institutes, regions, provinces, municipalities).

Future developments of the methodology will be: (i) performing a sensitivity analysis to reduce the uncertainty effects; (ii) assessing the impact of energy renovation measures on the thermal demand; (iii) including the impact of different energy uses or users' behaviour on the energy balance, (iv) evaluating the combined use of different RES and non-RES technologies for supplying the estimated energy demand. In conclusion, the described methodology and its outputs can represent a significant opportunity to promote a systematic, consistent and uniform collection of information gathered and stored by different administrations of cities and regions.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.109581.

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