A novel residential heating consumption characterization approach at city level from available public data: description and case study

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ABSTRACT

In the current transition towards a net-zero GHG emissions economy, residential building sector is one of the sectors with highest potential for energy efficiency. In order to assist the implementation of energy saving policies, in which the role of local authorities is crucial, the bottom-up engineering approach is the most suitable method for a reliable characterization of the energy consumption in an existing building stock. In the present paper a methodology is proposed to characterize the space heating energy consumption of a residential stock at city level, based on archetype buildings. The methodology is focused on addressing the challenges which often such approach involves. An evidence-based calibration procedure is proposed to address occupant behavioural patterns. Attention is also given to the constructed models results validation process, by comparing them with collected real data. The methodology is applied to the residential building stock of the city of Bilbao, where seventeen typologies of archetype buildings are constructed. The results demonstrate the practicability of accurately reproducing the existing space heating energy consumption of a city-scale residential building stock with available public data sources. The methodology has been conceived to be easily replicable to any city.

Keywords: *Building stock modelling; Archetype buildings; Residential sector; Energy efficiency; Space heating*

1. Introduction

Recently the average concentration of CO_2 in the atmosphere reached 403 ppm, which is a value about 40% higher than in the mid-1800s [1]. Based on scientific evidence, human-induced global warming has already reached 1°C above pre-industrial levels, and is increasing at approximately 0.2ºC per decade [2]. So the trend is clear. Climate change is a serious concern that deserves immediate action.

In this context, the European Union (EU) has taken a role of global leadership in reducing greenhouse gas (GHG) emissions, recognising for a long time climate change as an issue where coherent EU action is needed. The European Council confirmed in February 2011 the EU's objective of reducing GHG emissions by 80-95% by 2050 compared to 1990 [3]. In the European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy [4], the EU ratified its interest in working towards a net-zero GHG emissions economy by mid-century.

In this transition towards a competitive low carbon economy, building sector has been identified as one of the sectors with the highest potential for energy efficiency and GHG emission reduction. Indeed, in the EU the building sector causes 36% of the greenhouse gases (GHG) and is responsible for 40% of the EU's final energy consumption. One reason for these high rates is that about 35% of the EU's buildings are more than 50 years old [5]. Unfortunately, the replacement rate of existing buildings in Europe is low, accounting for approximately 1 – 3% per year [6]. Therefore the influence of new buildings in energy use and emission reduction is limited, which makes the current building stock a main target for energy saving policies.

In order to implement such policies, and determine priority targets that require mobilisation of investment, a reliable characterization of the energy consumption distribution across the building stock is essential. To his effect, several methods have been proposed, which according to two in-depth reviews [7] [8] can be divided into two main approaches: top-down and bottom-up. The top-down approach addresses the building stock energy consumption in an aggregated way, by assessing the impact of different factors, mainly socioeconomic, on it and determining their effect. On the other hand, bottom-up methods are developed from data of disaggregated elements, whose impact on energy consumption of a representative set of buildings is combined, and then extrapolated to the entire building stock. Within bottom-up methods, statistical (SM) and engineering methods (EM) are distinguished, depending on the nature of their input data. SM are based on historical consumption data, while EM rely on building physics definition and simulation [7].

Each method provides results with different applicability. Both top-down and bottom-up SM are capable to consider in their results the behaviour of occupants, which is always unpredictable and varies widely. Nevertheless, these methods do not reach the level of detail which is required to identify the specific underlying building elements with the largest energy efficiency improvement potential.

This information, which is crucial to estimate how different energy saving measures could affect the current energy consumption, can only be provided by bottom-up EM. However, these methods have also some limitations which must be overcome to reach trustworthy building models. Kavgic et al. [8] concluded that one of their main weaknesses is the inherent uncertainty associated with many model inputs, especially those related with the unpredictable nature of occupant behaviour. Furthermore, bottom-up EMs require large amount of input data, both to construct the models and to validate them, and often studies are limited by the absence of publicly available data. Thus, model inputs-related assumptions, which need to be based on author's experience when enough supporting data is not available, could leave the models with too many degrees of freedom and lack of credibility. Therefore, important focus should be given to the reliability of the models.

Bottom-up EMs typically classify an existing building stock into a set of reference or prototypical buildings that constitute the modelled domain, whose results are later extrapolated to the entire stock. There are two main approaches: i) the selection of a sample of real buildings [9], and ii) the development of archetype buildings [10], also called synthetic or virtual buildings. Archetype buildings are theoretical buildings created by a composite of several characteristics found within a category of buildings with similar attributes [11]. Potentially, the use of actual building samples could more faithfully reflect the heterogeneity of an existing building stock than archetype buildings. Nevertheless, a deep consideration of such high degree of diversity could require a large sample of representative buildings. Otherwise, an expert analysis is required to avoid that contextual features of the chosen sample jeopardize the extrapolation of the modelling results. In the end, the choice between these options could be made based on expert enquiries, statistical data availability, etc. [12] [13].

Several authors have developed bottom-up building stock models of multiple European countries [14][15][16][17]. In addition, several efforts such as TABULA and EPISCOPE projects [18] have tried to also contribute to a comprehensive description of existing building stocks at national level. However, working with such large building stocks necessarily limits the representation of their heterogeneity. Indeed, a single country can have multiple climatic zones, which affect residential energy consumption. Traditional constructive solutions can also differ between different regions, which in turn could have been developed in different historical periods and architectural styles. Even significantly unequal socioeconomic factors can exist between territories. All of this makes necessary to analyse a specific building stock energy consumption from a much closer perspective.

On the other hand, in the implementation of energy efficiency policies, local authorities have a crucial role to play. With this in mind, in 2008 the European Commission launched the Covenant of Mayors [19], the mainstream European initiative which involve thousands of local governments voluntarily committed to implement EU climate and energy objectives. In this sense, the development at city level of bottom-up building stock models could adequately describe the heterogeneity of the building stock and serve as a basis to predict the potential energy savings and outline measures for Sustainable Energy and Climate Action Plans.

Recent improvements in geo-referenced data availability and geographical information systems have allowed greater focus on urban contexts [20], encouraging intensive and detailed spatio-temporal assessments. Thus, Urban Building Energy Modelling (UBEM) [21] is a growing field in building energy modelling which accounts for not only the dynamics of individual buildings but also for the inter-building effects and urban microclimate, covering a spatial scale up to an entire city [22]. UBEM is often based on sophisticated methods which can combine buildings physics modelling, statistical inference in GIS environments, CFD programs to account for urban climatic conditions and energy supply simulation modules [23] [24] [25], which involves greater data management requirements and computational resources.

In fact, the development of city-scale databases of the existing building stocks is a crucial step of UBEM to automatically generate energy models of urban buildings. Building data needs for UBEM typically include the GIS footprint, building height, number of stories above ground, number of stories below ground, total floor area, heated floor area, number of dwellings, year of construction, year of refurbishment, building type, heating system type, annual electricity use, annual natural gas use, etc. [26]. Although more and more cities in the world are making their building stock data publicly accessible at their open data portals [27], it is not always available or is difficult to collect.

While extracting geometric building data from GIS databases is a relatively straightforward process [23], considering explicitly, but roughly, each urban building could lead to the generalization of the building models, losing accuracy on the dynamics of the building energy demand [28].

On the other hand, the consideration of the spatial (geographical) dimension on energy analyses is crucial for the optimization of energy supply systems and the assessment of related strategies as peak shaving, load shifting, etc. [29]. Nevertheless, demand-side analyses evaluating overall annual energy savings potential over an existing building stock does not necessarily require it.

To this effect, a new methodological approach has been developed by the authors to characterize an existing building stock at city level, aiming to set a comprehensive basis for further energy efficiency investment mobilizations assessments. The proposed methodology lies on a bottom-up engineering approach, which permits to construct and assess archetype building models that represent an entire building stock. In summary, the proposed methodology serves to (a) classify an existing city-scale residential building stock into a set of representative archetype buildings and, (b) reliably characterize their space heating energy consumption. The aim is not to focus on the geographical dimension perspective rather than to faithfully account for the dynamics of archetype buildings models, reaching a successful trade-off between the required detail of input data and desired precision.

Special care has been given to its applicability to multiple cities, as models become actually useful only if they are suitable for being easily replicable. The approach has been conceived to be applicable to any city, provided a primary understanding of the constructive evolution in the analyzed geographical context. Although the implementation described herein is tailored to the Spanish context, similar data sources can be found in many other countries. The kind of data that the procedure involves is often publicly available. Real information availability limitations have also been considered, which can sometimes make the implementation of the methodology more arduous. Accordingly, the methodology also contributes to the management of data collection related difficulties by proposing easy ways of gathering further information.

In addition to addressing the problem of data availability, the methodology also focuses on the other limitations of bottom-up EM. An empirical method is proposed to address the actual occupant behavior and calibrate the building models. Due to the capability of statistical methods to incorporate the occupant's behavior impact, the methodology also incorporates the application of a multiple linear regression for the process of validation of the models.

In the present paper, the aforementioned methodology is applied to the residential building stock of Bilbao, by constructing a comprehensive building stock aggregation model. It demonstrates the practicability of characterizing the energy consumption of a city-scale residential building stock with available data sources. This way, a trustworthy basis can be formed for a subsequent assessment of the impact of different energy saving policies. The models lay the groundwork for the assessment of different energy conservation measures' effect, representing a useful decision-making tool to identify cost-optimal sets of measures per building type and establish the appropriate energy efficiency strategies. These aspects are currently being addressed in further work.

The paper is structured as follows. Section 2 summarizes the methodological approach followed for this study, divided in three different phases. Section 3 describes the implementation of the procedure to the case study of Bilbao. Section 4 provides and analyzes the results. The paper ends with a final Section 5 which outlines most important conclusions.

2. Methodological Framework

A comprehensive description of the methodology is provided by [30]. The main guidelines are summarized herein to enable the understanding of the case study presented in this paper, which enables to further elaborate the approach presented in this section. The conceptual scheme of the methodology is presented in Fig. 1. The methodology is divided into three main phases: Building Stock Segmentation, Building Stock Modelling and Model Validation.

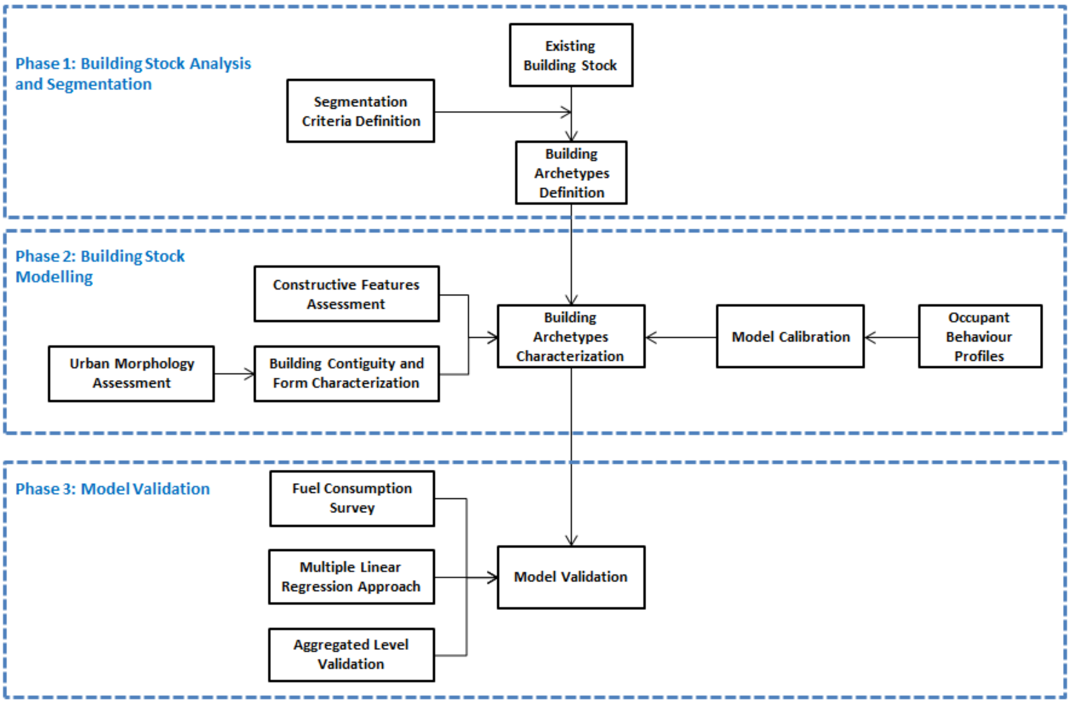


Fig. 1. Overall structure of the applied bottom-up methodological approach

Phase 1 aims to determine the archetype buildings to be modelled and simulated. The archetype buildings are obtained through the combination of three segmentation criteria:

a) building construction period (related to energy regulation)

b) building height, in terms of the number of storeys over ground

c) dwelling useful area

The heating system type is not introduced as a segmentation parameter, as it is preferable to perform energy performance simulations in terms of energy demands, which could be later converted to consumption terms by applying the corresponding mean seasonal efficiencies. Thus the definition of excessive segmentation criteria is avoided, permitting a deeper classification of the building stock based on the proposed three criteria.

By combining the segmentation criteria, a cluster map is generated, which permits to identify the most representative dwelling groups.

To carry out the analysis, the main data source is the Population and Housing Census from the National Statistics Institute [31]. It should be noted that, as usually happens with this type of sources, most of its data refers to individual dwellings, not entire buildings, while the archetypes to be constructed and simulated are entire buildings, and not individual dwellings. Therefore, different homogeneous group representativeness must be first assessed in terms of individual dwellings, and afterwards a relation must be set between those representative dwellings and the related archetype buildings, which are constituted by the formers.

In Phase 2, each archetype building is defined by its physical and technical parameters, as well as other data inputs required for the model construction. The construction of archetype building models often requires large amount of data as input, but there are certain building features which have higher influence than others on its thermal behaviour. The following three main factors have been identified as the most significant affecting the thermal performance of a building, which deserve special attention: i) building facade composition, ii) urban form where a building is located, which affects the building form and contiguity and, iii) occupant behaviour profiles. In addition, a useful empirical calibration method is proposed.

Finally, Phase 3 explores innovative methods to obtain real dwelling consumption data, in order to compare them with the archetype buildings simulations results and thus validate the models. An original survey is suggested to easily collect actual fuel consumption information from individual inhabited dwellings. In addition, a bottom-up statistical regression approach is proposed to obtain the heating demand of different dwelling typologies. Several studies exist which utilize postal code level energy consumption data in a regression [32][33]. Instead, this methodology adapts to the available data sources and alternatively applies the regression approach at regional scale, by using aggregated municipal-level domestic consumption values.

3. Methodology Application: Case Study

In order to show the application of the proposed approach, the developed methodology is applied to the residential building stock of Bilbao. Located in the province of Biscay, Basque Country region, Bilbao is the largest city in northern Spain, with a population of approximately 350,000 inhabitants. The urban area, located in a river valley, is surrounded by two mountain ranges on the northern and southern sides. The municipality is divided into eight districts, which are indicated in Fig. 2.

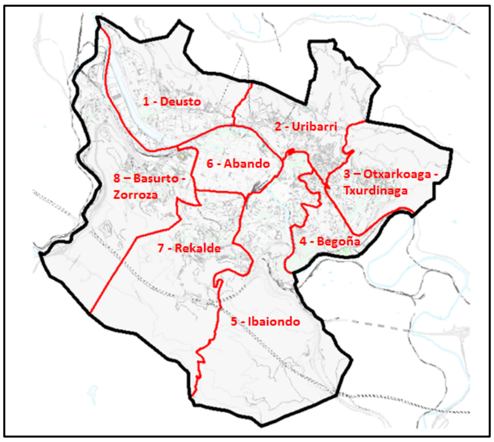


Fig. 2. Spatial distribution of the districts of Bilbao

Heating energy used in the residential stock is mainly provided from natural gas (approx. 50%). Apart from natural gas, the most used energy carriers for space heating are electricity (30%) and oil derivatives (20%, including gasoil and LPG). Gasoil is mainly used in communal heating systems, while natural gas and electricity are mostly used in dwelling's individual systems. The rest of fuels, such as wood or coal, are verified negligible.

3.1. Building Stock Segmentation

The present analysis focuses on main dwellings, i.e. dwellings which are used all year round, acting as usual home, and excludes secondary (occasionally used) and empty dwellings. Main dwellings represent more than the 90% of Bilbao's residential stock [31], and account for a stock of 147,655 houses, which is the target of the study.

Fig. 3 shows the distribution of Bilbao's main dwellings according to their construction period. Almost the half of the existing building stock was constructed within a timeframe of only 20 years, between 1960 and 1980, during the so-called *Developmentalism* period. In addition, approximately the 80% of the houses were constructed before the application of the Spanish NBE-CT-79 regulation [34], which came into force in 1979 and with which the utilization of building thermal insulation commenced. On the other hand, the number of houses that comply with the subsequent (more stringent from the energy point of view) CTE regulation [35], in force since 2006, is very low.

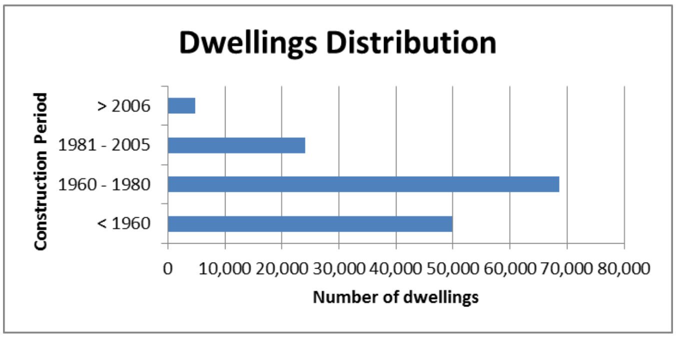


Fig. 3. Distribution of Bilbao's main dwellings according to their construction period.

There is literature which, when classifying an existing building stock, differentiates between single-family houses and multi-family houses [36][37]. Nevertheless, Bilbao has very few single-family houses (probably due to the complicated topographic nature and historical land scarcity), which are less than 1% of the entire building stock [38], and therefore this segmentation criterion is excluded for building classification.

By combining the three segmentation criteria proposed in the methodology, Table 1 is generated, which permits to identify the most representative groups of dwellings.

Table 1. Bilbao's main dwelling cluster map

		Dwelling's floor area			
Construction Period	**Storeys over ground (incl. ground floor)**	**< 60 m²**	**60 - 90 m²**	**90 - 120 m²**	**> 120 m²**
< 1960	**< 3**	0.47%	0.09%	0.05%	0.06%
	4 – 6	5.85% RD1	6.37% RD2	1.32%	0.23%
	7 - 9	3.72% RD3	8.38% RD4	3.42% RD5	2.40% RD6
	> 10	0.22%	0.68%	0.28%	0.06%
1960 – 1980	**< 3**	0.10%	0.00%	0.00%	0.00%
	4 - 6	4.79% RD7	5.56% RD8	0.92%	0.00%
	7 - 9	5.10% RD9	12.93% RD10	2.82% RD11	0.83%
	> 10	2.90% RD12	9.13% RD13	3.59% RD14	0.81%
1981 – 2005	**< 3**	0.00%	0.06%	0.00%	0.00%
	4 - 6	0.65%	3.99% RD15	0.47%	0.00%
	7 - 9	1.10%	4.93% RD16	1.52%	0.11%
	> 10	0.00%	2.01% RD17	0.53%	0.00%
> 2006	**< 3**	0.00%	0.00%	0.00%	0.00%
	4 - 6	0.13%	0.80%	0.00%	0.00%
	7 - 9	0.13%	0.36%	0.08%	0.00%
	> 10	0.00%	0.05%	0.00%	0.00%

Only dwelling types with a share greater than 2% are selected, resulting in the 17 representative dwellings shown in Table 1, which are named from "RD 1" to "RD 17". All together, they represent the 87.90% of the total residential stock of Bilbao, which is considered representative enough.

The archetypes to be modelled and simulated are entire buildings, not individual dwellings, and therefore a relation is established to transform each representative dwelling into an archetype building. To do so, the following approach is applied:

- Every dwelling contained in each archetype building is equal and corresponds to one of the defined representative dwellings.
- Every storey of the archetype building is equal: it has the same number of dwellings, and therefore has the same plot area.

So the last aspect to be defined is the total amount of dwellings per building type, and its distribution along the building storeys. The dwellings quantity of each archetype building is determined aiming to be as nearest as possible from the average values obtained from [38]. At the same time, archetype's number of storeys is also defined, adjusting it within the range of the corresponding building type. It is assumed that there is no dwelling in the ground floor. Table 2 shows the obtained dwellings distribution per archetype building.

Table 2. Dwellings distribution per archetype building

Construction Period	Storeys over ground (including ground floor)	Storeys over ground (excluding ground floor)	Representative dwellings per storey	Total dwellings obtained per archetype building	Average dwellings per building - [38]
Before 1960	**4 - 6 floors**	4	2	8	8.40
	7 - 9 floors	7	2	14	13.92
1960 - 1980	**4 - 6 floors**	4	3	12	13.07
	7 - 9 floors	6	3	18	18.17
	> 10 floors	12	3	36	37.92
1981 – 2005	**4 - 6 floors**	4	3	12	12.46
	7 - 9 floors	6	3	18	18.24
	> 10 floors	13	3	39	39.06

3.2. Building Stock Modelling

The following main input data categories are presented herein: i) geometrical characteristics, ii) construction characteristics and, iii) occupant behaviour profiles.

3.2.1. Geometrical characteristics

The main aim of this section is to determine the geometrical properties of the archetype buildings i.e. their shape and contiguity. To this effect, Bilbao's urban morphology is analysed.

Historical urban development

Initially, Bilbao's historical urban development is assessed to better understand and classify the different urban fabric zones of the city. The evolution of the city has resulted in clearly differentiated urban morphologies, which can be identified and associated with the different neighbourhoods.

On the one hand, in Bilbao a relation exists between the predominant urban morphology of an area and its topography. Thus, the flat sites of the city centre, in the middle of the valley and around the river, show a solid block urban fabric, typical of 19^{th} century Ensanche (city expansion in Spanish, which grew up in orthogonal layout beyond the existing Old Town). In turn, in the hillsides of the periphery the linear block is predominant, which better accommodates to the difficult topography.

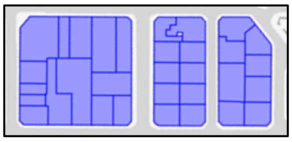
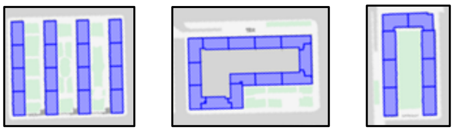
On the other hand, a relation between the construction period and the urban block types is also noted. Due to the historical development of the city, whose demographic and construction boom coincided with the prevailing rationalist style, the linear block is predominant in the peripheral neighbourhoods created from the 60s, during the *Developmentalism* period. In such areas, the building width, i.e. the structural span between facades, is often between 8 – 10 meters long. Such narrowness, influenced by the hygienic ideal of the rationalism, allowed for crossed ventilation in the whole dwelling.

On the contrary, the facade length of buildings located within solid block urban fabric can change significantly. In the Old Town, where the oldest buildings are located (from 19th century and before), the facades are in general short, with a typical length of approximately 8 meters. In contrast, late 19th century buildings in the Ensanche, which currently constitute the city centre, show usual facade lengths between 16 – 24 meters.

Considered Urban Blocks

Based on the previous assessment, Table 3 shows the three urban form typologies considered in the present analysis: solid block, linear block and detached buildings. A building contiguity index, i.e. the envelope's portions in contact with other buildings or the environment, is allocated to each urban form.

Table 3. Urban form types considered for urban form allocation to archetype buildings

Urban Form	**Characteristics**	**Examples**	**Allocated Contiguity Index**
Solid Block	Typical of the 19th century Ensanche. The building is integrated within a building compact layout, with a unique facade facing the street.		3 out of 4 envelope sides in contact with other buildings
Linear Block	Typical rationalist block framed within the hygienic ideal of light, ventilation and sunlight, while addressing the lack of housing through simple buildings serialization.		2 out of 4 envelope sides in contact with other buildings
Detached Buildings	Buildings with no envelope's portion in contact with other buildings		No envelope's portion in contact with other buildings

In Bilbao, the influence of solar irradiation is less severe than in other Spanish cities. Based on [39] measured solar irradiation data, obtained during the 1983 – 2005 period, Bilbao is the Spanish capital city with the lowest solar irradiance, with a daily average of 3.54 kWh/m^2. In addition, its particular topography, being located within a valley and surrounded by hills, makes it less exposed to the solar rays.

Therefore, the modelling of external shading created by the environment around a building is excluded from the analysis, which enables to include different urban layouts such as closed or open blocks with internal courtyards and linear blocks into a unique urban form typology, as it can be seen in Table 3. For the present analysis, all these urban layouts are considered equivalent in terms of their buildings shape and contiguity.

On the other hand, the small internal courtyards ("chimney courtyards") that might exist within a solid block layout are excluded from the assessment.

Shape and Contiguity Allocation to Archetype Buildings

Firstly, the geographic distribution of each representative dwelling is analysed, with the aim of identifying the city districts where a specific representative dwelling is concentrated the most (to this effect, "archetype building" term and its corresponding "representative dwelling" can be interchangeably used). It shall be noted that, at this point, having defined building height and dwelling useful area as segmentation criteria contributes to a clearer concentration of archetypes in specific districts. As an example, Table 4 indicates the district distribution that corresponds to each RD according to [31], in which the coloured cells show the districts where each RD is mainly concentrated.

Table 4. RD 7 representative dwelling distribution by district

	City Districts								
Representative Dwelling type	**Deusto**	**Uribarri**	**Otxarkoaga Txurdina**	**Begoña**	**Ibaiondo**	**Abando**	**Rekalde**	**Basurto Zorroz**	**Total analysed dwelling**
RD 1	11.90%	16.29%		14.80%	23.65%		20.91%	12.45%	75.65%
RD 2	33.93%	9.74%		6.89%	29.96%		13.33%	6.14%	77.23%
RD 3	13.96%	6.76%		1.80%	24.55%	26.35%	17.45%	9.12%	82.32%
RD 4	5.76%	4.55%		2.07%	21.63%	40.27%	13.85%	11.87%	87.62%
RD 5					9.45%	90.55%			90.55%
RD 6					7.37%	92.63%			92.63%
RD 7	9.98%	24.94%	25.02%	14.80%	4.42%		17.99%	2.86%	82.75%
RD 8	21.66%	30.23%	1.96%	12.21%	6.32%		20.13%	7.49%	84.23%
RD 9	10.21%	10.38%	14.91%	19.69%	17.55%	4.70%	15.24%	7.33%	67.38%
RD 10	16.46%	8.71%	1.36%	27.27%	14.66%	5.18%	14.33%	12.02%	72.73%
RD 11	25.35%	10.38%		17.96%	2.99%	25.95%	2.79%	14.57%	83.83%
RD 12	13.29%	9.93%	14.90%	47.11%	5.37%	3.49%	3.22%	2.68%	75.30%
RD 13	20.42%	14.66%	10.49%	23.47%	12.54%	2.88%	9.53%	6.01%	71.09%
RD 14	17.12%	20.02%	16.58%	7.10%	6.57%	10.87%	16.36%	5.38%	70.08%
RD 15	7.79%		47.21%	4.88%	17.33%		3.84%	18.95%	83.49%
RD 16	16.08%	2.59%	4.77%	6.95%	32.78%	4.05%	16.29%	16.49%	81.64%
RD 17	4.91%		31.01%	4.65%	24.81%		28.94%	5.68%	84.75%

Aging maps are built for each neighbourhood or city zone, for which the public data provided by the cadastre is used regarding year of construction of the buildings. Two examples of the constructed building's aging maps are shown in Fig. 4, which correspond to Otxarkoaga - Txurdinaga and Uribarri districts.

Fig. 4. Examples of maps with construction period of buildings

Afterward, focusing on the identified main districts for every archetype building, the archetype - related district's predominant urban form is assessed, by using the building's aging maps. As an example, RD 7 related urban morphology is assessed in Table 5.

Table 5. RD 7 related urban morphology assessment, district by district

	Construction Period	**Dwelling features**	**City District**	**Share over building typology (%)**	**Predominant Urban Form Typology**
RD 7	**1960 - 1980**	**4 - 6 floors & < 60 m^2**	**Otxarkoaga - Txurdinaga**	25.02%	Linear block
			Uribarri	24.94%	Linear block
			Rekalde	17.99%	Linear block
			Begoña	14.08%	No predominant typology: linear blocks and solid blocks

Finally, from the identification of the predominant urban form in each district, it is needed to converge to a unique urban form typology per archetype building, which applies to the whole city – scale. In the majority of archetype building cases, a predominant urban form typology tends to stand out, and therefore the outcome is straightforward. Following with previous example, a linear block form is allocated to the RD 7 (and therefore to the corresponding Arch. 7). Building layout dimensions, i.e. façade length and building width, are also analysed within the presented approach.

Regarding the orientation of Bilbao's urban morphology, it can be verified that, in general, it does not follow a north-south and east-west pattern. The solid block morphology of the city centre is in general north-east oriented. On the other hand, the orientation of the linear blocks of the periphery is conditioned by its adaptation to the topography, being basically south-west or south-east. Depending on the area, this orientation could be more or less pronounced, and in some cases, the morphology tends to be slightly random.

Table 6 summarizes the considered building layout dimensions and orientation for each archetype building model. A 20 m^2 stairwell layout area is considered for all the buildings. It also summarizes the number of storeys and the amount of dwellings per storey, according to the outcomes of Table 2.

Table 6. Allocation of building layout dimensions and orientation to archetype buildings

	Allocated Urban Block Typology	**Storeys (excl. ground)**	**Dwellings per storey**	**Dwelling floor area (m^2)**	**Dwelling area per storey (m^2)**	**Total area per storey (m^2)**	**Facade length (m)**	**Building width (m)**	**Facade orientation**
Arch. 1	Linear block	4	2	60	120	140	14	10	south-west
Arch. 2	Linear block	4	2	75	150	170	17	10	south-west
Arch. 3	Solid block	7	2	60	120	140	8	17.5	west
Arch. 4	Solid block	7	2	75	150	170	14	12.1	west
Arch. 5	Solid block	7	2	105	210	230	17	13.5	west
Arch. 6	Solid block	7	2	120	240	260	20	13.0	west
Arch. 7	Linear block	4	3	60	180	200	20	10	south-west
Arch. 8	Linear block	4	3	75	225	245	24.5	10	south-west
Arch. 9	Linear block	6	3	60	180	200	9.1	22	south-west
Arch. 10	Linear block	6	3	75	225	245	11.1	22	south-west
Arch. 11	Solid block	6	3	105	315	335	17	19.7	west
Arch. 12	Linear block	12	3	60	180	200	20	10	south-west
Arch. 13	Linear block	12	3	75	225	245	9.4	26	south-west
Arch. 14	Detached building	12	3	105	315	335	18.3	18.3	south
Arch. 15	Linear block	4	3	75	225	245	20.4	12	south-west
Arch. 16	Linear block	6	3	75	225	245	13.6	18.1	south-west
Arch. 17	Linear block	13	3	75	225	245	18	13.6	south-west

3.2.2. Construction characteristics

This section aims to analyse the most characteristic constructive features of the Basque Country, where the historical development of the facades is summarized below.

The facades of antique buildings were constructed by wide, load-bearing walls, as they were a structural part of the building. They experienced little change until the end of 19th century, and stone walls were used until the brick facades replaced them as usual constructive solution [40].

The introduction, from 1910 on, of the reinforced concrete from England and France started to change the way of constructing [41]. For the first time, the building envelope could be released from its bearing role, leading to less material use and weight relieve. The main way of achieving it was the introduction of the double layer facades with an intermediate air chamber. However, the new approach was rapidly disrupted by the Civil War and the corresponding post-war period, until approximately the 60's, coinciding with the highest demographic growth that Bilbao has ever experienced.

[42] identifies usual facade constructive typologies of the Basque building stock, which can be summarized as follows:

- 19th century or before: heavy masonry or adobe walls.
- First half of the 20th century: single-layer, 1 – 1.5 ft. width, brick facades.
- 1960 – 1980, *Developmentalism* period: double layer facades with an intermediate air chamber of 5 – 10 cm, internal layer of hollow bricks and a total width of 23 – 26 cm. Thermal transmittance could vary between 1.2 and 1.6 W/m^2K.

Constructive typologies referred to *Developmentalism* period are completely aligned with [43].

The next significant change in the facade's composition was the addition of an insulation layer, accommodated into the double layer solution, which was generalized from the 80's on, after the energy crisis and the subsequent Spanish NBE-CT-79 regulation in 1979. The thickness of the facade's insulation was calculated based on NBE-CT-79 requirements, in order the building not to exceed a maximum thermal transmittance value called K_G global coefficient, which in turn depended on the building's shape factor.

On the other hand, the assessment of Building Assessment Reports can also provide information about the real distribution of described constructive solutions within a specific location. In Spain, the Building Assessment Report (IEE hereunder, based on Spanish acronym), after the corresponding building analysis, demonstrates the status of the building in relation with three aspects: its conservation condition, its compliance with the universal accessibility regulation and its energy efficiency. IEE regulation relies on national legislation, with the 8/2013 law [44] as the reference regulation until it was largely derogated by the RD 7/2015 [45], but it is the regional and municipal regulation which further deploys it, so slight differences could arise between the regions. Due to the kind of information that the IEE contains, which includes characteristics of the building's facades and roofs, it can be an important data source regarding building constructive solutions.

Totally, information about 115 buildings is analysed, all of them constructed before 1980. Due to the fundamental purpose of the IEE, i.e. the building conservation assessment, it is unusual to find it for newer constructions. It is verified that the current way of fulfilling the IEE reports, which does not obviously consider their potential usage as constructive solutions database, does not allow to take full advantage of them. Usually, the number of facade sheets is missing. Except for rare cases, no air chamber or double-sheet is explicitly mentioned. If this information were more clearly shown, interesting information could be provided, which could help on buildings thermal performance assessments, without greater onsite effort.

Nevertheless, analysed IEEs have still provided information about the roof type distribution in Bilbao. The roof types distinguished by the IEE are the sloping roof and the flat roof, while this last is further divided into crossable and non – crossable roofs. Information about materials is also given. In Bilbao, the sloping roof accounts for more than 90% of the buildings, with an unquestionable predominance of the tile as roof cover. The roof support is usually made of concrete, except for the most antique buildings in which wood predominates. The collected information is introduced into the archetype buildings models.

<u>Allocation of Facade type</u>

The following criteria have been followed for facade type allocation to the archetype buildings:

- Facade 1, which is a structural facade constituted by heavy limestone masonry, is allocated to the oldest archetype building. In this case, it corresponds with Archetype 3, which is mainly located in the Old Town and surrounding areas. The other single-layer facade, formed by 1 ft. brick and defined as Facade 2, is assigned to the remaining archetype buildings corresponding to the construction period before 1960.
- Double brick wall without thermal insulation, Facade 3 and Facade 4, are allocated to the buildings constructed during the *Developmentalism* period.
- Facade 5, Facade 6 and Facade 7, which are the insulated double-layer facades, are introduced in post-1981 archetype buildings. Their insulation thickness is determined through an iterative approach performed until the regulatory KG global coefficient is complied.

Table 7 summarizes modelled facades.

Table 7. Facade type allocation to each archetype building

	Construction Period	Before 1960						1960 - 1980								1981 - 2005		
	Archetype	**n. 1**	**n. 2**	**n. 3**	**n. 4**	**n. 5**	**n. 6**	**n. 7**	**n. 8**	**n. 9**	**n.10**	**n.11**	**n.12**	**n.13**	**n.14**	**n.15**	**n.16**	**n.17**
	U (W/m^2K)																	
Facade 1	2.04																	
Facade 2	1.77																	
Facade 3	1.26																	
Facade 4	1.38																	
Facade 5	0.63																	
Facade 6	0.93																	
Facade 7	0.75																	

3.2.3. Occupant Behaviour - Calibration

The main aim of this section is to define the profiles of dwelling's occupancy, space heating demand and internal gains, which must be introduced in the archetype building models. Instead of precisely describing specific occupant behaviours, the present approach seeks to assess general behaviours in Bilbao. To this effect, an empirical calibration method is used, based on real consumption data from residential buildings with communal heating systems, aiming to increase the reliability of introduced occupational behavioural profiles.

In this type of buildings with centralized heating systems, the 2012/27/EU directive [46] demanded the installation of metering devices on each individual dwelling from the 1st January 2017, with the aim each household to be invoiced for its specific energy consumption. The prevision of the transposition of the directive made many communities install the metering devices without even waiting for the Spanish law publication, which was delayed. The present approach aims to benefit from that circumstance, which implies that gathering only few communal invoices enables the collection of numerous dwelling's data, which even discriminates between Domestic Hot Water (DHW) and space heating consumption. Thus, the methodology proposes to collect the data from several post-1981 buildings, when the installation of communal systems became more usual in Spain. As NBE-CT-79 regulation was at that time in force, which imposed the compliance of specific transmittances in buildings, the envelope U-values can be more reliably determined.

Buildings whose communal consumption data is gathered are constituted by a great number of dwellings, which may be inhabited by all sorts of sociodemographic groups. The proposed method mainly relies on the assumption that ensemble, the contribution of each group in terms of buildings space heating consumption can be considered representative of what takes place at entire building stock level.

In order to define different aspirant profiles, the following assumptions are made with regard to the relation between the three profiles, i.e. occupancy, space heating demand and internal gains.

- Internal gains from lighting and equipment take place only during active occupancy period of the dwelling.
- It is assumed that the space heating set point temperature always applies during active occupancy period of the dwelling, while during unoccupied time periods the setback heating temperature operates.

In addition, an important factor that may significantly affect the definition of above-mentioned profiles is the employment status of the dwelling occupants. It can be verified that, for every archetype building, a majority of dwellings exist with all of its members working [31]. Therefore, a reference occupancy schedule is defined for working days, corresponding to a usual working timetable in Spain. It is shown in Fig. 5. Thus, the aim is to capture the general trends of behaviour, as an analysis evaluating overall annual energy savings most likely does not require a sophisticated stochastic occupant behavioural model [29].

		Hours																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Occupancy																									
Equipment & Lighting (over a max. of 8.8 W/m^2								10%	10%						30%	30%					50%	100%	100%	100%	
Space Heating Set Point (ºC)	Sc. A)							19	19						19	19					19	19	19	19	
	Sc. B)							20	20						20	20					20	20	20	20	
	Sc. C)							21	21						21	21					21	21	21	21	
	Sc. D)	19	19	19	19	19	19	19	19						19	19					19	19	19	19	19
	Sc. E)	20	20	20	20	20	20	20	20						20	20					20	20	20	20	20
	Sc. F)	21	21	21	21	21	21	21	21						21	21					21	21	21	21	21

Fig. 5. Working days occupancy, internal gains and space heating demand profiles

According to the profiles of Fig. 5, six different space heating scenarios are defined (A, B, C, D, E, F), classified according to their heating set point temperature (19 ºC, 20 ºC, 21 ºC), which is considered one of the most influential parameters in building energy models, and whether they consider that such set point temperature applies or not during night periods.

The determination of the number of real buildings to be used for calibration would depend on the size and specific heterogeneity of the analysed city. In this study, four real post-1981 buildings with communal heating systems, shown in Fig. 6, are chosen aiming to cover different orientations and locations within the urban morphology of the city. In total, they constitute 107 dwellings, which is considered representative for a middle-size city as Bilbao. Their annual heating energy consumptions data is collected through annual communal bills. The buildings are visited and modelled in Design Builder v.4.7.0.027 [47] with their actual orientation, form, size, contiguity and internal courtyards. External elements which may imply external shading are also modelled, as well as the basement floors.

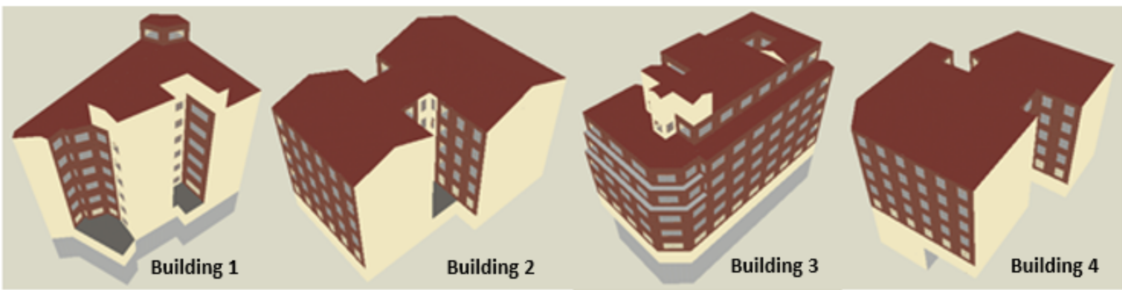


Fig. 6. Modelled real buildings

Infiltration rate could also be introduced as a third calibration parameter in the calibration process. Nevertheless, the present implementation benefits from the availability of several Blower Door Tests results, which have been recently performed by the University of the Basque Country in post-1981 dwellings. Totally, 12 dwellings were analysed, resulting in an annual infiltration rate (at 4 Pa) of 0.57 (with a variance of 0.02), which is introduced in the four buildings models.

The six scenarios are modelled and simulated in each of the four buildings. The set of obtained space heating consumption values is compared to the building's real annual consumption value, averaged for different years with the aim of making the consumption value independent from any specific climatic condition's severity. The space heating profile that more faithfully approximates to the reality is selected.

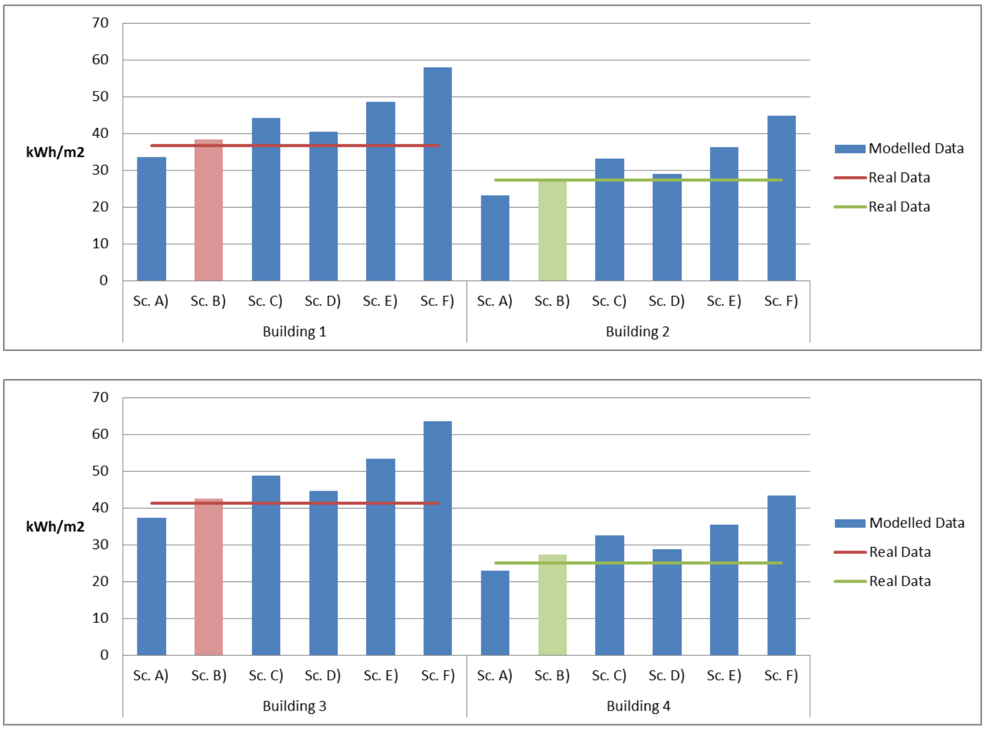


Fig. 7. Calibration results in terms of annual space heating energy demand

Fig. 7 shows that the results vary significantly depending on the scenario, i.e. depending on the modelled occupant behaviour. In all cases, the scenario B provides an annual space heating demand which fits well the real data. Therefore, Scenario B is introduced within the modelled archetype buildings, which corresponds to a set point temperature of 20 ºC and no heating set point during night periods. The number of occupants is modelled according to the average values provided by the INE for each representative dwelling [31].

3.3. Model Validation Data Attainment

3.3.1. Literature

An initial validation is proposed by using information from literature. Concerning the distribution of the residential energy consumption by different end-uses, the SECH-SPAHOUSEC project [48] is probably the most extensive study carried out in Spain. In dwellings located in the Atlantic climatic zone, where the city of Bilbao is located, the mean energy consumption is 10,331 kWh per year and the space heating end-use implies the 40.1% of it. Considering the mean floor area of 93.7 m^2 that the study defines for Atlantic zone dwellings, a mean annual space heating consumption of 44 kWh/m^2 is obtained.

Concerning the domestic energy consumption distribution in the Basque Country, [49] provides, based on SECH-SPAHOUSEC data, a slightly adjusted fuel consumption structure for the Basque Country, which is shown in Table 8.

Table 8. Fuel consumption distribution in the Basque Country [49]

Basque Country, Coastal Climatic Zone	
	Fuels consumption distribution (%)
Space Heating	59%
DHW	30%
Cooking	11%

3.3.2. Fuel Consumption Survey

An excellent method for the validation of modelled building's heating demand is to gather actual energy consumption data from inhabited houses of Bilbao, which is contained in energy bills. To this effect, a survey is conducted, which aims to collect actual fuel consumption information from individual inhabited dwellings, by asking the survey respondents about their annual fuel use.

Nevertheless, the complexity that this type of survey entails is not trivial. Dwelling billing data is often considered private information, without an obvious disposition to share it. In addition, answering the survey implies the necessity of looking for a certain amount of bills which may cover at least one-year period, and summing the different monthly-invoiced consumptions, which is obviously tedious. An innovative approach is proposed, aiming to overcome those problems and facilitate data collection:

- It is only requested a picture of the graph that is included in any bill, which contains historical information about the fuel consumption of the last two years. The graph shows the different months in x-axis and the corresponding fuel consumption in kWh as y-axis. Thus, required response times are significantly reduced, without substantially affecting the quality of the collected data.
- In addition to the mentioned graph, three supplementary data are requested, which are easy to answer: dwelling address, number of inhabitants and kitchen type (electrical or fuel-fired). Dwelling address serves to obtain dwelling's area from the cadastre.

In total, 65 dwellings domestic fuel consumption data are collected, mainly for Bilbao but also from municipalities of its metropolitan area. The error of using this sample is estimated using the Eq. 1 [50]. Provided Biscay's building stock volume, this sample gives a margin of error of 5 kWh/m^2, with an associated 90% confidence interval.

$$n = \frac{N \cdot z^2 \cdot \sigma^2}{(N-1) \cdot e^2 + z^2 \cdot \sigma^2} \qquad \text{Eq. 1}$$

Where n is the survey's size, N is the size of the population (building stock volume), Z is the accepted deviation from the mean value to achieve the assumed confidence level (given by the gaussian distribution form), e is the error margin and σ^2 is the expected variance of the population.

Two different approaches are applied to analyse collected data. The first method, shown in Fig. 8, is based on DHW consumption estimation using summer period fuel consumption, and relies on the assumptions that during summer there is no space heating-related fuel use, and that DHW consumption is not likely to significantly vary with seasons. The second approach consists on the application of the average fuel use distribution (%) by domestic end-use, previously shown in Table 8.

Comparing the obtained normalized annual heating consumption values (kWh/m^2), a fair consistency is verified between both approaches. Fig. 9 shows how the obtained values from each approach are very coherent, considering the underlying variability that actually exists behind average fuel distribution shares of Table 8. Nevertheless, it seems that in the cases of higher space heating demands, the DHW estimation approach underestimates the consumption referred to space heating in comparison with the end-use shares of Table 8.

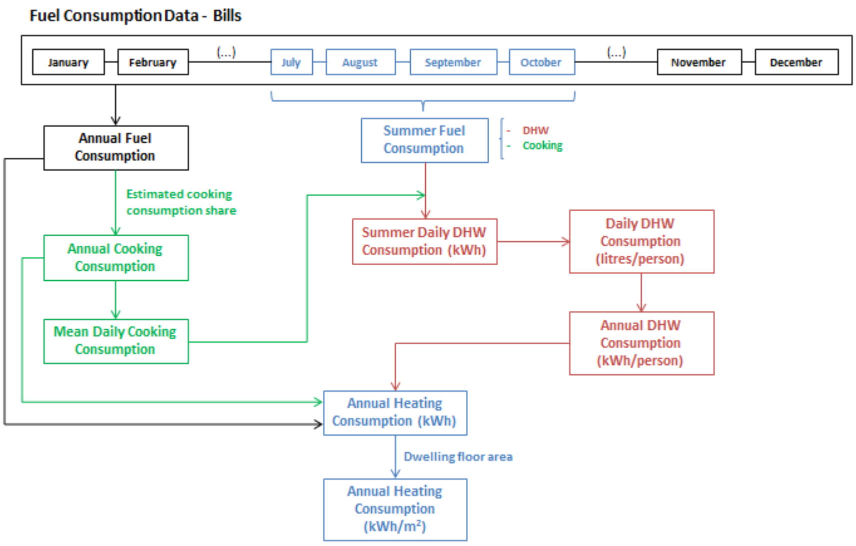


Fig. 8. Data analysis approach based on estimated DHW summer consumption

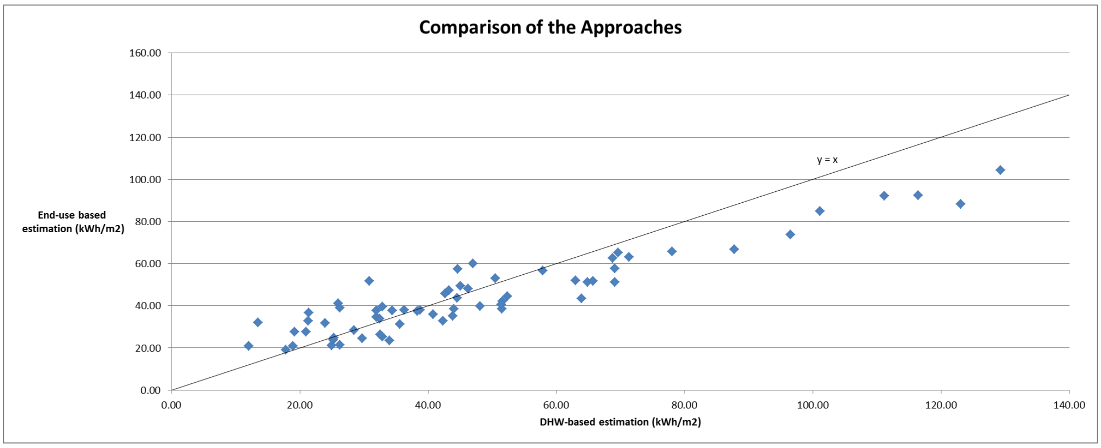


Fig. 9. Comparison of the annual space heating energy consumptions obtained with the two approaches

3.3.3. Regression model

This section aims to obtain the space heating demand of different dwelling typologies through a bottom-up statistical regression approach. This method is based on real aggregated level consumption data, so its output constitutes an additional basis for the constructed models' validation.

The multiple linear regression is a statistic modelling technique used to adjust linear models between a dependent variable (y) and more than one explanatory or independent variables (x_i). The aim is to obtain b_i coefficients from an equation system consisting of j equations as Eq. 2.

$$y_j = b_0 + b_1 \cdot x_{1j} + b_2 \cdot x_{2j} + b_3 \cdot x_{3j} + \ldots + b_n \cdot x_{nj} \qquad \text{Eq. 2}$$

Due to the lack of consumption data at postal code level, the regression approach is applied in a regional scale, by using municipal-level domestic consumption values from municipalities located in the Basque Country, around Bilbao. The implementation of Local Action Plans (LAPs), within the framework of Agenda 21 processes, has led to the measurement and publication of several sustainability indicators, which often include natural gas municipal consumption.

DHW and cooking average fuel use shares in Table 8 are discounted from the residential natural gas consumption, thus obtaining the domestic space heating natural gas consumption. To transform it into demand terms, mean seasonal efficiencies based on [51] are used, which are averaged for each municipality according to the heating systems and fuel distributions.

In order to extrapolate, municipality by municipality, the heating demand satisfied by natural gas into a total domestic heating demand, natural gas heated dwellings floor area's share is considered, over total municipal dwellings floor area [31].

This way, in this regression approach the dependent variables (y) are the aggregated space heating demands of the different municipalities, normalized over the total dwelling stock floor area (kWh/m^2). The x_i variables are the shares (%) of each dwelling typology's floor area, over the total stock floor area in each municipality. The pursued b_i coefficients would therefore be the heating demands (kWh/m^2) of each dwelling typology.

Municipalities with a population lower than 4,000 inhabitants have been excluded from the analysis. Due to their lower amount of dwellings, it is considered that the lower accuracy of the statistical data could otherwise distort the application of the regression method. Totally, municipal residential natural gas consumption is obtained from 17 municipalities of the Basque Country. All of them are located in the same coastal climatic zone, so the consistency of the approach is ensured. Average municipal consumptions are obtained from the consumption values of different years within the 2005 – 2011 historical period, depending on the available information in each municipality.

Concerning dwelling typologies, it would be desirable the present regression analysis to include the same 17 representative dwelling types used to construct modelled archetype buildings. However, the dwelling breakdown detail level to be introduced in the analysis depends on the amount of available data, i.e. aggregated municipal consumption data. Therefore, a simplified classification must be performed. Due to the low share that the dwellings constructed after 2006 imply, they are excluded from the analysis. The rest of dwellings are classified into the three dwelling typologies shown in Table 9, based on their construction period. It is analysed the possibility of further distinguishing the dwellings according to their number of storeys, but the shares of 1 – 2 storeys buildings, which include single-family houses, are generally observed negligible. Ultimately, the number of the dwelling typologies introduced in the regression approach complies with the rule of thumb of ensuring a minimum ratio of five samples per each independent variable [52]. In this case, the ratio is 17:3.

Table 9. Introduced dwelling typologies in the regression analysis

	Typology 1	**Typology 2**	**Typology 3**
Building Construction Period	Before 1960	1960 - 1980	1981 – 2005

3.3.4. Assessment of Energy Performance Certificates

There is no doubt that the introduction of Energy Performance Certificates (EPCs) in the EU constitutes an interesting and extensive data source for energy policy planning purposes. Recent studies point to a wider spectrum of potential applications for EPCs data than originally intended, including the validation of building stock models [53]. Therefore, it is assessed the applicability of the EPCs as an additional source for building energy modelling results validation.

An EPCs registry is publicly available in the webpage of the Basque Government [54]. Instead of the complete EPCs, the database provides the final energy efficiency label for each dwelling, which includes CO_2 emissions and primary energy consumption values. According to dwellings energy certification procedure in Spain, those values correspond to the space heating, space cooling and DHW end-uses. Considering that cooling end-use could be considered negligible in Bilbao, a calculation procedure is set based on the application of the corresponding conversion factors, to estimate mean annual space heating consumption.

Totally 228 EPCs are analysed. The obtained mean annual space heating consumption is inconsistent with the rest of collected real data: it is significantly higher than the values assessed in the literature review and fuel consumption survey. Therefore, it seems that the current practice on EPCs drives to an overestimation of heating energy demand.

Such performance gap, i.e. the difference between estimated and actual energy performance, has been widely assessed in the literature [55][56][57][58] [59]. In fact, there is a broad agreement that buildings with poor thermal performance tend to consume less than predicted in the EPCs [60][61][62], mainly due to the overestimation of factors usually set by standards and other assumptions used in EPC ratings [63][64][65][66]. Therefore, the possibility of building energy model's results validation through EPC databases is excluded from the proposed methodology.

4. Results

The constructed 17 archetype buildings models are simulated by Design Builder v.4.7.0.027 [47] software. Fig. 10 summarizes the normalization per heated floor area of the annual space heating demands of archetype buildings, presented per construction period and urban form.

The space heating demands show a correlation with the construction period and urban form. On the one hand, the evolution of constructive features tends to reduce the heating demand. For example, with the same urban form and similar building dimensions, but different façade composition, Arch. 7 (U = 1.26 W/m^2K) and Arch. 15 (U = 0.63 W/m^2K) show an annual heating demand 15% and 52% lower, respectively, than Arch. 2 (U = 1.77 W/m^2K). On the other hand, due to the higher contiguity, buildings located in solid blocks present lower demands than the ones placed as linear blocks or detached buildings. For example, with the same facade composition and similar building dimensions, but different urban form, Arch. 1 (linear block) shows a heating demand 70% higher than Arch. 4 (solid block). In addition, the most recent buildings seem to be distinguished by a lower heating demand, thanks to the introduction of first energy regulations and related thermal insulation.

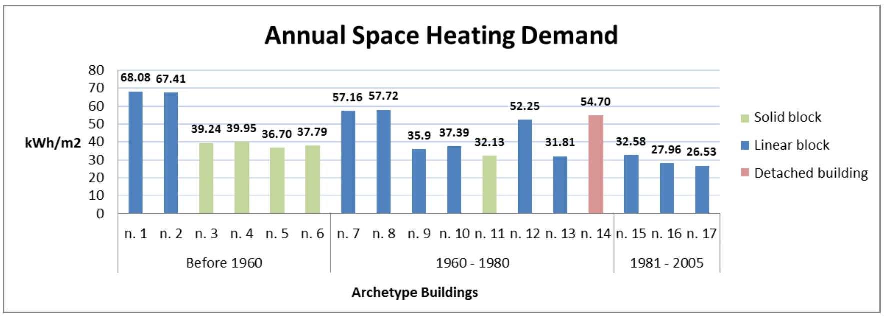


Fig. 10. Annual space heating demands of archetype buildings, by construction period and urban form

Section 3.2 above summarized the outputs of the depth assessment conducted to determine the model parameters which are considered most influential. The results obtained in the present analysis support such assumption. Nevertheless, there are other input parameters which has not been such exhaustively assessed, either due to lack of available databases or because standards or regulation values have been applied. In order to analyse the effect of their uncertainty, the local sensitivity analysis [67] is conducted to obtain the normalised sensitivity coefficients, which represent the percentage change in the annual space heating demand of the models given a 1% change in the input parameter.

The analysed input parameters are the following: facade glazed area (%), infiltration rate, heating setback temperature, internal gains, occupancy and storeys' wall to floor thermal bridge's linear thermal transmittance. Table 10 shows the average of the normalised sensitivity coefficients for all archetype buildings, in relation to the space heating demand.

Table 10. Average of the normalised sensitivity coefficients for all archetype buildings

Average - All Archetype Buildings	**Normalised sensitivity coefficient, S_j**
Facade glazed area (%)	-0.078
Infiltration rate (ACH)	0.704
Heating setback temperature (ºC)	1.250
Equipment and lighting (maximum W/m²)	-0.196
Occupancy (occupants per m²)	-0.204
Ψ wall to floor thermal bridge	0.078

It is verified that the heating setback temperature represents, by far, the parameter which the results are more sensible to, followed by infiltration rate. In a much lower step, internal gains can be found, with a similar influence of equipment and lighting, and occupancy. Finally, the results sensitivity to facade glazed area and wall to floor thermal bridge Ψ value is very similar and negligible. Fig. 11 shows the described order of magnitude of the results sensitivity to each parameter, as well as the oscillation of normalised sensitivity coefficients depending on the archetype building. It is verified that the variability of the results due to these parameters, in their usual range, is notably less than that caused by the urban form, façade composition or the occupant behaviour.

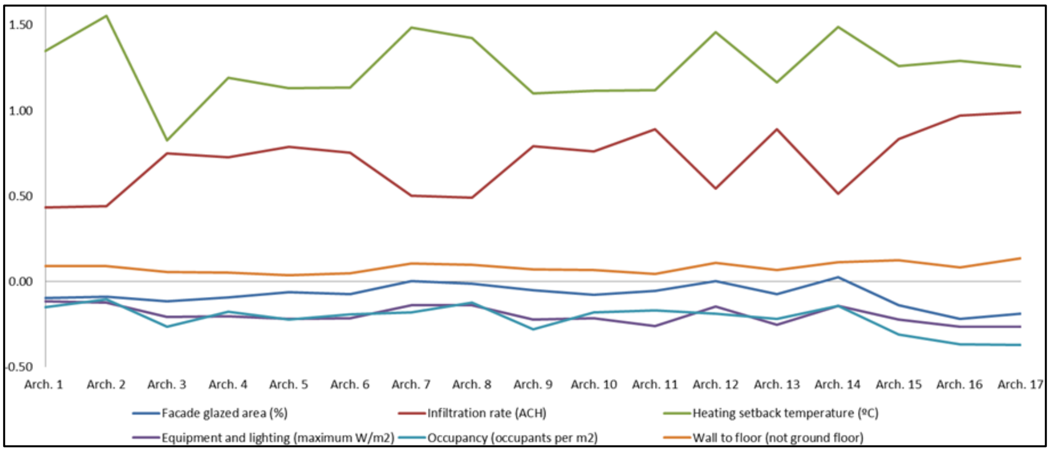


Fig. 11. Archetype buildings results' sensitivity to each input parameter

Using a weighting factor for each modelled building archetype, based on its share over the total residential stock, an annual space heating demand of 43.08 kWh/m² is obtained on average, which is considered to correspond to a space heating energy consumption of 49.58 kWh/m² per year. A mean seasonal efficiency of 86.89% is estimated for Bilbao's space heating, based on [51] reference data, and considering the heating system distribution in Bilbao [31].

These results are compared to validation data obtained in Section 3.3. Table 11 shows that the resulting average space heating energy consumption is close to the values obtained from fuel consumption survey and literature: it is 1% above than the outcome of the survey considering the DHW-based approach and 10% above the survey output based on end-use ratio application approach.

Table 11. Comparison of the annual heating energy consumption

Building Modelling Result	Fuel Consumption Survey		Literature
	Approach based on estimated DHW	Approach based on end-use ratio	SECH-SPAHOUSEC Atlantic Zone [48]
49.58 kWh/m²	48.98 kWh/m²	44.67 kWh/m²	44 kWh/m²

On the other hand, focusing on a disaggregated level, Fig. 12 shows the comparison between the modelled space heating demands, averaged per construction period, and the demands obtained from the regression approach. The coefficient of determination was $R^2 = 0.51$, meaning a moderate adjustment. The model was globally significant with a p-value of 0.022, and all variables rejected the null hypothesis for an alpha value of 0.01. The assumption of independence of residuals was analysed through the Durbin-Watson test, obtaining a value of 2.16 that demonstrates the lack of autocorrelation. The assumptions of linearity and homoscedasticity were also verified through the scatter plot of residuals against predicted values. Comparing the regression results with the outputs from the archetype buildings modelling, the demand values corresponding to the construction period before 1960 and the *Developmentalism* period are very similar, being the modelled demand slightly higher in the case of post-1981 buildings.

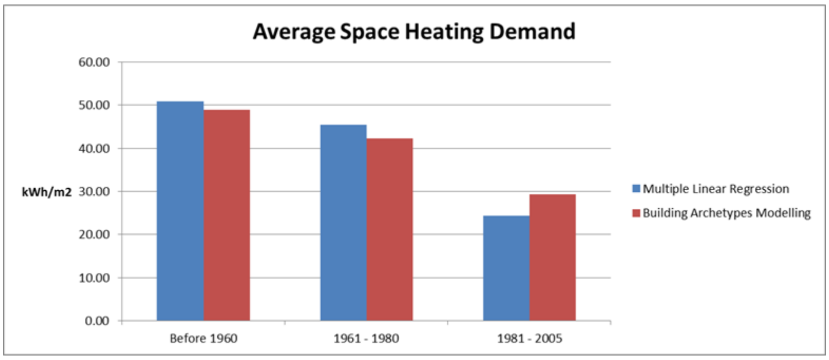


Fig. 12. Comparison between the modelled space heating demands, and the ones obtained from the regression

Nevertheless, the obtained mean annual heating demand for modelled 1981 – 2005 archetype buildings, which is 29.38 kWh/m², corresponds to an annual consumption of 33.81 kWh/m², which is only 5% higher than the mean energy consumption (32.13 kWh/m²) of the complete set of 107 dwellings formed by the four real buildings used for occupant behaviour calibration. Therefore, the difference with the demand obtained from the regression approach may be caused by the limited number of samples introduced in such approach, which combined with the usual lower share of post-1981 buildings over the total stock, could drive to greater error in their result.

Finally, the results are analysed at an aggregated level. The Environmental Department of the City Council is contacted with the aim of collecting further information about the historical evolution of the residential natural gas consumption in Bilbao. Thanks to its collaboration, the full 2004 – 2017 historical consumption trend is completed, which is converted to residential space heating demand terms by applying the same assumptions described for regression.

The obtained disaggregated energy demand estimates are extrapolated to the whole residential stock by multiplying the results by the number of houses which fit the description of each building archetype. Table 12 shows that the obtained total space heating demand for Bilbao is very similar to the mean demand value derived from real consumption data of 2004 – 2017 period. The difference is only about 4%.

Table 12. Comparison of Bilbao’s residential heating energy demand

Estimated Residential Space Heating Demand (MWh) Bilbao Average 2004 - 2017	461,584
Building Modelling Result (MWh)	481,915

5. Conclusions

An appropriate energy characterization of an existing building stock can help to implement the necessary energy efficiency policies in the most effective way. Recent improvements in geographical information systems have led to a rise in models developed for urban building stocks. Nevertheless, data availability on which they rely is not always available, and the sophistication of certain models could become a disadvantage for being replicable. At the same time, local authorities can constitute a significant bottom-up support in implementing the imperative energy saving policies. Aiming to contribute to such field, this paper describes an easy-to-implement methodology for the characterization of residential heating energy consumption at city level. Particular attention has been given to its applicability, so the methodology lies on available public data sources and assumes real limitations of information tools availability. The method has been conceived to be applicable to any city, provided a primary understanding of the constructive evolution in the analysed geographical context.

The presented method lies on a bottom-up engineering approach, which often involves several challenges to deal with. This approach requires large amount of input information for model construction and validation processes. To contribute to data collection related difficulties, the introduced methodology proposes original ways of gathering further information, as benefitting from the content of fuel consumption invoices. Another weakness of this kind of approaches lies on the unpredictable nature of human behaviour, which can lead to important gaps between actual and modelled energy consumption. In the developed methodology, an empirical calibration procedure is proposed to construct occupant behaviour profiles, based on real consumption data from buildings with communal heating systems.

The lack of transparency regarding other model inputs-related assumptions based on author’s experience, as well as the common utilization of standard values for certain input parameters, often lead the model outputs to lack credibility if rigorous validation is not performed. In the described methodology important focus is given to the process of verifying models results, by collecting real data for an evidence-based testing. Validation methods, at both disaggregated and aggregated level, allow the reliability of the results to be ensured. A multiple linear regression approach is also proposed, applied at a reginal scale instead of the usual postal code level. In addition, sensitivity analysis helps to delimit the influence of subjective assumptions.

The described method was implemented for the residential building stock of Bilbao, where a total of 17 representative buildings were identified. The results constitute a data set which is significantly aligned with gathered real consumption information. Applying the methodology to Bilbao demonstrates that the proposed method can accurately reproduce the existing heating energy consumption, providing a good estimate of the thermal performance of the residential stock. The implementation of the presented procedure provides an aggregated heating energy demand that only differs around 4% from real historical data which, being in the order of magnitude of the differences achieved in other analyses [10][14][25][32][58], is considered successful.

Accurate modelling of buildings energy demand constitutes a key tool to assist energy retrofitting policies. The outcome of this study provides Bilbao’s baseline energy consumption estimation, disaggregated per building type, forming a basis for further investigations aimed at exploring the economic effects of different energy efficiency strategies, identifying cost-optimal sets of measures per building type and estimating the required investment for the achievement of different energy targets. This research is currently being conducted and the authors expect to publish its results soon.

In building stocks modelling through archetype buildings, one of the challenges is to find a limited number of essential building parameters as segmentation criteria, which permit to maintain a reasonable computational time. The results show that energy consumption variation between buildings in different urban morphologies can be much larger than the differences caused by the varying facade solutions due to different construction periods. The urban forms have a significant impact on the energy performance of a building, and that is why it is crucial to include, within segmentation criteria of Phase 1, parameters that could indirectly be related with different urban morphologies, such as building height and dwelling floor area. The outlines of such relation must be search within the historical evolution of a city and the development of the different architectural styles.

Although the application of the presented methodology is verified completely feasible with existing data sources, there are some limitations related to the lack of sufficient databases that make it more arduous its implementation. As it is broadly mentioned in the literature [22][26] there is room for improvement in the development of the existing building stock features databases, as well as in the knowledge of domestic energy consumption characteristics. Furthermore, a great potential exists for IEEs to become an important data source for building energy modelling.

The applicability of Energy Performance Certificates (EPCs) is also evaluated as an additional way for validation of building energy modelling results. Nevertheless, it seems that the current practice on EPCs drives to an overestimation of heating energy demand, which is aligned with outcomes of other studies [55][57][61]. Therefore, the possibility of building energy model's results validation through EPC databases is excluded from the proposed methodology

Nevertheless, the results demonstrate the practicability of characterizing the heating energy consumption of a city-scale residential building stock with available data sources, aiming to provide a basis for the investigation of energy savings potential and related CO_2 emission reductions.

Acknowledgements

The authors would like to acknowledge the natural gas consumption data provided by the Environmental Department of the City Council of Bilbao.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] International Energy Agency. *CO_2 emissions from fuel combustion. Highlights.* 2017.

[2] Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5 ºC. Summary for Policymakers*. 2018.

[3] European Commission (EC). *Energy Roadmap 2050 [COM/2011/885]*. 2011.

[4] European Commission (EC). *A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.* 2018.

[5] European Commission (EC). Buildings [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings [accessed 15.01.2019]

[6] POMBO, O.; RIVELA, B.; NEILA, J. *The challenge of sustainable building renovation: assessment of current criteria and future outlook*, Journal of Cleaner Production, 2016, vol. 123, pp. 88-100.

[7] SWAN, L. G; UGURSAL, I. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renewable and Sustainable Energy Reviews, 2009, vol. 13, pp.1819-1835

[8] KAVGIC, M.; MAVROGIANNI, A.; MUMOVIC, D.; SUMMERFIELD, A.; STEVANOVIC, Z.; DJUROVIC-PETROVIC, M. *A review of bottom-up building stock models for energy consumption in the residential sector*, Building and Environment, 2010, vol. 45, pp. 1683-1697.

[9] GHIASSI, N.; MAHDAVI, A. *Reductive bottom-up urban energy computing supported by multivariate cluster analysis*, Energy and Buildings, 2017, vol. 144, pp. 372-386.

[10] NAGELI, C.; CAMARASA, C; JAKOB, M.; CATENAZZI, G.; OSTERMEYER, Y. *Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks*, Energy & Buildings, 2018, vol. 173, pp. 443-460.

[11] MONTEIRO, C. S.; PINA, A.; CEREZO, C.; REINHART, C.; FERRAO, P. *The use of multi-detail building archetypes in urban energy modelling*, Energy Procedia, 2017, vol. 111, pp. 817-825.

[12] BALLARINI, I.; CORGNATI, S.P.; CORRADO, V. *Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project*, Energy Policy, 2014, vol. 68, pp. 273-284.

[13] Official Journal of the European Union. *Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and buildings elements (2012/C 115/01).* 19th April 2012.

[14] MATA, E.; SASIC KALAGASIDIS, A.; JOHNSSON, F. *Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK*, Building and Environment, 2014, vol. 81, pp. 270-282

[15] SARTORI, I.; SANBERG, N. H.; BRATEBO, H. *Dynamic building stock modeling: general algorithm and exemplification for Norway*, Energy and Buildings, 2016, vol. 132, pp. 13-25.

[16] GANGOLELLS, M.; CASALS, M.; FORCADA, N.; MACARULLA, M.; CUEVA, E. *Energy mapping of existing building stock in Spain*, Journal of Cleaner Production, 2016, vol. 112, pp. 3895-3904.

[17] STREICHER, K. N.; PADEY, P.; PARRA, D.; BÜRER, M. C.; SCHNEIDER, S.; PATEL, M. K. *Analysis of space heating demand in the Swiss residential building stock: Element-based bottom-up model of archetype buildings*, Energy and Buildings, 2019, vol. 184, pp. 300-322.

[18] Intelligent Energy Europe Project "EPISCOPE" [online]. Available: http://episcope.eu [accessed 21.09.2019

[19] Covenant of Mayors for Climate & Energy. Covenant initiative [Online]. Available: https://www.covenantofmayors.eu/about/covenant-initiative/origins-and-development [accessed 15.01.2019]

[20] ÖSTERBRING, M.; MATA, E.; THUVANDER, L.; MANGOLD, M.; JOHNSSON, F.; WALLBAUM, H. *A differentiated description of building stocks for a georeferenced urban bottom-up building stock model*, Energy and Buildings, 2016, vol. 120, pp. 78-84.

[21] REINHART, C.F.; CEREZO DAVILA, C. *Urban building energy modelling - A review of a nascent field*, Building and Environment, 2016, vol. 97, pp. 196-202.

[22] HONG, T.; CHEN, Y.; LUO, X.; LUO, N. LEE, S.H. *Ten questions on urban building energy modelling*, Building and Environment, 2020, vol. 168, 106508.

[23] CEREZO DAVILA, C.; REINHART, C.F.; BEMIS, J.L. *Modelling Boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets*, Energy, 2016, vol. 117, pp. 237-250.

[24] BRAULIO-GONZALO, M.; JUAN, P.; BOVEA; M.D.; RUA, M.J. *Modelling energy efficiency performance of residential building stocks based on Bayesian statistical inference*, Environmental Modelling & Software, 2016, vol. 83, pp. 198-211.

[25] D'ALONZO, V.; NOVELLI, A.; VACCARO, R.; VETTORATO, D.; ALBATICI, R.; DIAMANTINI, C.; ZAMBELLI, P. *A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale*, Energy & Buildings, 2020, vol. 206, 109581.

[26] CHEN, Y.; HONG, T.; LUO, X.; HOOPER, B. *Development of city buildings dataset for urban building energy modelling*, Energy & Buildings, 2019, vol. 183, pp. 252-265.

[27] BUFFAT, R.; FROEMELT, A.; HEEREN, N.; RAUBAL, M.; HELLWEG, S.; *Big data GIS analysis for novel approaches in building stock modelling*, Applied Energy, 2017, vol. 208, pp. 277-290.

[28] FRAYSSINET, L.; MERLIER, L.; KUZNIK, F.; HUBERT, J.L.; MILLIEZ, M.; ROUX, J.J.: *Modelling the heating and cooling energy demand of urban buildings at city scale*, Renewable and Sustainable Energy Reviews, 2018, vol. 81, pp. 2318-2327.

[29] HAPPLE, G.; FONSECA, J.A.; SCHLUETER, A.; *A review on occupant behaviour in urban building energy models, Energy & Buildings*, 2018, vol. 174, 276-292.

[30] FERNANDEZ, J.; DEL PORTILLO, L.; FLORES, I.; HERNANDEZ, P. *Assessing residential heating energy consumption in a city-scale: a bottom-up methodological approach*. 11CNIT. XI National and II International Engineering Thermodynamics Congress. Proceedings book, 2019, pp. 122-133.

[31] INE (Spanish National Institute of Statistics). Population and Housing Census [Online]. Available: https://www.ine.es/censos2011/tablas/Inicio.do [accessed 18.01.2019]

[32] MASTRUCCI, A.; BAUME, O.; STAZI, F.; LEOPOLD, U. *Estimating energy savings for the residential building stock of an entire city: A GIS-based statistical downscaling approach applied to Rotterdam*, Energy and Buildings, 2014, vol. 75, pp. 358-367.

[33] HOWARD, B.; PARSHALL, L.; THOMPSON, J.; HAMMER, S.; DICKINSON, J.; MODI, V. *Spatial distribution of urban building energy consumption by end use*, Energy and Buildings, 2012, vol. 45, pp. 141-151.

[34] Boletín Oficial del Estado. *Real Decreto 2429/79, de 6 de julio, por el que se aprueba la Norma Básica de la Edificación NBE-CT-79, sobre Condiciones Térmicas en los edificios*. 6th July 1979.

[35] MITYC. *Código Técnico de la Edificación*, 2006.

[36] GOUVEIA, J.P.; FORTES, P.; SEIXAS, J.; *Projections of energy services demand for residential buildings: Insights from a bottom-up methodology*, Energy, 2012, vol. 47, pp. 430-442.

[37] MCKENNA, R.; MERKEL, E.; FEHRENBACH, D.; MEHNE, S.; FICHTNER, W., *Energy efficiency in the German residential sector: A bottom-up building-stock-model-based analysis in the context of energy-political targets*, Building and Environment, 2013, vol. 62, pp. 77-88.

[38] INE (Spanish National Institute of Statistics). Population and Housing Census [Online]. Available: http://www.ine.es/censo/es/inicio.jsp [accessed 18.01.2019]

[39] AEMET. *Atlas de Radiación Solar en España utilizando datos del SAF de Clima de EUMETSAT*. 2012.

[40] Nieves Basurto Ferro. *Los maestros de obras en la construcción de la ciudad: Bilbao*, 1876-1910. 1999

[41] Eraikal Program. *GUÍA AZALA: Rehabilitación Energética Integral de la Envolvente de los Edificios en Euskadi*. 2015. Available: http://www.garraioak.ejgv.euskadi.eus/r41-18971/es/contenidos/informacion/guia_azala/es_def/index.shtml [accessed 09.06.2019]

[42] Departamento de Empleo y Políticas Sociales del Gobierno Vasco. Dirección de Vivienda. *Catálogo de Rehabilitación Energética*. 2014.

[43] Iñigo Lizundia. *La Construcción de la Arquitectura Residencial en Gipuzkoa durante la Época del Desarrollismo*. Universidad del País Vasco – Euskal Herriko Unibertsitatea. 2012.

[44] Boletín Oficial del Estado. *Ley 8/2013, de 26 de junio, de rehabilitación, regeneración y renovación urbanas.* 28th June 2013.

[45] Boletín Oficial del Estado. *Real Decreto Legislativo 7/2015, de 30 de octubre, por el que se aprueba el texto refundido de la Ley de Suelo y Rehabilitación Urbana.* 31st October 2015.

[46] Official Journal of the European Union. *Directive 2012/27/UE*. 25th October 2012.

[47] DesignBuilder simulation tool. DesignBuilder Software Ltd, UK. Available online: https://designbuilder.co.uk

[48] IDAE. *Proyecto SECH-SPAHOUSEC. Análisis del consumo energético del sector residencial en España.* 2011.

[49] EVE. *Claves energéticas del sector doméstico en Euskadi*. 2013.

[50] TRIOLA, M.F.; *Estadística*. 2009.

[51] IDAE. *Escala de calificación energética. Edificios existentes.* 2011.

[52] HAIR, J.F.; TAHAM, R.L.; ANDERSON, R.E.; BLACK, A.W. *Multivariate Data Analysis*. 1999.

[53] PASICHNYI, O.; WALLIN, J.; KORDAS, O.; *Data-driven building archetypes for urban building energy modelling*, Energy, 2019, vol. 181, pp. 360-377.

[54] Departamento de Desarrollo Económico e Infraestructuras. *Certificado de eficiencia energética*. Available: https://www.euskadi.eus/certificado-eficiencia-energetica/web01-a2indust/es/ [accessed 14.03.2019]

[55] MAJCEN, D.; ITARD, L.C.M.; VISSCHER, H. *Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications*, Energy Policy, 2013, vol. 54, pp. 125-136.

[56] DE WILDE, P. *The gap between predicted and measured energy performance of buildings: A framework for investigation*, Automation in Construction, 2014, vol. 41, pp. 40-49.

[57] HARSMAN, B.; DAGHBASHYAN, Z.; CHAUDHARY, P. *On the quality and impact of residential energy performance certificates*, Energy and Buildings, 2016, vol. 133, pp. 711-723.

[58] BALARAS, C.; DASCALAKI, E.G.; DROUTSA, K.G.; KONTOYIANNIDIS, S. *Empirical assessment of calculated and actual heating energy use in Hellenic residential buildings*, Applied Energy, 2016, vol. 164, pp. 115-132.

[59] COZZA, S.; CHAMBERS, J.; PATEL, M.K.; Measuring the thermal energy performance gap of labelled residential buildings in Switzerland, Energy Policy, Available online 18 November 2019, 111085.

[60] HENS, H.; PARIJS, W.; DEURINCK, M. *Energy consumption for heating and rebound effects,* Energy and Buildings, 2010, vol. 42, pp. 105-110.

[61] KELLY, S.; CRWAFORD-BROWN, D.; POLLIT, M.G., *Building performance evaluation and certification in the UK: is SAP fit for purpose?*, Renewable and Sustainable Energy Reviews, 2012, vol. 16, pp. 6861-6878.

[62] MAJCEN, D.; ITARD, L.; VISSCHER, H. *Actual heating energy savings in thermally renovated Dutch dwellings*, Energy Policy, 2016, vol. 97; pp. 82-92.

[63] BURMAN, E.; MUMOVIC, D.; KIMPIAN, J.; *Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings*, Energy, 2014, vol. 77, pp. 153-163.

[64] HOFFMANN, C.; GEISSLER, A. *The prebound-effect in detail: real indoor temperatures in basements and measured versus calculated U-values*, Energy Procedia, 2017, vol. 122, pp. 32-37.

[65] KRAGH, J.; ROSE, J.; KNUDSEN, H.N.; JENSEN, O.M. *Possible explanations for the gap between calculated and measured energy consumption of new houses*, Energy Procedia, 2017, vol. 132, pp. 69-74.

[66] SUMMERFIELD, A.J.; ORESZCZYN, T.; PALMER, J.; HAMILTON, I.G.; LI, F.G.N.; CRAWLEY, J.; LOWE, R.J. *What do empirical findings reveal about modelled energy demand and energy ratings? Comparisons of gas consumption across the English residential sector*, Energy Policy, 2019, vol. 129, pp. 997-1007.

[67] FIRTH, S.K., LOMAS, K.J. AND WRIGHT, A.J. *Targeting household energy efficiency measures using sensitivity analysis*, Building Research & Information, 2010, vol. 38, pp. 25-41.