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Building heat consumption and heat demand assessment, characterization, and mapping on a regional scale: A case study of the Walloon building stock in Belgium

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ABSTRACT

Energy consumption in buildings results in CO_2 emissions and it is necessary to reduce energy consumption thus its related emissions. This research is included in the Wal-e-cities project, which is funded by the European Regional Development Fund (ERDF) and aims to create tools that facilitate the transition toward smart territory. The annual heat consumption (HC) and heat demand (HD) of Wallonia building stock of more than 1,700,000 buildings are assessed. Subsequently, the developed energy models are coupled with a geographic information system (GIS) to calculate and map the HC and HD. The HC and HD are calculated for each building and are represented by different levels of territorial aggregation, namely neighbourhood, municipality, and urban region scales. The highest HC values were observed in large cities and main industrial areas, whereas the lowest values were observed in rural areas. For residential sector, HC is mainly related to the number of dwellings, which differs from that of tertiary and industrial sectors where HC also depends on the nature and function of buildings. Based on mean values at the neighbourhood scale, the HD is 16.44% lower than the HC for the residential sector, 15.78% lower than the HC for the tertiary sector, and 9.26% lower than the HC for the industrial sector. The proposed energy models are validated. The relative differences between annual HC calculated in this study and that provided in the regional energy reports are −5.82% for the residential sector, −14.29% for the tertiary sector, and −2.02% for the industrial sector.

1. Introduction

In Europe, the energy consumption in buildings is approximately 40% of the total primary energy consumed [1], and it is also responsible for 36% of CO_2 emissions. In addition, a large proportion of buildings in the European Union (EU) are more than 50 years old, and a majority of these buildings (i.e., 75%) are not energy efficient [2]. To reduce the energy consumption of buildings and their related CO_2 emissions, European countries are developing wide ranging strategies to attain energy reduction and increase local renewable energy production. In this study, the authors aim to assess the building stock energy consumption in Wallonia, which is the south region of Belgium (Europe). The European Energy Performance of Buildings Directive (EPBD) mainly applies to new buildings, whereas the existing Belgian building stock is huge, and is often poorly or non-insulated. This is responsible for the extended building renovation periods. The smart energy management of existing buildings, neighbourhoods, and cities will contribute to fewer incidences of problems related to the increase of pollution due to energy consumption of buildings.

This research aims to create tools related to building energy management in the Walloon territory. The study is included in the Wal-e-Cities project, which addresses the challenge of transforming the Walloon built environment into a smart territory. The Wal-e-Cities project aims to create smart tools for the Walloon Region in Belgium (Europe) in terms of connectivity, governance, living environment, mobility, energy, and environmental impacts.

The building heat demand (HD) is the quantity of heat that the building systems provide to guarantee thermal comfort of the users and is related to the building characteristics and function. The final heat consumption (HC) of a building is the value of the invoice related to heating consumption, and in addition to the HD, it includes all of the losses due to the heating systems, namely the production, distribution, and emission losses. The building HC is related to the performance of the heating systems. In this research, in order to analyse the territorial distribution of the Walloon building stock energy consumption, the

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Nomenclature

AJAX	Asynchronous JavaScript XML
AQUAWAL	Aqua Wallonia (union of public water cycle operators in Wallonia)
CEHD	Centre d'Etudes en Habitat Durable de Wallonie (asbl)
csv	Coma Separated Values
dBASE	ESRI File Format
EU	European Union
ERDF	European Regional Development Fund
ESRI	Environmental Systems Research Institute
GHG	Greenhouse Gas
GIS	Geographic Information System
GWh	Gigawatt Hour
HC	Heat Consumption
HD	Heat Demand
HDD	Heating Degree Days
ICEDD	Institut de Conseil et d'Etudes en Développement Durable (asbl)
kWh	Kilowatt Hour
LEMA	Local Environment Management and Analysis
LHV	Lower Heating Value
log	Logarithm
QGIS	Quantum GIS
SBSM	Spatial Building Stock Modelling
SS	Statistical Sector
TWh	Terawatt Hour
ZEB	Zero Energy Building

assessment of the HC and HD of all buildings in Wallonia is performed, including all residential, tertiary, and industrial buildings. This study includes various types of built areas, including large and small cities, suburbs, peri urban areas, and rural areas. Subsequently, regional HC and HD maps were produced with different levels of territorial aggregation, from the statistical sector scale corresponding to the neighbourhood scale, municipality scale, and urban region scale.

The main aims of this study are (1) to study the spatialised distribution of buildings' HC in a regional territory, (2) to compare the HD and HC at different territorial scales, and (3) to analyse the impact of the three building sectors (residential, tertiary, and industrial) on the energy consumption of neighbourhoods, municipalities, and urban areas in Wallonia (Belgium). A mapping of the existing buildings' annual heating energy consumption and demand at various territorial scales will help municipal and regional decision makers as well as energy suppliers, energy network operators and energy consultant engineers to better manage buildings' energy consumption and networks. This will result in the promotion of adequate energy policies and analyses of the potential integration of various technologies, such as new district heating networks and renewable energies.

This article is divided into six sections. Section 1 introduces this study. Section 2 presents the existing literature review on the smart city concept and references on cities' energy modelling, and Section 3 discusses the research methodology employed. In Section 4, the research results and discussion are presented: the spatial data visualisation helps to assess the relationship between the HD, HC, and the number of buildings in each statistical sector, municipality, and urban region, for the different building types. Section 5 validates the newly developed model. Finally, the conclusions of the study and future works are presented in Section 6.

2. Literature review

This study is included in the smart city and energy field, which is sustained by the European Commission. Many researchers have developed tools to supply electronic data to citizens, city decision makers and governments [3–6]. Others proposed GIS based platforms or e platforms to link the government and stakeholders for smart cities management and partnerships [7–12].

With respect to energy consumption and management in cities, 75% of worldwide energy consumption takes place in cities, which produce 80% of greenhouse gas (GHG) emissions [13]. The inclusion of energy in smart city models will help to reduce the management of buildings' energy consumption owing to the development of smart buildings, smart networks, and smart communities. In order to improve energy efficiency, European countries have developed many approaches and tools, some of which are very costly. For this reason, Europe has set an Intelligent Energy Program, which promotes clean and sustainable solutions [13]. Smart city models should clearly help to control and reduce building energy consumption in cities owing to the implementation of smart energy solutions. In addition, smart cities are promoted by the European Commission in terms of the use of renewable energies, green mobility, and energy efficiency [14,15]. Calvillo et al. focused on energy design and operation in smart cities [11] by reviewing energy generation technologies, energy distribution systems, energy storage techniques and infrastructure, and ultimately energy system models. Kylili and Fokaides explained the role of zero-energy buildings (ZEBs) for smart cities aiming to attain energy and smart city goals in Europe owing to their energy efficiency, management, and generation of renewable energy [16].

The following studies are based on a spatial modelling of entire building stocks, and were performed to assess the energy consumption of a city or an urban region [17–27]. Reiter and Marique mapped the total annual energy consumption of households at the city scale, taking into account the energy consumption due to residential buildings and daily mobility, using prospective scenarios to study their potential future developments [17]. Later on, Österbring et al. developed a bottom-up residential building stock model using energy performance certificates, and validated the results using the energy consumption of 433 multi-family dwellings in Gothenburg [18]. The main advantage of incorporating GIS in building stock modelling is explained in Refs. [19]: a GIS based building stock model cannot only be used to evaluate different environmental solutions, but also to link building statistics to the spatial location of the different building types within the urban setting. The study by Nishimwe and Reiter, which focused on an urban area, modelled the annual HC and HD of residential and tertiary buildings [20]. Caputo et al. defined energy strategies in the building sector at an urban scale using GIS in Milan City [21]. The Canadian Urban Institute went further by taking into account the annual energy use of all types of buildings and energy production, while mapping them at the city scale and using the maps which were produced to evaluate improvement opportunities [22]. Moghadam et al. developed a GIS model coupled with multiple linear regressions on real measured data in buildings for the assessment of the annual heating consumption of a residential building stock at the urban scale [23]. However, in all of these previous studies of spatial building stock modelling (SBSM) based on GIS using annual average data, the focus was only on urban areas. On the other hand, Coste et al. [24] worked on the energy transition in rural areas, including the analysis of the energy consumption and local energy resources (renewable or not) coupled with a social forum, bringing together potential operators of an energy transition. At a smaller spatial scale, other studies produced energy models for the assessment and analysis of the energy consumption of neighbourhoods [28–33].

Some studies on SBSM have led to the creation of web based visualisation platforms [25–27]. Kim et al. built a city web based energy management approach which included plug-ins of Google maps and

Google Earth for visualisation utilizing environmental GIS, and monitored energy consumption data [25]. Sayar A. et al. worked on a framework that integrates AJAX into GIS visualisation web services [26]. Then, with the aim to make building energy data comprehensive and available, Kontokosta C. et al. built a web tool that provides consumers with the spatial distribution of buildings' electricity and gas consumption in New York [27].

In addition to these references on the HC of a building stock, other studies focused on the HD assessment of building stocks located in Europe and worldwide [20,34–38]. The choice of the study scale and the data sources vary widely in these studies. The energy demand estimations can range from smaller scales, such as neighbourhoods and districts, to larger scales, such as cities, regions or countries. The degree of complexity for the heat estimation increases with the increase of the area studied [34]. The estimation methods with building scale modelling approaches allow the optimization of energy demand planning for urban areas [34]. Berger and Worlitschek worked on the estimation of residential area heating demand using the top-down approach for the HD time series calculations for Switzerland, but this research did not consider domestic hot water in their calculations [35]. Strzalka et al. [36,37] estimated the HD of a building stock at the city scale by considering building information and weather conditions. A similar method was applied by Carrión et al. [38] to estimate the HD of buildings in the City of Berlin, with an average error of about 19%.

Based on this literature review, the authors observed that in the past years, the HC and HD of building stocks were often estimated using a combination of a GIS and building energy models by employing either national statistical data or empirical measurements. The choice to estimate the HC or HD in previous studies depends on the purpose of the research. Three questions emerge from this literature review, and this article is aimed at answering them:

(1) Considering that Wallonia covers a territory much larger than a city, and includes urban areas, peri urban and rural areas, is it possible to assess the HC and HD of all buildings of Wallonia and map them on different spatial scales? The spatial scales include neighbourhood, municipality and urban regions. The authors found that previous studies of SBSM based on GIS have always been limited to the study of a single urban area.
(2) Are the HD and HC of buildings related to constant average factors at different scales for the same territory? Should they be specifically assessed each time at the various territorial scales? The authors aim to determine whether there is a link between buildings' HC an HD at various scales, which could limit the number of energy maps needed for regional and municipal energy managers. In the previous studies, most of the researchers did not focus on both HC and HD at the same time and did not compare them. This study focused on determining the relationship between HC and HD on different scales. Knowing the values of HC can help determine the values of HD and vice versa on the same scale.
(3) What are the main parameters that influence the energy consumption of residential, tertiary, and industrial sectors at the regional scale? Although few studies have already evaluated the energy performance of residential, tertiary, and industrial buildings, the vast majority of them neglect industrial buildings, and a significant number of them assess only the energy performances of residential buildings. Moreover, most of the references cited in this article explain the methods that authors used to map the energy performance of a building stock. However, the authors aim to go beyond this step by analysing the produced energy maps and the impact of the distribution of residential, tertiary, and industrial buildings on the territory of the Walloon region.

3. Methodology

In this study, a method was first developed to assess the HC and HD of all residential, tertiary, and industrial buildings of Wallonia. After calculating the HC and HD of each building in the Walloon region, maps representing the spatialisation of buildings' HC and HD are produced and analysed at different scales of results aggregation in order to achieve better visualisation. The methodology includes data collection and cleaning, energy modelling, as well as HC and HD mapping and analysis at various scales considering the building scale as the base of the heat estimation and three representation scales: the statistical sector, the municipality, and the urban region scales. In this research, the estimation of HC and HD will provide insight into their mutual relationship and their links with building typology.

3.1. Case study

This study covers the whole Walloon building stock in Belgium. The Wallonia region is in the southern part of Belgium, and is composed of more than 1,700,000 buildings. The subdivision of Wallonia is carried out as follows: there are five provinces (Hainaut, Liège, Luxembourg, Namur and Walloon Brabant), 20 boroughs, 262 municipalities (cities or villages) with 40 main or big cities [39] and 9876 statistical sectors (SS) [40] as shown on the Fig. 1. The Walloon Region includes the four types of built areas defined and characterized by Van Hecke et al. [41]: agglomeration, suburbs, peri-urban and rural areas. In Belgium, the SS corresponds to a neighbourhood in urban areas or a village in rural areas with more than 150 inhabitants. The building scale is used in the modelling methodology. The statistical sector, municipality and urban region scales have been carefully chosen for the presentation of results in order to meet the requirements of data confidentiality and clear spatialisation output.

In the European Union, the average annual energy consumption of buildings varies from 150 kWh/m^2 to 320 kWh/m^2, with a mean of nearly 200 kWh/m^2 for existing residential buildings and 295 kWh/m^2 for non-residential buildings [42]. In Europe, Belgium is positioned as the eighth largest energy consumer (data for 2012) [43]. The residential sector in Wallonia consumes an average of 22,152 kWh of energy (heat and electricity) annually per dwelling [44]. In 2015, the total final energy consumption of the whole Walloon building stock was 30.5 TWh lower heating value (LHV) for the residential sector, 13.1 TWh LHV for the tertiary sector and 44.5 TWh LHV for the industrial sector [45].

3.2. Data description

The first set of data used is a cadastral database, which contains all buildings in Belgium for the year 2010. While each building has its affected attributes, not all matrix attributes are used in this study. Only five important buildings attributes are used in this research, namely the floor area, the type and nature of the building, the number of floors, and the presence of an inhabited attic.

The second type of data used comes from two energy regional reports for the year 2014 [46,47] for the residential and tertiary sectors. These are the most recently available regional energy reports for Wallonia, with the values being measured in 2012. In addition, considering the heating degree days (HDD) [47], the year 2012 is a representative year for the average climate in Wallonia for 30 years. The reference number of HDD is 1914.7° days in 2012, which is almost equal to the normal HDD value of 1913.4° days in the Walloon Region between the years 1981 and 2010 (with a relative difference of 0.07%). Values of these energy reports give the global energy consumption of the residential and tertiary regional building stock of Wallonia, depending on usage, which are: the main heating, domestic hot water, auxiliary heating and cooking. For the industrial sector, the data used were obtained from a specific energy report of 2016 which was published in 2018 [48]. This industrial energy report presents the global energy consumption of the industrial

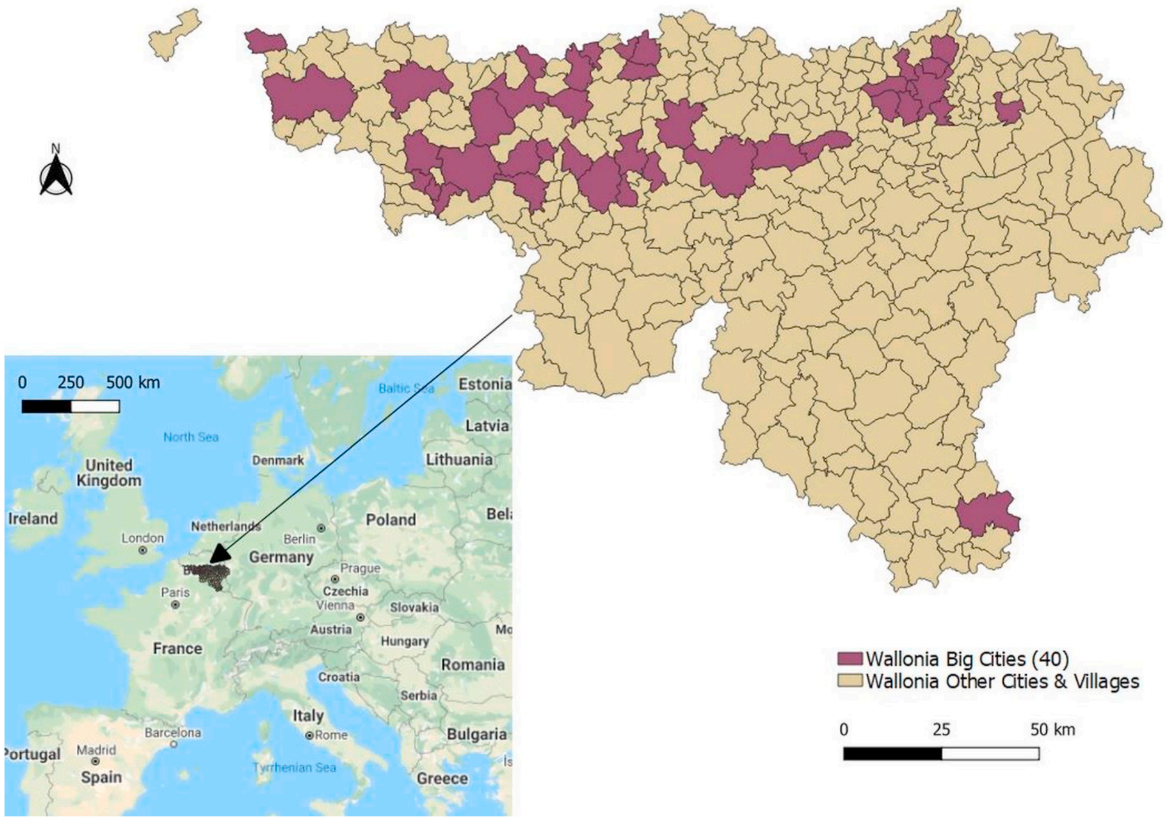

Fig. 1. Wallonia geographic situation and presentation of Wallonia big cities. Wallonia is the southern region and French speaking part of Belgium. It has 262 cities, amongst those cities there are 40 big cities.

regional building stock of Wallonia. In addition, the number of HDD in 2016 was 1947.6, which remains very close to that of the reference of 1913.4° days (a relative difference of 1.76%), which appears to be acceptable.

From the energy regional reports, the global HC related to 19 building types was extracted. The given average global consumption values are measured in GWh LHV (gigawatt-hour lower heating value), and the given average floor areas for each building type are in m^2. The global consumption values were obtained through brute sample conducted by VITO, ICEDD et al. [49] where a sample was selected proportionally to the size of each region in Belgium. The households' selection on municipality level was done following a simple random sampling scheme. The households were extracted from the National Population Register after the interviews performed on the field. For the residential sector, there are four categories of buildings: (1) apartment buildings, (2) terraced houses (i.e. single-family houses with 2 fronts) (3) semi-detached houses (i.e. single-family houses with 3 fronts), and (4) detached houses (i.e. single-family houses with 4 fronts) [46,47]. For the tertiary sector, there are eight categories of buildings: (1) administration; (2) banks, insurance, business services; (3) commercial buildings and shops; (4) culture, sport, and other services; (5) education (schools, universities, etc.); (6) buildings for the production and management of energy and water; (7) buildings for health care (hospitals, etc.) and (8) buildings for transport-communication services (stations, airports, etc.) [46,47]. The industrial sector is composed of seven categories, namely (1) chemistry, (2) food, (3) metallic manufacturing, (4) non-metallic minerals, (5) steel and iron, (6) textile and paper and (7) other industries [48]. Note that for mixed residential and tertiary buildings (such as commercial houses including one or several apartments), the building appears in both categories, but the square footage is distributed among them according to the typology of the building.

The consumption types that are considered for HC assessment for the residential buildings are the main heating, domestic hot water, auxiliary heating, and cooking. Furthermore, the 10 fuel types used in the residential sector in Wallonia are diesel, natural gas, coal, butane, propane, wood, steam cogeneration, geothermal energy, heat pump, solar thermal, and electricity. For the tertiary sector, the three fuel types are natural gas, oil/petrol or diesel products, and other energies. For the industrial sector, the four fuel types used in Wallonia are: solids and gases derived, natural gas, oil/petrol or diesel products, and other products.

3.3. Data cleaning

The data were fetched in the Belgian Cadastral database which is composed of more than 6.6 million buildings. Initially, the Belgian cadastral matrix is cut to keep all buildings that are in Wallonia, covering 20 boroughs (urban areas), 262 municipalities and 9876 SS using a spatial join in ArcMap software. This process eliminated buildings outside the studied area and kept only the buildings that are in the studied zone, Wallonia. Next, all buildings with invalid geometries are removed from the cadastral database. Afterwards, the authors kept only closed buildings and buildings with a shape file above 15 m^2. Lastly, buildings like monuments, car parks, etc. are not considered. The process is performed under mapping software. The final cadastral matrix database is composed of 1,520,650 residential dwellings, 157,247 tertiary buildings, and 39,765 industrial buildings. The used data are summarised in Table 1.

3.4. HC and HD modelling

The authors developed energy models to assess the HC and HD of the Walloon building stock, on the basis of annual average HC and used fuels for each type of building provided in Ref. [46–48]. The HC and HD of

Table 1
Data description summary. The first data are input variables for the residential, tertiary and industrial building for the HC and HD assessment. The other needed data are cadastral matrix and SS, municipality and urban region shapefiles required for the spatialisation of HC and HD.

	Data	Description	Source
Residential	Building category	Apartment, single houses (detached, semi-detached and terraced)	ICEDD 2014 [47]
	Number of buildings by category	Total number of buildings in each category	
	Consumption by usages	Consumption of each usage. Usages are main heating, domestic hot water, cooking and auxiliary heating	
	Used fuels	Diesel, natural gas, coal etc.	
Tertiary	Building category	Administration, banks, insurance, commercial etc.	ICEDD 2014 [47]
	THC_j by building category	Total HC of all buildings of the same category j	
	TA_j by building category	Sum of the shape areas of all buildings of the same category j	
	% of used fuels	Solids and gases derived, natural gas, etc.	
Industrial	Building category	Chemistry, food, etc.	ICEDD 2016 [48]
	% of each building category		
	THC_w of all industrial buildings	Total annual HC for all industrial buildings in Wallonia	
	TA_k by building category	Sum of the shape areas of all buildings of the same category	
	% of used fuels	Solids and gases derived, natural gas, etc.	
Cadastral	GIS database	Matrix of 1,717,662 buildings composed of different attributes mainly shape area, number of floors, attics and nature	Wallonia administration (2010)
Shapefiles	Statistical sectors Municipalities Urban regions	ESRI shapefiles	Géoportail de la Wallonie [40]

each building category were calculated based on fuel usages, fuel types, and their average performances. The HC and HD per m^2 for each building type were calculated, taking into account the global built surfaces of the different building types in Wallonia. This first step of the assessment is a top-down method. The second step includes characterizing each building by its annual HC and HD, owing to the cadastral database, using a bottom-up approach. The first step is used as the input of the second step, together with data coming from the cadastral database (floor area, floor number, and inhabited attics). Then, a third step involves mapping the HC and HD of the regional building stock at different representation scales, and performing statistical analyses of the results. The outputs are mapped on the SS, municipality and urban region scales. Fig. 2 summarizes the combined methodologies.

3.5. Assessment of building heat consumption (HC)

The HC is assessed using the formulas described below for residential, tertiary, and industrial buildings. These formulas are executed step by step in Excel and R programming. Note that inhabited floor attics are considered only for residential and tertiary buildings, but not for industrial buildings.

3.5.1. Residential HC

For the residential sector, the annual HC of each building in Wallonia is calculated as follows: First,

$$HC_{ui} = THC_{ui} / N_i \tag{1}$$

Where HC_{ui} is the annual average HC per residential building of a given category i related to the usage u, THC_{ui} is the total annual HC related to the usage u of all buildings of the same category i [47], N_i is the number of buildings of the residential category i [47]; u represents the main heating, domestic hot water, cooking, and auxiliary heating; i corresponds to the residential building categories (apartment, detached, semi-detached, and terraced houses).

$$HC_i = \sum_u HC_{ui} \tag{2}$$

where HC_i is the annual average HC per residential building of building category i, and HC_{ui} has been defined in formula 1.

Next, the shape area for each building in the cadastral database is calculated based on the following formula:

$$A_{ci} = S_c * (n_c + 1) \text{ If attics are not inhabited} \tag{3}$$

$$A_{ci} = S_c * (n_c + 2) \text{ If attics are inhabited} \tag{4}$$

where A_{ci} is the shape area of a specific cadastral building of the category i, S_c is the area of one floor of a specific residential building in the cadastral database, and n_c is its number of floors.

Then, using the cadastral database, the sum of all shape areas per building category is calculated as:

$$TA_i = \sum c\, A_{ci} \tag{5}$$

where TA_i is the sum of all shape areas of the same residential building category i.

Thus, the annual HC of each specific residential building of the cadastral database is given by:

$$HC_r = (HC_i * m_i / TA_i) * S_c * (n_c + 1) \text{ If attics are not inhabited} \tag{6}$$

$$HC_r = (HC_i * m_i / TA_i) * S_c * (n_c + 2) \text{ If attics are inhabited} \tag{7}$$

where HC_r is the annual HC of each specific residential building of the cadastral database, HC_i is the annual average HC per residential building of the building category i calculated earlier (formula *2*), m_i is the number of buildings of the same category i in the cadastral database, TA_i is the total shape area of the buildings of the same category i in the cadastral database, S_c is the shape area of one floor of the specific building in the cadastral database, and n_c is its number of floors. If the attic is inhabited, it is considered as a floor.

3.5.2. Tertiary HC

For the tertiary sector, the annual HC of each building in Wallonia is assessed as follows:

First,

$$HC_j = THC_j / TA_j \tag{8}$$

where HC_j is the calculated annual average heat consumption per m^2 for each tertiary building category j, THC_j is the total HC of all buildings of the same category j [47] and TA_j is the sum of the shape areas of all buildings of the same category j [47].

Thus, the annual HC of each specific tertiary building of the cadastral database is given by:

$$HC_t = HC_j * S_c * (n_c + 1) \text{ If attics are not inhabited} \tag{9}$$

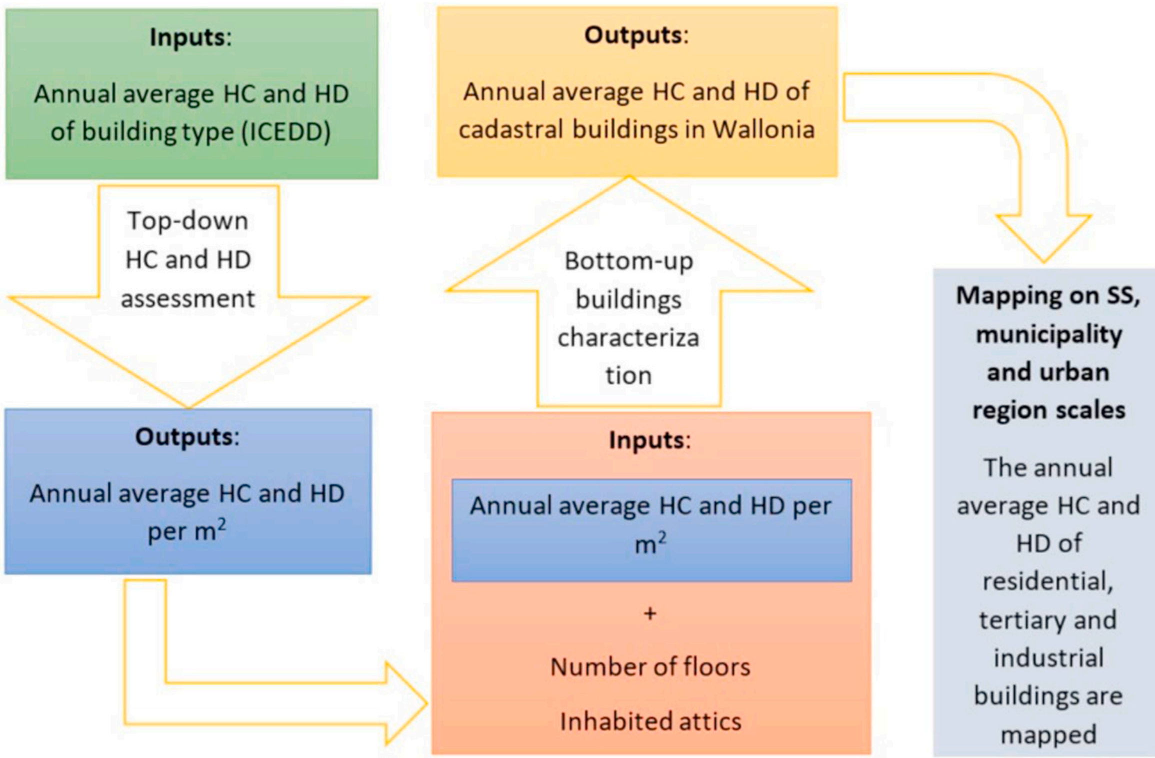

Fig. 2. Top-down, bottom-up, and mapping approaches. The top-down inputs are from assessment based on the input variables from ICEDD energy reports. The outputs of the top-down approach became the inputs data in the bottom-up approach together with cadastral data required attributes. The outputs of the bottom-up approaches are used in the mapping of HC and HD on different scales in Wallonia.

$$HC_t = HC_j * S_c * (n_c + 2) \text{ If inhabited attics} \tag{10}$$

where HC_t is the annual HC of each specific tertiary building in the cadastral database, HC_j is the annual average HC per m^2 for each tertiary building category j calculated earlier (formula 8), S_c is the shape area of one floor of this specific tertiary building in the cadastral database, and n_c is its number of floors. If the attic is inhabited, it is considered as a floor.

3.5.3. Industrial HC

The HC of an industrial building is calculated by first estimating the HC of each industrial building category, after which its HC per m^2 is calculated:

$$THC_k = THC_w * P_k \tag{11}$$

where THC_k is the calculated total HC of all industrial buildings of the building category k, THC_w is the total annual HC for all industrial buildings in Wallonia [48], and P_k is the percentage of HC of industrial buildings of the category k compared to the HC of the whole industrial building stock of Wallonia [48].

$$HC_k = THC_k / TA_k \tag{12}$$

where HC_k is the calculated annual average HC per m^2 for each industrial building category k, THC_k has been calculated in formula 11, and TA_k is the sum of the shape areas of all buildings of the same category k [48].

Therefore,

$$HC_w = HC_k * S_c \tag{13}$$

where HC_w is the HC of each specific industrial building in the cadastral database, S_c is its specific shape area given in the cadastral database, and HC_k has been calculated in formula 12 (see Table 1).

3.6. Assessment of building heat demand (HD)

To estimate the HD, the heating system performances have to be taken into account. The global heating system performance reflects all the losses (due to production, distribution, emission and regulation) related to the heating system installation. A survey is conducted in Wallonia [49] to obtain the values of the boilers performances. The Table 2 represents the used fuel vectors in Wallonia and the system performances. Note that the system performances of diesel or natural gas boilers are calculated using the following formula:

$$\eta_f = (\eta_{he} * p_{he}) + (\eta_{cb} * p_{cb}) + (\eta_o * p_o) \tag{14}$$

Where (η_f) is the global heating system performance, η_{he} is the high performance boiler's performance, p_{he} is the percentage of high performance boilers, η_{cb} is the condensing boiler's performance, p_{cb} is the percentage of condensing boilers, η_o is the other boilers performance and p_o is the percentage of other boilers.

3.6.1. Residential HD

For the residential sector, the annual HD of each building in Wallonia is calculated as follows:

First,

$$Q_{fu} = P_{fui} * HC_{ui} \tag{15}$$

where Q_{fu} is the quantity of used fuel per vector f (diesel, natural gas, coal, etc.) by usage u (main heating, domestic hot water, etc.) per residential building for a given residential building category i, P_{fui} is the percentage of fuel vector f utilized by usage u for a building category i, and HC_{ui} is the average HC by usage u per building of a given category i, as calculated earlier (formula 1).

Next,

Table 2
Heating systems performance. The quantity of fuel used are measured through the conducted survey [49] for residential, tertiary and industrial buildings.

Fuel vector		Boiler performance (η_{fb})	Percentage (p_b)	Global heating system performance
Diesel	High performance boilers	90%	23%	80% (η_f)
	Condensing boilers	102%	7%	
	Other boilers	75%	70%	
Natural gas	High performance boilers	90%	28%	86% (η_f)
	Condensing boilers	105%	21%	
	Other boilers	75%	51%	
Coal				74%
Butane propane				76%
Wood				72%
Steam cogeneration				90%
Geothermal				100%
Heat pump				100%
Solar thermal				100%
Electricity				100%
Solids and gases derived				100%
Other products				100%

$$HC_{fi} = \sum_{u} Q_{fu} \quad (16)$$

where HC_{fi} is the annual average HC related to the fuel vector f per residential building of a given category i, Q_{fu} was calculated earlier (formula 15).

Considering the global heating system performances described in Table 2, the HD of residential buildings is assessed as follows:

$$HD_{fi} = HC_{fi} * \eta_f \quad (17)$$

Where HD_{fi} is the annual average HD by used fuel vector f per residential building of the building category i, HC_{fi} has been calculated earlier (formula 16) and η_f is the system performance for the fuel vector f.

Therefore, the HD per residential building of category i is calculated by:

$$HD_i = \sum_{f} HD_{fi} \quad (18)$$

Finally, using the results from formula *(18)* combined with the cadastral database, the HD of each specific building (in the cadastral database) is given by:

$$HD_r = (HD_i * m_i / TA_i) * S_c * (n_c + 1) \text{ If attics are not inhabited} \quad (19)$$

$$HD_r = (HD_i * m_i / TA_i) * S_c * (n_c + 2) \text{ If inhabited attics} \quad (20)$$

where HD_r is the annual HD of each specific building of the cadastral database, HD_i was calculated earlier (formula *18*), m_i is the number of buildings of the same category i in the cadastral database, TA_i is the total shape area of the buildings of the same category i in the cadastral database, S_c is the shape area of one floor of a specific dwelling in the cadastral database, and n_c is its number of floors. If the attic is inhabited, it is considered as a floor.

3.6.2. Tertiary HD

The tertiary sector in Wallonia uses three types of boilers: old boiler, condensing boiler, and high performance boiler [49]. Considering the system performances description provided in Table 2, the HD for tertiary buildings is assessed by:

$$HD_j = \sum_{f} (HC_j * (\sum_{b} (\eta_{fb} * p_b))) \quad (21)$$

where HD_j is the annual average HD per m^2 for each tertiary building category j, HC_j is the average HC per m^2 for each tertiary building of category j assessed in formula 8, η_{fb} is the performance for the tertiary heating system related to fuel vector f and boiler b, p_b is the percentage of boiler type b for the heating system, and f is the fuel vector (natural gas, petrol products, and other products).

$$HD_t = HD_j * S_c * (n_c + 1) \text{ If attics are not inhabited} \quad (22)$$

$$HD_t = HD_j * S_c * (n_c + 2) \text{ If attics are inhabited} \quad (23)$$

where HD_t is the HD of each specific tertiary building in the cadastral database, HD_j was calculated earlier in formula 21, S_c is the shape area of one floor for that specific building in the cadastral database, and n_c is its number of floors. If the attic is inhabited, it is considered as a floor.

3.6.3. Industrial HD

Industrial buildings require the same types of boilers and performances as the tertiary sector. However, industrial buildings also use natural gas, petrol products, and other products, as well as solid and gas derived fuels [49]. The system performances used in industrial sector are also described in Table 2.

Thus HD of industrial buildings is given by:

$$HD_k = \sum_{f} (HC_k * \sum_{b} (\eta_{fb} * p_b)) \quad (24)$$

Where HD_k is the annual average HD per m^2 of one industrial building of category k, HC_k is the calculated annual average HC per m^2 for each industrial building category k, already given in formula 12, η_{fb} is the performance for the heating system related to the fuel vector f and the boiler b; p is the percentage of boiler type b for the heating system, and f is the fuel vector (natural gas, petrol products, solids and gases derived fuels and other products).

$$HD_w = HD_k * S_c \quad (25)$$

where HD_w is the annual HD of each specific industrial building of the cadastral database, HD_k is the calculated average HD per m^2 of one industrial building of category k, and S_c is the shape area given in the cadastral database for this specific industrial building.

3.7. Development of a spatialised energy cadastre

All of the buildings of the Wallonia cadastral database are characterised by the assessed HC and HD using a bottom-up approach. The obtained results are used for cartography. The spatialisation is executed according to different result aggregation scales, ranging from SS to urban region scales. Using Quantum GIS (QGIS) software, the authors performed an attribute join of the assessed HC and HD with SS, municipalities, and urban region shape files. The natural threshold classification "Natural breaks of Jenks" was used with five classes. The results are distributed in classes with defined limits corresponding to the places where there are large differences in the data. Natural threshold classes are functions of natural groupings essential to the data, which group better similar values and optimize the differences between the classes. Indeed, the natural threshold seeks to reduce the variance within classes and maximize the variance between classes, and it looks for the natural trends of data to classify them.

In the following sections, the distribution of the building stock HD and HC related to residential, tertiary, and industrial buildings in Wallonia is presented and discussed. Furthermore, the HD is mapped on SS and municipality scales. Finally, the comparison of HC and HD on the urban region scale employed the quantile classification.

In fact, the spatialisation of energy cadastre is performed on different scales for a better representation of the HC and HD. The spatialisation used two classification methods: natural breaks of jenks and quantile classification. The first method of classification "natural breaks of jenks" is used to map the HC or HD of residential, tertiary and industrial buildings. The second method of classification "quantile classification" which stresses the difference in relative position between groups is used to compare HC to HD of a building sector (either residential, or tertiary or industrial).

3.8. Descriptive statistics and analysis of calculated HC and HD

Descriptive statistics of the calculated HC and HD on the Walloon building stock will be used for the results analysis and discussion. First, ArcMap software has been used to represent a histogram, comparing the total number of buildings of each building category per urban area. This will be useful later to analyse how the number of buildings in each category is related to the annual average HC and HD of its total building stock. The shape files containing residential, tertiary, and industrial cadastral data are exported as dBASE tables, and converted into csv using arc toolbox. Then, using R software, the average, maximum and minimum values of the total annual HC and HD of the residential, tertiary, and industrial building stock of each SS, municipality, and urban region are calculated. Moreover, linear regression models are developed to analyse the relationship between HC, HD and the number of buildings in an SS. These results are necessary in order to compare the obtained results with those used in other studies, and to better understand the link between the HC and HD of a building stock at different territorial scales.

4. Results and discussion

The results presented in the following sections show the total number of buildings per urban region (boroughs) in Wallonia, the maps of HD on the SS scale and the municipality scale, the maps of HC on the urban region scale, the HC and HD comparisons on the SS scale, municipality, and urban region scales, and some descriptive statistics results. The map showing the distribution of the Walloon building stock HC is visually identical to the representation of its HD distribution for the Walloon territory. Hence, only one map is presented at each representation scale. However, the average, minimum, and maximum values of HD and HC are presented in a tabular form, and an analysis of these comparisons is given.

4.1. Number of buildings for each urban area

Fig. 3 presents the number of buildings in the 20 urban areas of Wallonia and their distribution in the three building sectors (residential, tertiary, and industrial). This figure indicates that residential buildings are dominant in the Walloon building stock. Moreover, the number of residential buildings is the highest in the Liège urban region, followed by Charleroi and Nivelles. The highest numbers of tertiary and industrial buildings are also in the same urban areas. Bastogne has the lowest number of residential, tertiary, and industrial buildings.

4.2. Spatialised heat demand on the statistical sector (SS) scale

Fig. 4 shows the spatial distribution of the HD for all residential buildings in Wallonia, aggregated at the SS scale for better visibility. Figs. 5 and 6 show the building HD distribution in Wallonia at the SS scale for tertiary and industrial sectors, respectively. The estimated HD of the Walloon building stock was mapped on a SS scale using QGIS software.

4.2.1. Residential HD of each SS

The neighbourhoods (SSs) of the large cities mostly account for the greatest values of HD. This is because of the highest number of dwellings in city centres such as Liège, Charleroi, and Namur. The highest annual HD for residential buildings at the SS scale is 30.80 GWh LHV in an SS.

4.2.2. Tertiary HD of each SS

The HD of the Walloon tertiary buildings have almost the same grouping trend as the HD for residential buildings, but here, the highest annual HD at the SS scale reaches 42.18 GWh LHV, which is higher than the highest HD for residential buildings in the SS. However, comparing the annual HD of residential and tertiary sectors in each SS, the number of residential buildings in an SS as well as its HD are often higher compared to the number of tertiary buildings and its HD.

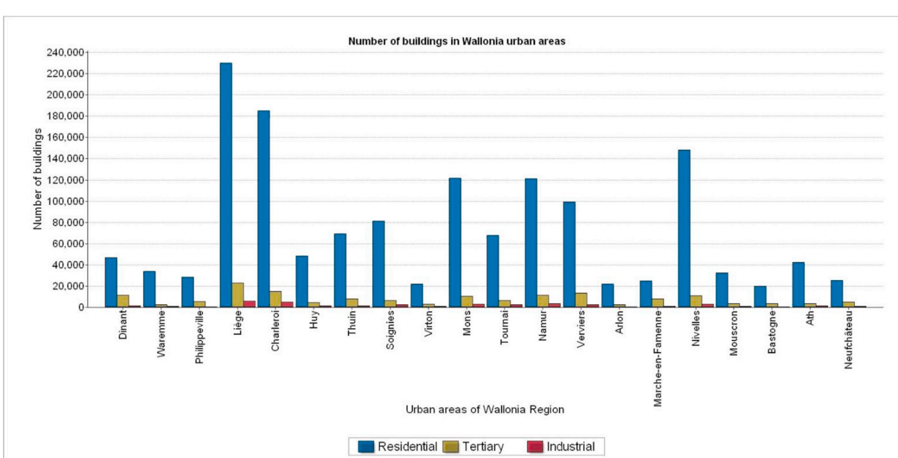

Fig. 3. Number of residential, tertiary, and industrial buildings in the urban areas of Wallonia. There are few industrial buildings compared to tertiary and residential buildings in urban areas. Generally, Wallonia presents higher residential buildings.

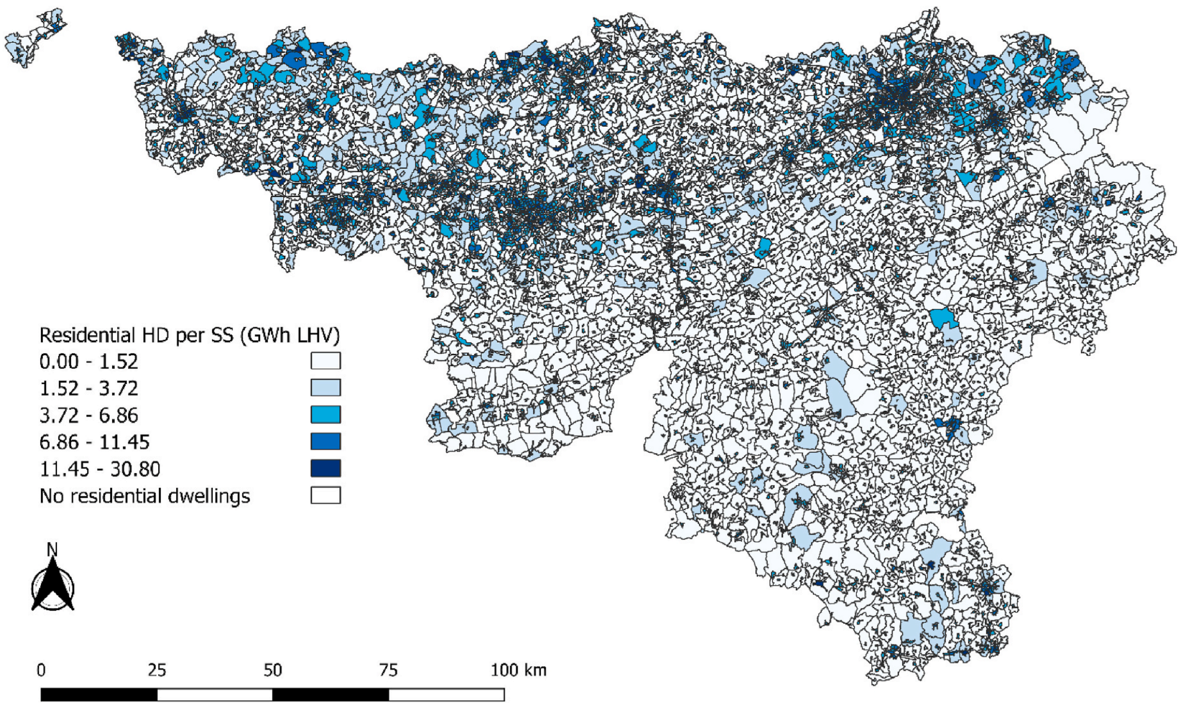

Fig. 4. Total annual HD of Walloon dwellings on SS level. The 0.00 GWh of HD in an SS reflects the absence of residential buildings in that SS.

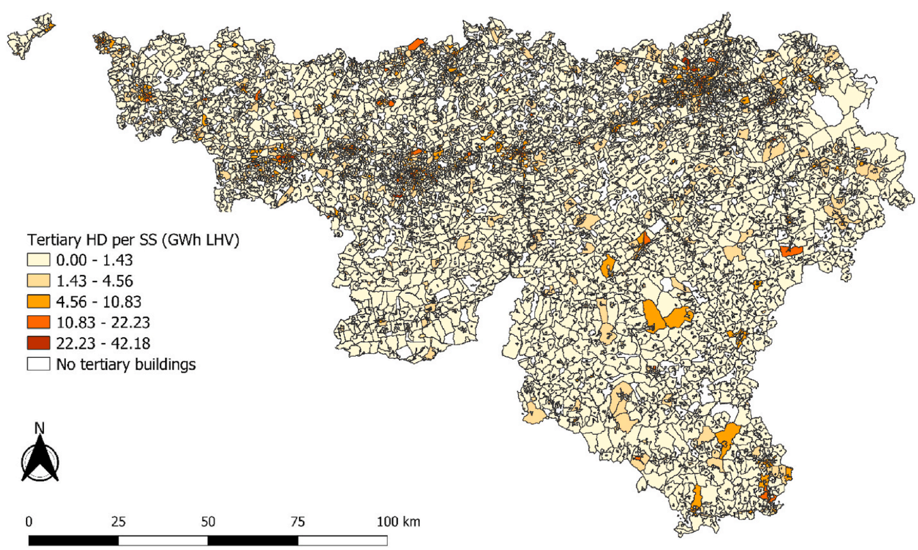

Fig. 5. Total annual HD of Walloon tertiary buildings on SS level. Some SSs do not have tertiary buildings. Thus the HD in those SSs correspond to 0.00 GWh.

4.2.3. Industrial HD of each SS

The map of the HD of Walloon industrial buildings clearly shows the line of dense cities in Wallonia, where the industrial HD is observed to be higher as compared to other parts of Wallonia on an SS scale. This conclusion is similar to that for the residential and tertiary buildings at the same scale of representation.

4.3. Heat demand on municipality scale

After analysing the territorial annual HD on the smallest scale of our study (SS), trends are observed on a municipality level. Figs. 7–9 show the HD distribution of buildings in Wallonia at the municipality scale for residential, tertiary, and industrial sectors, respectively.

4.3.1. Residential HD of each municipality

On the municipality scale, the total annual HD of Walloon dwellings varies from 13.52 to 1201.70 GWh, as shown in Fig. 7. Based on this map and to reduce energy consumption due to residential heat consumption in Wallonia, decision makers should develop energy policies and renovation subsidies which focus particularly on the agglomerations. For example, some measures should be taken in the municipalities of Liège and Charleroi, where the residential HD is significantly higher compared to other municipalities. However, these two cities include the largest number of dwellings. Other municipalities with high residential HD are Namur, La Louvière, Seraing, Verviers, Mons, Tournai, and Mouscron. At the municipal level, the lowest residential HD is found in the municipality of Houffalize.

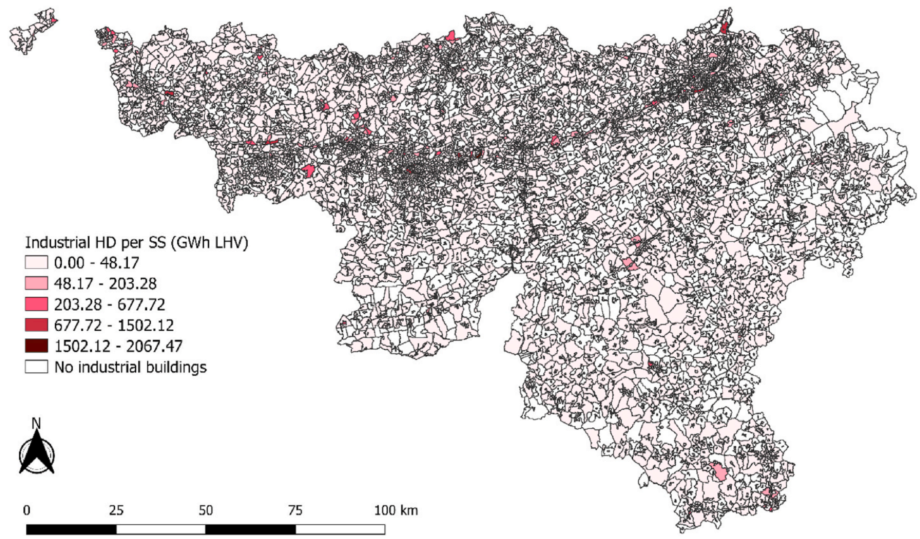

Fig. 6. Total annual HD of Walloon industrial buildings on SS level. For the industrial buildings as well, some SSs lack the industrial buildings, therefore the HD corresponds to 0 GWh in those SSs.

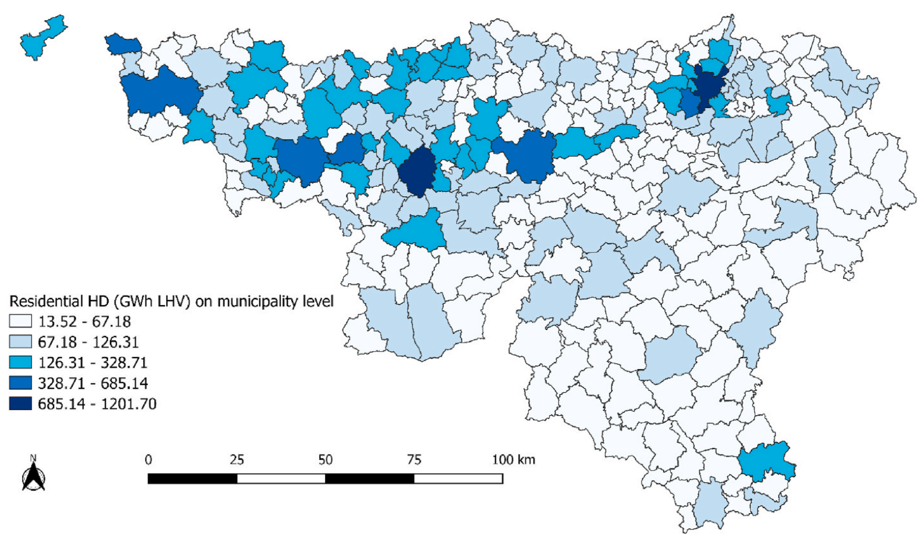

Fig. 7. Total annual HD of Walloon dwellings on municipality level. Mostly big or main cities of Wallonia present higher residential HD.

4.3.2. Tertiary HD of each municipality

On the municipality scale, the total annual HD of the Walloon tertiary building stock varies from 2.77 to 823.23 GWh (see Fig. 8). Again, the highest annual tertiary HD is observed in Liège, then Charleroi, which have the highest annual tertiary HD and the largest number of building types per municipality. These are followed by Namur, Mons, and Tournai, respectively. The lowest HD for Walloon tertiary buildings at this scale is located in the Arlon municipality.

4.3.3. Industrial HD of each municipality

On the municipality scale, the total annual HD of the Walloon industrial building stock varies from 0.19 to 3470.40 GWh (see Fig. 9). The highest municipal industrial HD value is very high compared to the highest municipal HD for residential and tertiary sectors. Unlike the previous maps, the HD of industrial buildings is more centralized in a few Walloon municipalities compared to the HD for Walloon residential and tertiary buildings. Moreover, the highest industrial HD at the municipal scale is found in Charleroi, followed by Jemeppe-Sur-Sambre, which are the two Walloon municipalities with the most pronounced industrial history. In contrast, the HD of industrial buildings in the city of Liège is much lower, although it is the municipality that shows the highest HD for residential and tertiary buildings.

4.3.4. Residential, tertiary and industrial sector HD map

Fig. 10 summarizes in a single map the HD for residential, tertiary, and industrial buildings in Wallonia at the municipality scale.

This map highlights the observations made in Figs. 4–9, in that the highest HD for residential and tertiary buildings in Wallonia are found in large cities, while the highest industrial HD is found in areas surrounding directly dense cities. Summarizing the HD of residential, tertiary, and industrial buildings on the municipality scale, Charleroi, Mons, and Jemeppe-sur-Sambre have the highest global HD for the whole Walloon building stock, which shows the important influence of industrial buildings. The rural and very sparsely populated municipalities of Martelange and Daverdisse are seen to be the least consumers globally, taking into account all residential, tertiary and industrial buildings in Wallonia. This confirms that the building stock HD is generally higher in large cities, while it is lower in mostly rural areas.

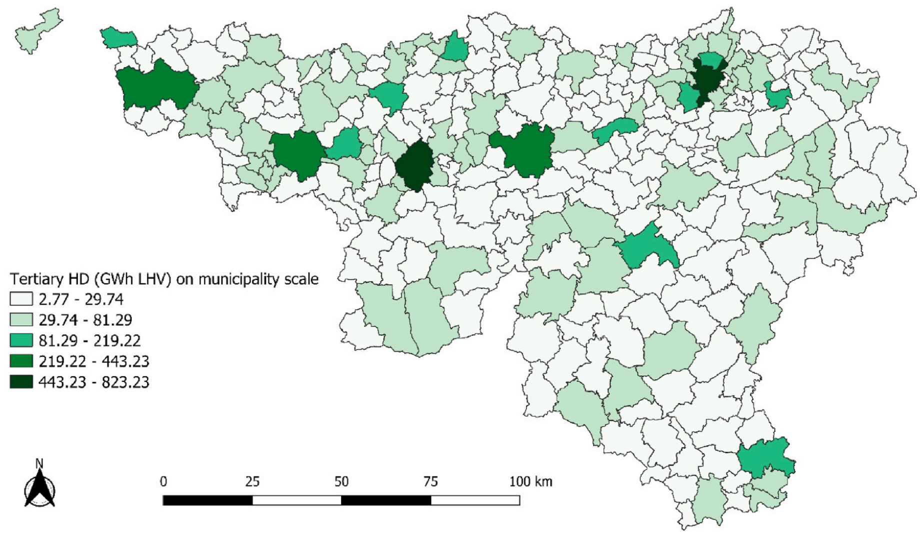

Fig. 8. Total annual HD of Walloon tertiary buildings, on municipality level. Some big cities present higher tertiary HD.

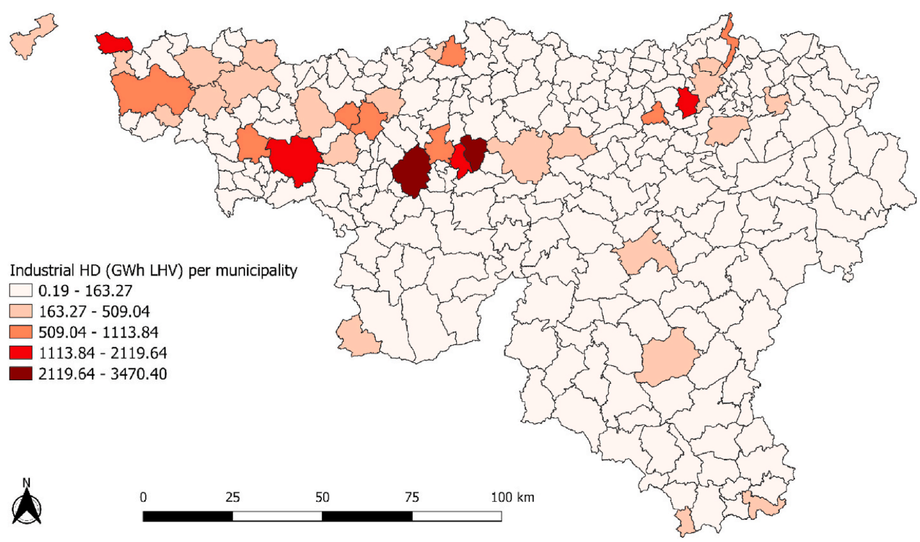

Fig. 9. Total annual HD of Walloon industrial buildings on municipality scale. Only one city (Jemeppe-Sur-Sambre) not included in the 40 main cities presents higher industrial HD.

4.4. Heat demand and consumption on urban region scale

4.4.1. Residential, tertiary, and industrial sector HC map

Fig. 11 presents in three maps the HC for the residential (left), tertiary (in the middle) and industrial (right) buildings in Wallonia at the urban region scale. This scale of representation is less interesting for studies of the energy performance of a territory. However, the northern part of Wallonia, which includes most of its big cities, has a higher HC than the more rural southern part. On the urban region level, Fig. 11 shows that the Liège urban region has the highest HC owing to the presence of residential buildings. Fig. 3 shows that the Liège urban region includes the greatest number of dwellings. However, in the tertiary sector, in addition to the Liège urban region, the Namur, Charleroi, and Verviers regions also have high HC. In the industrial sector, the Namur and Charleroi urban regions have the highest HC.

4.4.2. HC and HD comparison at urban region scale

Fig. 12 presents a comparison of the total HC and HD of the complete Walloon building stock (including residential, tertiary, and industrial buildings) at the urban region scale. The percentages on this map represent the relative difference between the total HC and HD in each urban region.

The building stock HC is higher than its HD in all urban areas in Wallonia because of the low percentage of heating installations with excellent performances (gas condensing boilers, heat pumps, etc.). The sum of residential, tertiary, and industrial HC and HD at the urban region scale shows that the urban regions of Liège, Namur, and Charleroi have the highest HC and HD. For Liège, which has the highest HC, the relative difference between its whole building stock HC and HD is 13.36%. For Philippeville, which has a low HC compared to other urban areas, its HC and HD have a relative difference of 16.17%, which is the highest at this level.

4.5. Descriptive statistics and analysis

Tables 3–5 give the minimum, mean, and maximum values of the building stock HD and HC on the three studied scales (SS, municipality, and urban regions), for residential, tertiary, and industrial buildings, respectively. The assessed HC and HD summaries facilitate the comparison of HC to HD on the three studied levels. These tables show that

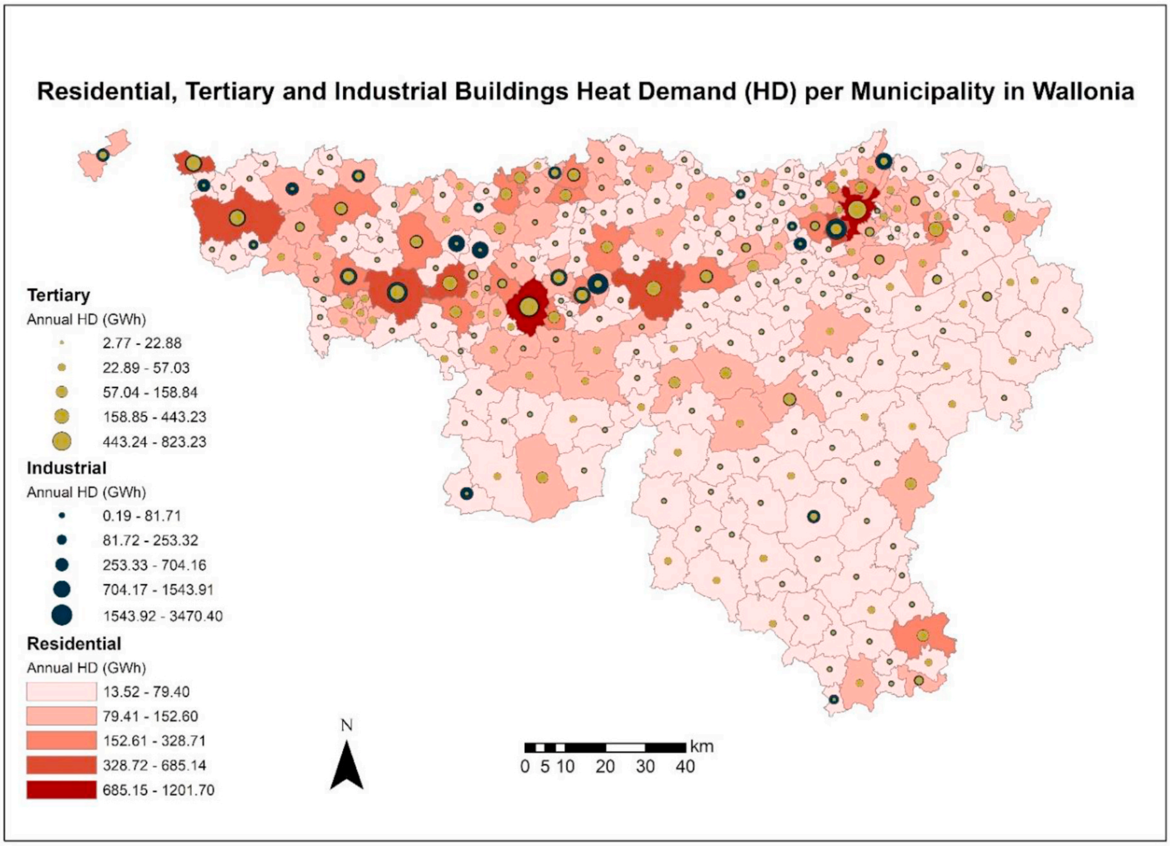

Fig. 10. Total annual HD of Walloon residential, tertiary, and industrial buildings on the municipality scale. Even though residential buildings are highly presented in Wallonia, their HD is lower compared to few industrial buildings and also tertiary HD is less compared to industrial HD. Industrial buildings are more consuming compared to residential and tertiary buildings.

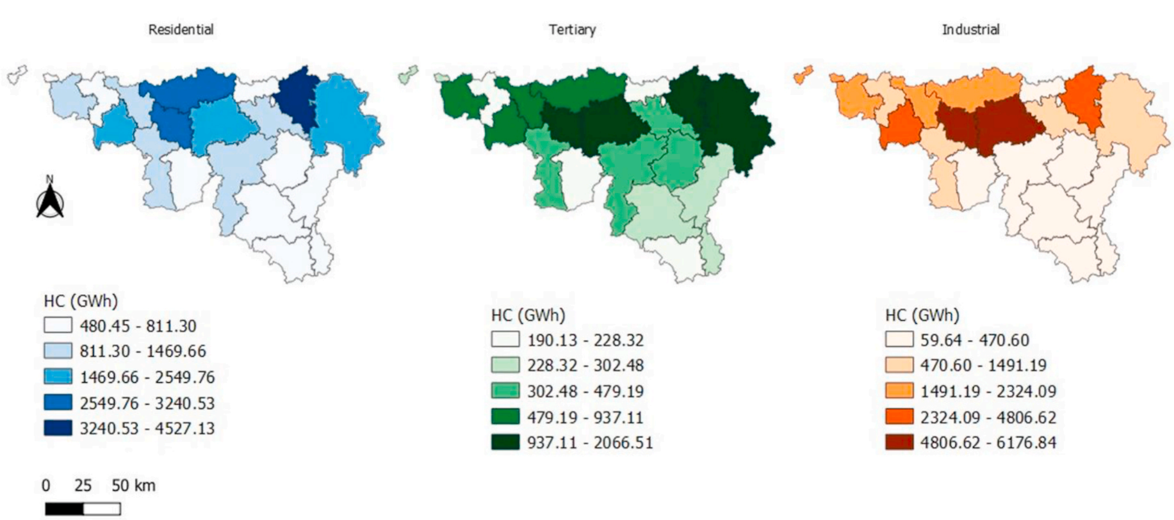

Fig. 11. Residential, tertiary, and industrial HC per urban area. The tertiary HC is nearly 3 times less to the residential HC while industrial HC is generally higher in highly industrial areas which are Charleroi and Namur urban regions.

the industry sector has significantly higher mean and maximum values of HC and HD, as compared that of residential and tertiary sectors at the SS, municipality, and urban region scales.

4.5.1. Residential sector

Table 3 presents the minimum, mean, and maximum values of the HD and HC for the residential building stock on the three studied scales (SS, municipality, and urban region). Note that there are 197 SS which do not include any residential building. However, the minimum value is calculated by excluding those statistical areas which do not include any residential building.

The mean values of the residential HD show that the HD is 16.44% lower than the HC on the SS level, 16.36% lower on the municipality level, and 16.59% lower on the urban region level. The minimum HD for the residential building stock at the SS scale is 18.23% lower than the HC, 17.02% lower on the municipality level, and 17.35% lower on the

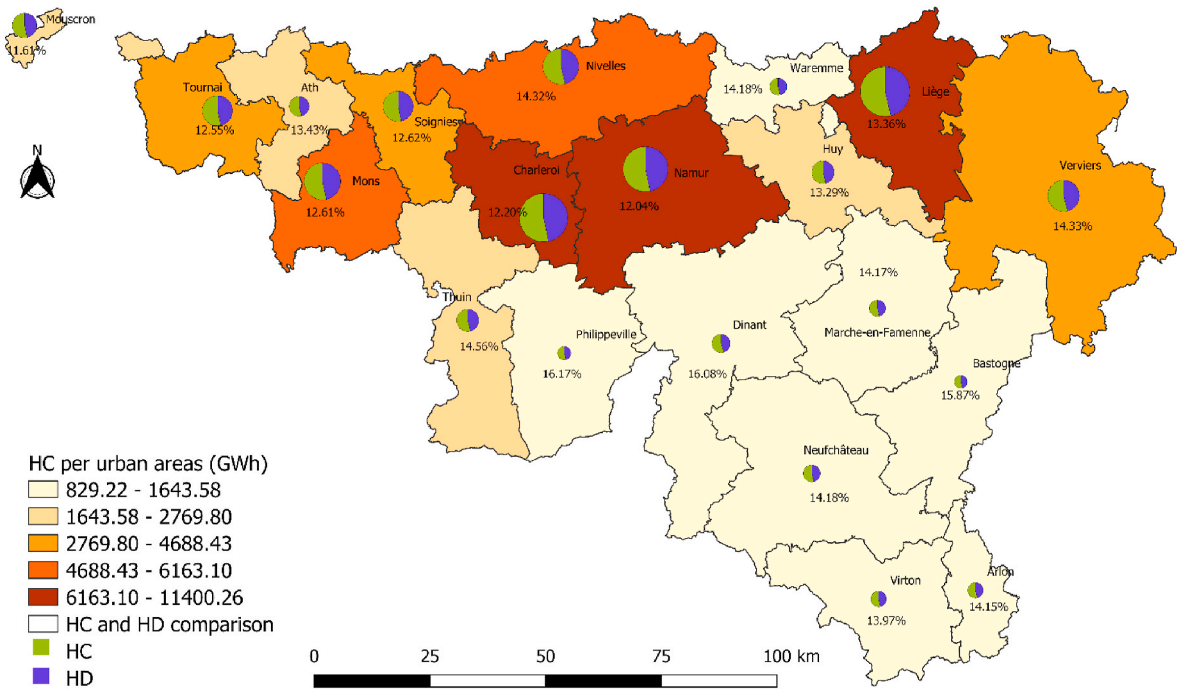

Fig. 12. Residential, tertiary, and industrial total (sum) of HC and HD per urban area.

Table 3
Residential heat consumption and demand summary.

	Minimum (GWh)	Mean (GWh)	Maximum (GWh)
HC by SS	0.00175843	7.10263855	36.665290
HD by SS	0.001437944	5.934931889	30.795870
HC by municipality	16.28844	322.51648	1431.85602
HD by municipality	13.51674	269.76187	1201.69725
HC by urban region	480.4522	2345.3232	4527.1251
HD by urban region	397.094	1956.248	3785.696

urban region level. The maximum values of the residential HD show that the HD is 16.01% lower than the HC on the SS level, 16.07% lower on the municipality level, and 16.38% lower on the urban region level. Additionally, the HD of the Walloon residential building stock is always lower than its HC at the three studied scales, with the calculated differences ranging from 16.01 to 18.23%.

4.5.2. *Tertiary sector*

Table 4 presents the minimum, mean, and maximum values of the HD and HC of the tertiary building stock on the three studied scales (SS, municipality, and urban regions). Note that there are 1048 SS that do not include a tertiary building. However, a minimum value is calculated by excluding those statistical areas that do not include any tertiary building.

For the tertiary sector, the mean values show that the HD is 15.78% lower than the HC on the SS level, 15.81% lower on the municipality level, and 15.80% lower on the urban region level. The minimum values show that the HD is 16.15% lower than the HC on the SS level, 15.81% lower on the municipality level, and 15.78% lower on the urban region level. Furthermore, the maximum values show that the HD is 15.71% lower than HC on the SS level, 15.83% lower on the municipality level, and 15.82% lower on the urban region level. The HD of the Walloon tertiary building stock is always lower than its HC at the three studied scales, with the calculated differences ranging from 15.71 to 16.15%.

4.5.3. *Industrial sector*

Table 5 presents the minimum, mean, and maximum values of the HD and HC of the industrial building stock for the three studied scales (SS, municipality, and urban regions). Note that there are 3357 SS which do not include any industrial building. However, minimum value is calculated by excluding those statistical areas which do not include any industrial building.

Here, the mean values show that the industrial HD is 9.26%, 9.33%, and 9.36% lower than the industrial HC on the SS, municipality, and urban region levels. The minimum shows that the industrial HD is 12.85% lower than the industrial HC on the SS level, 12.84% lower on the municipality level and 10.76% lower on the urban region level. In addition, the maximum values show that the industrial HD is 9.13%, 9.31% and 9.34% lower than industrial HC on the three levels. The HD of the Walloon industrial building stock is always lower than its HC at the three studied scales, with differences calculated between 9.13 and 12.85%.

Table 4
Summary of tertiary heat consumption and demand.

	Minimum (GWh)	Mean (GWh)	Maximum (GWh)
HC by SS	0.00087357	5.60708306	50.04087826
HD by SS	0.00073248	4.72223690	42.17877181
HC by municipality	3.293758	173.659190	978.068553
HD by municipality	2.77317	146.20684	823.22826
HC by urban region	190.1265	859.1238	2066.5108
HD by urban region	160.1303	723.4063	1739.6898

Table 5
Summary of industrial heat consumption and demand.

	Minimum (GWh)	Mean (GWh)	Maximum (GWh)
HC by SS	0.0012014	52.4314131	2275.2639310
HD by SS	0.001047	47.574416	2067.474129
HC by municipality	0.215835	607.052366	3826.600958
HD by municipality	0.188132	550.440067	3470.403828
HC by urban region	59.63715	2970.51843	6176.83971
HD by urban region	53.21781	2692.62076	5600.06937

4.6. Comparison of residential total HC and HD per number of buildings in an SS

Fig. 13 illustrates the relationship between the total residential HC (left) or HD (right) and the number of dwellings in each SS. Both the HC or HD and the number of dwellings are log transformed to get a better understanding and visualisation of the data. The HC and HD are exponentially related to the number of dwellings in an SS respectively by the relations HC = exp(-3.5476 + 0.9259 * log(Number of dwellings) + 0.1767) and HD = exp(-3.7582 + 0.9309 * log(Number of dwellings) + 0.1760). For every 1% increase in the number of dwellings, the HC increases by about 0.9259% and the HD increases by about 0.9309% in the same SS. In an SS, the HD increases almost at the same rate as for the HD (with a tiny difference of 0.005%) each time the number of dwellings increases. The negative intercept results from the lower and sometimes zero number of dwellings in some SS. The relationship between HC or HD and the number of dwellings in an SS changes over an extended range. The values of the number of dwellings have a range from 1 to 1822, and the values of the HC and HD have a range from 0.0018 to 37 GWh and from 0.0014 to 31 GWh respectively. In this case, the plots show negative values for the constant (intercept). This is explained by the SS that has zero or few residential dwellings.

4.7. Comparison of tertiary total HC and HD per number of buildings in an SS

Fig. 14 illustrates the relationship between the total tertiary HC (left) or HD (right) and the number of tertiary buildings in each SS. The plots are represented by the following equations: HC = exp(-2.9752 + 1.0079 * log(Number of buildings) + 0.8749) and HD = exp(-3.1471 + 1.0079 * log(Number of buildings) + 0.8750). The HC and HD increase by the same rate of about 1.0079% every 1% increase in the number of tertiary buildings in an SS. The plots, at some point, are no longer linear and the differences between the number of buildings become narrower. This means that the tertiary HC and HD are not only related to the number of tertiary buildings in an SS, but are also linked to their functions and building types. The actual relationship between HC or HD and the number of buildings in an SS changes over an extended range. The number of tertiary buildings in an SS ranges from 1 to 599. However, the values of the HC have a range from 0.00087 to 50 GWh and from 0.00073 to 42 GWh for the HD. In this case, that is why there are negative values for the constant (intercept). In addition, there are some SS which have zero or very few tertiary buildings.

4.8. Comparison of industrial total HC and HD per number of buildings in an SS

Fig. 15 illustrates the relationship between the total industrial HC (left) or HD (right) and the number of industrial buildings in each SS. The HC and HD increase rapidly as the number of industrial buildings increases. This is explained by the equations: HC = exp(-4.9089 + 2.0140 * log(Number of buildings) + 1.5380) and HD = exp(-5.0491 + 2.0210 * log(Number of buildings) + 1.5490). Every 1% increase in industrial buildings in an SS increases the HC and HD by about 2.0140% and 2.0210% respectively. The relationship between HC or HD and the number of buildings in an SS depends on the availability, functions, and type of industrial buildings. Additionally, the negative coefficient (intercept) is explained by the lower and sometimes zero industrial building in some SSs. The actual relationship between HC or HD and the number of buildings in an SS changes over an extended range. The values of the number of industrial buildings in an SS have a range from 1 to 240, the values of the HC have a range from 0.0012 to 2275 GWh and from 0.0010 to 2067 GWh for the values of the HD. When the number of buildings is higher in an SS for tertiary (Fig. 14) and industrial (Fig. 15) the HC and HD do not increase linearly. The type, nature and size of tertiary and industrial buildings also influence the HC or HD.

5. Validation of the developed energy models

In this section, the authors compare research results of this study to values found in regional energy reports and a previous study [47,48,50]. Table 6 presents a comparison of the average floor area of some residential buildings in Wallonia reported in with the values calculated in this study, which were obtained from the cadastral database. Table 7 presents a comparison of the average annual household energy consumption assessed in this study and a survey of 2119 Walloon households [50]. Finally, Table 8 shows a comparison of the calculated HC of the whole residential, tertiary and industrial building stocks with the same HC assessed by the regional energy reports [47,48].

By comparing the shape area used in this study and by ICEDD [46, 47], the relative difference is found to be negative for terraced and semi-detached houses, which means that this study uses surfaces which are about 10% lower than those used by ICEDD. However, the relative difference is positive for detached houses; this study uses surfaces which are about 14% higher than those used by ICEDD. Based on these values, the authors concluded that the used shape area is acceptable. In Table 7, the authors compare the mean heat consumption per dwelling modelled in this study, including heating, and hot water production, with the average household heat energy consumption given by AQUAWAL and

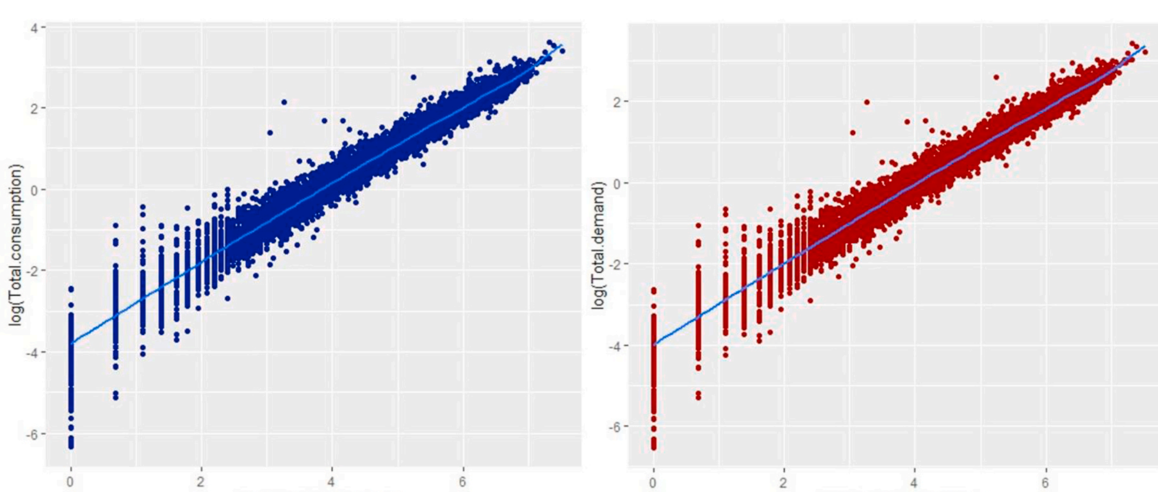

Fig. 13. Residential HC (left) and HD (right) per number of dwellings in an SS.

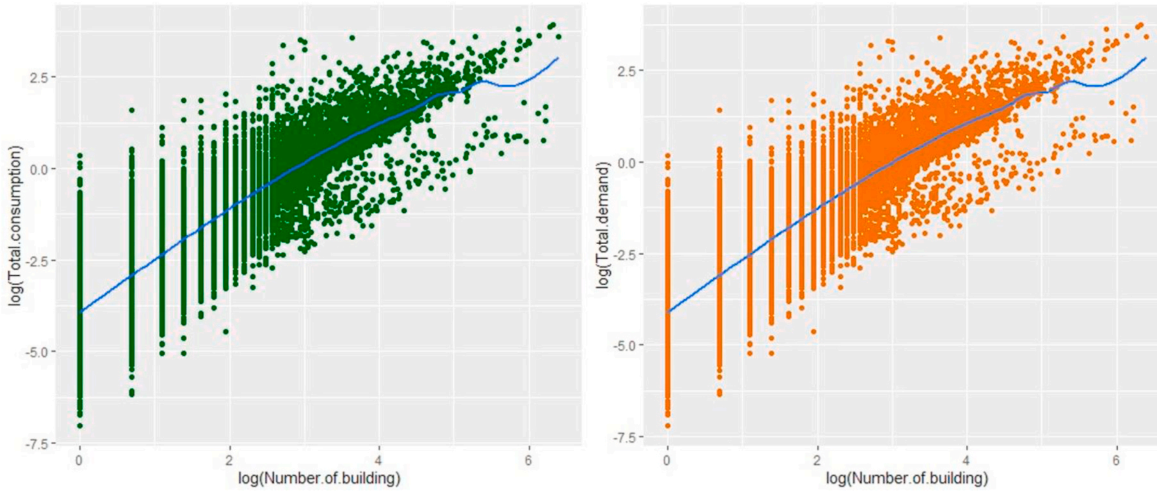

Fig. 14. Tertiary HC (left) and HD (right) per number of buildings in an SS.

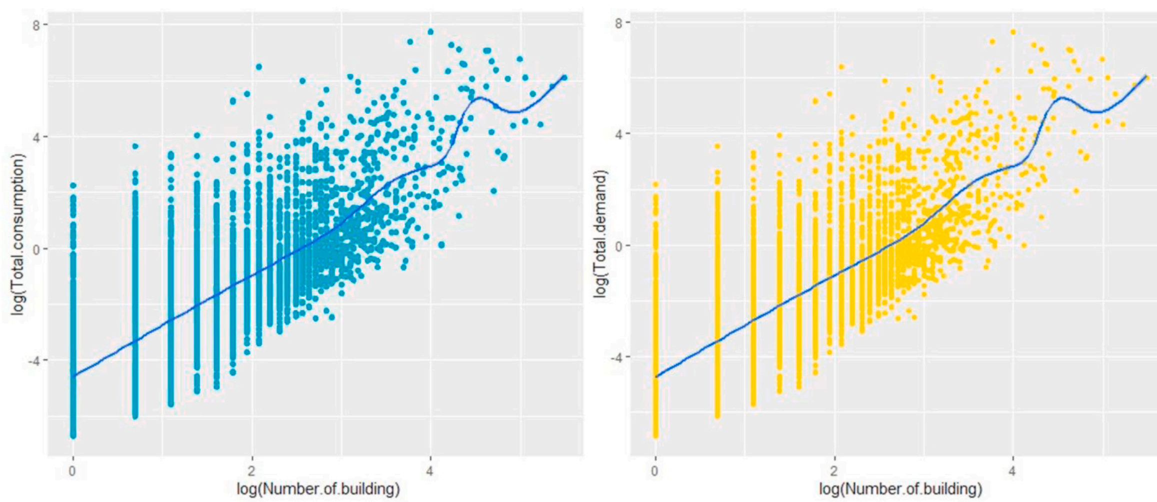

Fig. 15. Industrial HC (left) and HD (right) per number of buildings in an SS.

Table 6
Shape area: ICEDD values versus this study values (cadastre 2010).

	Terraced houses (m^2)	Semi-detached houses (m^2)	Detached houses (m^2)
This study (cadastre 2010)	69.99	77.55	113.4
ICEDD values (2014)	77.4	85.3	97.7
Relative difference	**−10.59%**	**−9.99%**	**13.84%**

Table 7
Comparison of household heat energy consumption, including heating and hot water production.

	This study	AQUAWAL and CEHD (2016)	Relative difference
Average household heating consumption (kWh LHV)	19,244.192	19,338.696	**−0.49%**

CEHD [50], whose results were obtained from a survey of 2119 households distributed throughout the whole territory of Wallonia. Table 7 indicates that the relative difference between the results of this study and those in Ref. [50] is very small (−0.49%) for the average household annual HC, which is an interesting first validation.

Table 8
Comparison of the residential, tertiary, and industrial building stock total HC results with those of regional energy reports.

	This study (2010 cadastral data) total annual regional HC (TWh)	ICEDD (2014) total annual regional HC (TWh)	Relative difference
Residential	29.39	31.1	**−5.82%**
Tertiary	11.9	13.6	**−14.29%**
Industrial	44.6	45.5	**−2.02%**

Table 8 gives a comparison of the total annual HC of the residential, tertiary, and industrial building stock of all of Wallonia calculated in this study and the values given through the regional energy reports [46–48]. This table shows that the calculated total annual HC values due to the residential, tertiary and industrial sectors in Wallonia are lower than the values reported in the regional energy reports [47], with a relative difference of −5.82%, −14.29% and −2.02% respectively. These observed relative differences confirm the validity of the energy models used in this study.

This study is validated on regional scale. The study created the models on 3 scales namely neighbourhood or SS, municipality and urban region scales. The limitations are that in the previous studies, the authors did not find a study based on the neighbourhood or urban region scales in Wallonia to compare to. The created model could help future researchers. Therefore, as the validation on the entire region is acceptable, the authors made the assumption that models on neighbourhood and urban region scales are valid. A more precise validation based on data collection at the neighbourhood scale is an interesting research perspective for further studies.

Additionally, the methods used in this study are applied to a small region compared to the whole world, even with more than 1.7 million buildings of this study. However, the methods can be applied anywhere. This requires having the same kind of data, which are presumably already available in Europe or other developed countries. Nevertheless, this kind of data could be difficult to find in non developed regions where other methods could be more recommended to reproduce the same study.

6. Conclusions and further developments

Throughout literature, some researchers have been shown to estimate only the HC or HD of neighbourhoods and cities, and this is most often only for some types of buildings (residential and tertiary). This study covered the whole Walloon region, including more than 1,700,000 buildings representative of the residential, tertiary, and industrial sectors in Belgium. The methodology can be applied to other cities, regions or even countries throughout the world, but especially in countries of Europe where the generation of energy reports is a usual practice. An awareness of the actual HC or HD is required for consumers, decision makers, and stakeholders, and enables them to take measures related to the best use of energy and development of renewable energies. The energy mapping that is performed on the whole Walloon building stock, at the neighbourhood, municipality, and urban region scales, will assist with the strategic decision making about energy management in Wallonia and in its cities, favouring energy strategies and policies that can reduce HC and HD by considering the heat system performances, building renovations (taking into consideration better insulation), the use of renewable energies and better performing technologies. For example, these results can be used in the design of urban heating networks in Wallonia and for the promotion of renewable energy production.

In this research, the annual HC and HD of the whole Walloon building stock are assessed. The relative difference between the mean building stock HC and HD, at the neighbourhood, municipality, and urban region scales, varies between 16.36 and 16.59% for the residential sector, between 15.78% and 15.81% for the tertiary sector, and between 9.26 and 9.36% for the industrial sector in Wallonia. Therefore, a knowledge of either HC or HD will simplify the prediction of the other. Furthermore, this study shows that the HC and HD for residential buildings is mainly related to the number of buildings, whereas for tertiary and industrial buildings, it is related to the number of buildings and the distribution of the different types and functions of tertiary and industrial buildings. Thus, different SSs with the same number of tertiary and/or industrial buildings present much larger differences in their HC and HD values than is the case in SSs with the same number of residential buildings. Furthermore, for every 1% increase in the number of buildings in an SS, the HC and HD increase by the same rate of about 0.93% for residential sector and of about 1% for tertiary sector. The HC and HD increase by about 2.01% and 2.02% respectively at every 1% increase in industrial buildings in an SS. Dense cities and important industrial areas have higher HC and HD in general, while rural areas have the least consumption patterns. The HD of the Walloon building stock is always lower than its HC at the three studied scales owing to the low percentage of high performance heating systems currently implemented in Wallonia.

The next step of this research involves estimating the average annual electricity and cooling consumption for every building category in Wallonia. These results will be saved with this study results in a database, which will be used for building dynamic modelling based on typical energy synthetic load profiles. Therefore, this model will contribute to the development of a smart energy management system for the built environment in Wallonia, development of future plans, and attain European objectives to reduce energy consumption and increase local renewable energy production.

Data availability

The Wallonia cadastral database used to conduct this study is confidential and cannot be shared. The energy regional reports can be found on: https://energie.wallonie.be/fr/bilans-energetiques-wallons.html?IDC=6288. The Wallonia shapefiles can be accessed via: https://geoportail.wallonie.be/home.html.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110170.

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