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Methodology to characterize a residential building stock using a bottom-up approach: a case study applied to Belgium

Samuel Gendebien[1], Emeline Georges, Stéphane Bertagnolio and Vincent Lemort

University of Liège, Aerospace and Mechanical Engineering Department, Thermodynamics Laboratory, Energy Systems - Belgium

ABSTRACT

In the last ten years, the development and implementation of measures to mitigate climate change have become of major importance. In Europe, buildings account for about 40% of the final energy consumption. Within this context, the detailed characterization of residential building stocks in terms of age, type of construction, insulation level, energy vector, and of evolution prospects appears to be a useful contribution to the assessment of the impact of implementation of energy policies. In this work, a methodology to develop a tree-structure characterizing a residential building stock is presented in the frame of a bottom-up approach that aims to model and simulate domestic energy use. The methodology is applied to the Belgian case for the current situation and up to 2030 horizon. 992 cases are distinguished for the 2012 tree-structure description. This building stock model has been used and updated to illustrate the impact of heavy retrofit scenarios by 2030. Up to 13% reduction in primary energy consumption were estimated for the entire residential building stock. Insights regarding prospects for required installed power capacity for space heating per type of buildings are presented as well as potential penetration of given HVAC technologies such as heat pumps and μ-CHP.

Keywords:

bottom-up modeling,
building stock description,
residential,
building simulation

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1. Introduction

In Europe, the residential sector accounts for 27% of the final energy consumption [1], and therefore contributes significantly to CO_2 emissions. In the context of mitigation of climate change, roadmaps towards energy-efficient buildings have been proposed [2] and detailed characterizations of residential building stocks and end-user consumption are of major importance.

1.1. Building stock models review

Swan and Ugursal [3] identified two methods in their review of modeling techniques of end-use energy consumption in the residential sector: top-down and bottom-up. In the top-down approach, the residential sector is seen as an energy sink. The consumption is based on widely available macroeconomic variables as well as on climate conditions, appliances ownership and so on. No attention is given to the end-uses and to possible improvements at that level. Bottom-up approaches, on the other hand, focus on the modeling of end-use consumptions and extrapolate them to larger sets of buildings (districts, regions...). One can distinguish the inverse and forward methods: the former refers to statistical methods, based on historical information and data regressions, and the latter is based on a physical description of the components and envelope of the building. The higher level of details of forward models makes them suitable for the identification of technological improvements at the building level.

So far, most estimations of the amount of energy use per sector are derived from statistical analysis of energy consumption data, but a few bottom-up approaches are also available in the literature. Kavgic *et al.* [4] identified

1 Corresponding author email: sgendebien@ulg.ac.be

different bottom-up building physics residential stock models which present different levels of complexity, data input requirements, and structure. Huang and Brodrick [5] used a so called engineering bottom-up approach to conduct an estimation of the aggregate heating and cooling loads of the U.S. building stock (residential and commercial). Sixteen multi-family and forty-five single family prototypical buildings were identified and their envelope and HVAC (Heating, Ventilation and Air-Conditioning) systems were modeled in order to develop hourly load profiles that could be used for future energy efficiency or pricing scenarios. In Canada, Farahbakhsh *et al.* [6] conducted a study over residential end-use consumption and the impact of an upgrade of existing dwellings. However, only single-detached and single-attached houses built after 1967 (which represents 60% of the residential buildings) were considered in the model. In the UK, several studies were conducted on physics-based energy models. The BREHOMES model was developed by Shorrock and Dunster [7], and considered over 1000 different categories of buildings according to the type, age and heating systems. The model was used to derive scenarios of evolution of consumption and CO_2 emissions.

With regards to previous works, it appears that the choice of the set of representative buildings highly impacts the results and conclusions drawn from such bottom-up methods. Cyx *et al.* [8] make a distinction between two different identifiable approaches:

"*The representative dwelling types approach involves modeling a set of fictional buildings based on average values. This set of fictional buildings is used to model the entire building stock. The established parameters are then iteratively adjusted to correspond to energy consumption for the total building stock known e.g. from energy balances.*

The typical dwellings approach involves composing a set of typical dwellings closely related to existing buildings and existing building components, chosen for their reference value compared to the examined stock. Considering that actual buildings and building characteristics are used as a basis, it is possible to examine the impact of various saving measures on a specific individual dwelling type."

1.2. Literature review in the Belgian context

A large amount of studies in the field of the residential building stock has been carried out in Belgium but a lack of homogeneity is observed between the different developed methodologies.

The most recent Belgian national census related to residential buildings was performed in 2001 by Vanneste *et al.* [9]. Most of the studies published during the last decade considered it as a starting point.

Hens *et al.* [10] presented a study of the Belgian residential building stock up to 1990. For the first part, 960 cases were investigated characterized by the type of dwelling (individual, double, terraced and flat), the floor area, the energy vector, and heating system. Four construction periods were considered for which average heat transfer coefficients for façades, floors, roofs and windows were estimated. Evolution perspectives in terms of retrofit were investigated up to 2015.

More recently, the Flemish Institute for Technological Research (VITO) was involved in the TABULA project [8], which consists in the establishment of residential building typologies for 24 European countries. The typologies are based, among others, on the following criteria: age, size, envelope characteristics and energy vectors. The project also proposed showcase calculations of the possible energy savings and provided statistical data for buildings and heating and cooling system types.

The purpose of the LEHR project [11] aimed at identifying successful refurbishment case studies and systematically collecting information on the design, realization and operation of such refurbished buildings. Within the frame of the LEHR project, Kints *et al.* [12] analyzed the potential of retrofit options and identified the most suitable ones for the Walloon building stock. The stock is divided into approximately ten typologies, for which potential retrofit measures are explored. This analysis is mainly based on the national census of 2001 (Vanneste *et al.* [9]), the study on the Walloon energy balance [13] and the enquiry on the Walloon dwelling stock quality [14].

Relevant information about Belgian housing typology also comes from the SuFiQuaD project [15]. This project analyses the complex interrelations between housing typology, lifestyle, spatial characteristics, technical solutions for building elements and related financial and ecological aspects.

To the best knowledge of the authors, the most recent study in the field of residential sector in Brussels-Capital Region is the one carried out by Thielemans *et* al. [16]. It consisted in evaluating the potential of passive housing techniques for new and refurbished buildings in Brussels-Capital Region.

On the Flemish Region level, Briffaerts *et al.* [17] investigated the impact of various energy policy scenarios up to 2020 on the household energy consumption associated to space heating and domestic hot water production.

The present work supplements the studies from Hens *et al.* [10] and Cyx *et al.* [8] by adding detailed characterization of the building geometry and distinguishing different insulation levels within a sub period of time, allowing for a better identification of the potential of retrofit options, and of the disparities specific to the Belgian residential building stock.

2. Objectives

In this paper, a methodology to develop a comprehensive tree-structure characterizing the Belgian residential building stock is presented. Each end of the tree represents a type of building characterized by design features (wall, window, roof areas and corresponding thermal performance factor), heating system as well as energy vector dedicated to domestic hot water production (DHW) and space heating (SH). In a very diverse building stock such as in Belgium, decisions made to reduce the set of representative buildings to a reasonable and manageable number while preserving a sufficient level of details and accuracy are of major importance.

One final objective of this work is to simulate domestic energy use for the current situation and up to 2030 horizon in Belgium. For this purpose, the developed tree-structure can easily be coupled to building simulation models with various levels of details. It also allows quick estimations of the percentage of penetration of new Heating, Ventilation and Air-Conditioning (HVAC) technologies and the cumulative distribution of the required installed power according to the type, age and envelope characteristics of the buildings. The development of this tree-structure responds to a growing need for researchers, decision makers and actors from the private sector to investigate the impact of energy policies at national scales as well as future market trends and needs in building energy sectors.

3. Methodology : design steps of the housing tree-structure

This section presents the steps and assumptions to carry out the description of the Belgian residential housing stock in the frame of a bottom-up approach.

In the particular case of Belgium, significant disparities are observed in terms of construction methods, dwelling types and ages of construction between the three Regions (Flanders, Wallonia and Brussels). The main difference between the Walloon and the Flemish housing stock is that Walloon housing stock is globally older compared to the Flemish one: half of the residential building stock dates from before 1945 and 75% dates from before 1980, whereas most of the buildings dates from after 1945 in Flanders. The question of considering one or three different typologies to characterize the Belgian residential building stock then naturally arises. Cyx *et al.* [8] chose to develop only one typology for Belgium, which was a simplifying assumption due to the lack of statistical data for each Region regarding dwelling types, constructions methods and thermal performance. Within the frame of the creation of the whole Belgian housing stock dedicated to a bottom-up approach, it has been decided not to differentiate the three Regions and to determine one single typology for Belgium.

Outlines of the creation of the housing stock are given in the following sections. The employed methodology consists in starting from a "large" tree-structure incorporating many cases and then, reducing the number of investigated cases by making simplifications/repartition assumptions to obtain a simplified tree structure, so called final tree structure.

3.1. Choice of the approach

The proposed approach is qualified as "hybrid" which is a mix between "typical" and "representative" approach (as defined in the introduction section), for the following reasons:

- The typical approach extends the characteristics of a typical dwelling to a set of buildings, as already mentioned by Hens *et al.* [8], Cyx *et al.* [9] and Allacker [10]. In the proposed tree structure, the geometry characteristics of one specific building have been extended to a set of building to represent the different typologies and age classes. As an example, the same geometry characteristics of a single freestanding house constructed before 1945 is extended to all freestanding houses constructed before 1945. This type of approach is clearly typical.
- For the same construction time-period and associated building geometry, the tree-structure developed here further differentiates different

cases based on the insulation level, the type of energy vector for SH and DHW and the type of heating system (decentralized vs centralized). The final definition of each case combine existing typical geometries to average U values, different energy vectors and average efficiencies of the heating system, leading to a set of representative but fictional buildings. This type of approach is thus clearly representative.

The hybrid approach permits to combine the strength of each approach. The main weakness of the typical approach is to only investigate one case for a type of building. The hybrid approach counterbalances this weakness by taking into account a set of several U values for the different construction (depending on the insulation level) for each type of building. Moreover, a hybrid approach has been previously validated for the Walloon housing stock (comparison with the annual energy use from top down results) by Gendebien [18]. The same methodology has been extended to the Belgian level and a greater number of cases have been investigated.

3.2. Large tree structure

The largest building stock tree-structure can be created by taking into account all possible cases from the available statistical data. As observed in Table 1, this leads to a very high number of investigated cases and involves a significant number of assumptions. Such a high number of cases is prohibitive to combine the branching structure with dynamic building simulations. Indeed, by assuming a very optimistic calculation time of one second to simulate one year (which is unrealistic for building dynamic simulation), it would take more than 2 days to compute all the cases. From this fact, simplifications have to be introduced.

3.3. Database reduction and simplifying assumptions

Reducing the number of investigated cases of the “large” building stock tree-structure can be realized in two steps:

- Consolidating some cases of the large branching structure.
- Making some repartition assumptions which are unavoidable in the creation of the tree-structure due to the lack of available statistical. Most of the released studies present a global repartition (as an example, there are X% of houses with double glazed windows in Belgium) and not a detailed repartition (for instance, amongst the 4 frontages houses constructed before 1945, Y% has totally insulated windows and roofs, Z% has ...).

3.3.1. Consolidation of cases

Based on past studies, it has been decided to correlate the type of building, the inhabitable area and the year of construction by extending geometric characteristics of one house to a same type of building.

Table 1: Large building stock arborescence.

Type of building (Separated, Semi-detached and Row houses + Apartment)	4
Area (Small, Medium, Large and Very large)	4
Year of construction (<1919, 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, >1990)	7
Wall (Insulated, Partially insulated, Not insulated)	3
Roof (Insulated, Partially insulated, Not insulated)	3
Window (Insulated, Not insulated)	2
Floor (Insulated, Partially insulated, Not insulated)	3
Heating production system (Centralized, Not centralized)	2
Type of combustible (Gasoil, Natural gas, Electricity, Wood, Butane/Propane, Coal, Unknown)	7
Domestic hot water (Gasoil, Natural gas, Electricity, Others)	4
Total number of cases	338 688

Allacker [19] proposed a division of the housing stock as proposed hereafter: "*Four dwelling types are selected: a detached house, a semi-detached house, a terraced house and an apartment. Dwellings of different ages are chosen since these occur in the current dwelling stock. Four construction periods are differentiated: the period before 1945, 1945 – 1970, 1971 – 1990 and 1991 – 2007.*"

Matrix defined within the frame of the TABULA project [8] and the SuFiQuaD [15] project are quite similar even if two main differences can be observed:

- Four construction periods are differentiated within the frame of SuFiQuaD [15] instead of five construction periods within the frame of TABULA [8],
- Characteristics of the whole multi family houses (entire building) are presented in the TABULA project [8] instead of characteristics related to single apartment within the frame of the SuFiQuaD project [15].

The SuFiQuaD project [15] proposes a repartition of each typical case for the three Regions and also for the whole Belgium. However, the repartition for Belgium is only given until 2007.

The website of the *National Institute of Statistical* gives the official number of delivered building permissions after 2007 for apartments and single family houses.

The repartition between types of building is unfortunately not given by the *National Institute of Statistics* website (single houses are not differentiated). However, this allows to update the repartition of the housing stock by assuming the same repartition of detached, semi-detached and terraced houses as for the period 1991–2007.

The updated building stock distribution (in function of year of construction and type of building) is given in Figure 1. According to this updating procedure, the total number of dwellings in Belgium in 2012 was equal to 4 675 433.

Simplifications concerning the wall, roof and floor characteristics consist in neglecting the partially insulated cases, which are quite negligible (Kints *et al.* [12]). Parts relative to the partially insulated cases have been equally distributed between not insulated and totally insulated cases. Walloon statistical repartition (Kints *et al.* [12]) by year of construction about wall insulation has been extended to the national level.

No simplifications can be made concerning the type of heating production system (the latter is described as centralized or decentralized).

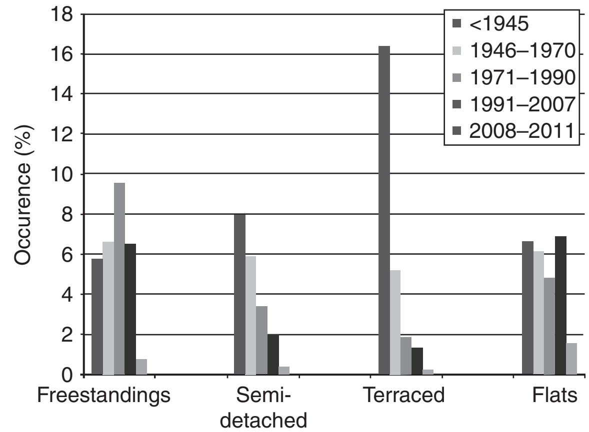

Figure 1: Distribution of the Belgian dwelling types differentiating the five considered construction period.

The simplification concerning the energy vector used for space heating and domestic hot water production is to focus only on the main combustible used in Belgium: heating oil, natural gas and electricity. Because of their low incidence in Belgium, coal, wood and butane have been consolidated in one case called "Others". Moreover, another simplification consists in assuming that production of domestic hot water can be done only by the same type of combustible as the one used for space heating or by electricity. Houses with "Others" as fuel source for space heating are assumed to only use "Others" for DHW production. This was assumed since these cases are negligible.

The simplified building stock tree-structure is given in Table 2:

3.3.2. Repartition assumptions

The creation of this comprehensive tree-structure requires the use of some repartition hypotheses. The following repartition assumptions have been made:

- Obviously the attic and basement for apartment are not taken into account (not considered as an external area). Partition walls dimensions are given in the tree-structure but they have not been considered as an external area either.
- For buildings constructed after 2007, no distinction between "insulated" and "not insulated" is made for walls, windows, floors

Table 2. Simplified building stock arborescence.

Type of building correlated with mean inhabitable area (Separated, Semi-detached and Row houses + Apartment)	4
Year of construction (<1945, 1946-1970, 1971-1990, 1990-2005)	4
Wall (Insulated, Not insulated)	2
Roof (Insulated, Not insulated)	2
Window (Insulated, Not insulated)	2
Floor (Insulated, Not insulated)	2
Heating production system (Centralized, Not centralized)	2
Energy vector for SH and DHW (Gasoil + Gasoil, Natural gas + Natural gas, Gasoil + Electricity, Natural gas + Electricity, Others + Others, Electricity + Electricity)	6
Total number of cases	3072

and roofs as well. The chosen U values are the ones provided by EPB 2010, the Walloon region transposition of the European directive for energy performance of buildings [20].

- The global repartition of windows (considered as insulated or not) is the one given by Kints *et al.* [12]. It has been assumed that the time-evolution of occurrence of windows insulation follows that of the walls insulation.
- The global repartition of roofs (considered as insulated or not) is the one given by Kints *et al.* [12]. It has also been assumed that the evolution of roofs insulation follows the same time-evolution as the walls insulation.
- The global repartition of floors (considered as insulated or not) is the one given by Kints *et al.* [12]. Given the high global proportion of not insulated floors, it has been decided to only assume insulated floor for houses with walls, windows and roofs insulated.
- Energy vectors (coal, wood and butane) gathered in the case called "Others" are considered as negligible for building constructed after 1970.

3.4. Relative share of each end of the tree-structure

A very schematic representation of the tree-structure is given in Figure 2. a, b, c... are the building occurrence of the branches. occ_1, occ_2... are the final share of a specific type of building.

The developed tree-structure follows the same rules as the probability tree ones:

- The sum of the building occurrence of the branches from the same vertex is 1 (i.e. a + b = 1; c+d = 1; e + f + g = 1...)
- The final share of a specific type of building is the product of the occurrences of the branches that compose it (i.e. occ_1 = a.c.e; occ_2 = a.c.f; occ_1 = a.c.g...);

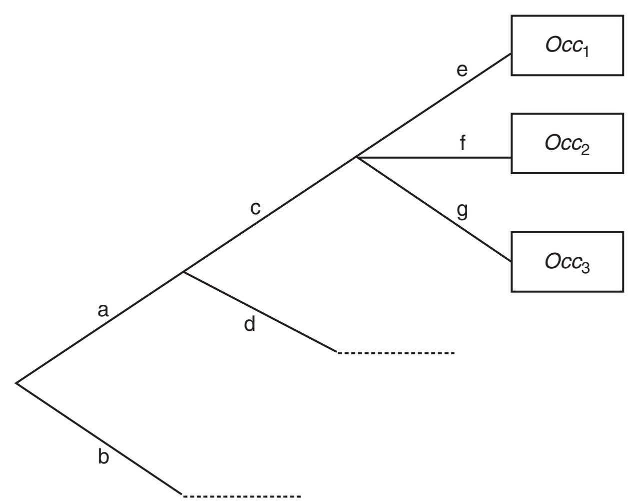

Figure 2. Schematic representation of the tree structure for the relative share determination.

3.5. Building characteristics

3.5.1. Geometric characteristics of investigated cases

Each building is divided into five zones: living room, bedrooms, kitchen, bathrooms, unheated and corridor zones. Based on architects plan given by Allacker [19] each geometry is detailed in terms of walls, floor, windows, roof, doors, adjacent (in contact with adjacent houses) and internal (in contact with another internal zone) areas related to each zones of the building.

3.5.2. Constructive elements characteristics

The determination of constructive elements characteristics, namely material thickness, heat transfer coefficient and thermal capacity, is explained hereafter.

For uninsulated elements, their composition was provided by TABULA [8].

For additional insulation level of walls, roofs and floors, the insulation thickness was determined thanks to a weighted average of values provided by Kints *et al.* [12]. It has been assumed that this insulation layer was added to the existing wall of buildings built before 2007. The determined weighted average insulation thickness for the walls and roofs are given in Table 3.

Coefficients of heat transmission have been calculated for each investigated external area, as recommended by ISO 13789 [21] and based on the following equation:

$$U_{element} = \frac{1}{\frac{1}{h_{comv;out}} + \frac{1}{h_{cond}} + \frac{1}{h_{comv,ind}}} \qquad (1)$$

where h_{cond} represents the heat transfer coefficient in conduction of a wall. As recommended by ISO 13790 [22], the outdoor and indoor combined radiation-convection heat transfer coefficients are assumed to be respectively equal to 25 W/m^{2}K and 7.5 W/m^{2}K.

For newly constructed buildings (after 2007), the values are provided by EPB 2010 [20] and summarized in Table 4.

For retrofitted windows of buildings constructed before 1990, the methodology followed is similar to the case of walls, roofs and floors. However in this particular case, it was more appropriate to consider the U value for each type of windows. The U value dedicated to triple, double and double super insulating corresponds to typical values [23] and are gathered in Table 5 with their weighted average value for buildings from before 1990.

Table 3: Weighted average insulation thickness.

wall	0.05 m
roof	0.079 m

Once again, for windows of buildings constructed after 2007, the value is provided by EPB 2010. The overall coefficients of heat transmission determined for each case are summarized in Table 6.

In the case of a bottom-up approach involving dynamic simulation, total capacities for each element have been determined by means of constructive characteristics and as recommended in the ISO 13786 standard [24]. Capacity of windows and doors were neglected (light external area). Values are summarized in Table 7.

3.5.3. Thermal bridging

Janssens *et al.* [25] conducted a study on the development of limits for the linear thermal transmittance of thermal bridges in buildings. They provided typical U-values increase to be added to the average thermal transmittance per type of dwelling for Belgium to be used in a pragmatic approach to incorporate the effect of thermal bridging within the EPBD-regulation [26].

The following assumptions are made to apply them to the different buildings:

- For buildings with totally uninsulated walls (before 1970) thermal bridging were not taken into account.
- For retrofitted buildings, values of 0.15, 0.10, 0.08 and 0.07 W/m^{2}K were applied respectively for apartments, terraced houses, semi-detached houses and detached houses [25].
- For buildings built or retrofitted after 2012, values of 0.04, 0.02, 0.01 and 0.005 W/m^{2}K were applied respectively for apartments, terraced houses, semi-detached houses and detached houses [25].

3.5.4. Infiltrations and ventilation

TABULA [8] provides infiltration rates at 50 Pa in m^3/h-m^2 for the various dwelling types per construction years. Values from EPB 2010 have been added for walls externally insulated after retrofit. They are summarized in Table 8. Conversions between ACH (Air Change per Hour) values at 50 Pa to values for 2 Pa pressure

Table 4: EPB 2010 - U values.

Conduction coefficient of heat transmission		U_{wall} [W/m²K]	$U_{windows}$ [W/m²K]	U_{roof} [W/m²K]	U_{floor} [W/m²K]	U_{door} [W/m²K]
EPB 2010	YOC* > 2008	0.4	2	0.3	0.4	3.3

* YOC: year of construction

difference were obtained using a conversion exponent of 0.66 determined for Belgian dwellings by [27]:

$$ACH_{2Pa} = ACH_{50Pa} * \left(\frac{2}{50}\right)^{0.66} \qquad (2)$$

For houses heavily retrofitted between 2012 and 2030 and new buildings from after 2007, air-tightness is assumed to be greatly improved, and use of mechanical ventilation systems becomes mandatory. In new buildings, mechanical air supply and extraction systems with heat recovery are installed. 80% heat exchanger efficiency is assumed. For retrofitted buildings, air extraction systems are installed. In both cases, the renewal air flow rate is imposed to 0.6 volume per hour based on EN 15251 standard [28] category II, which corresponds to a normal level for new and refurbished buildings.

Table 5: U values for glazing.

Double glazing	2.9 W/m²K
Super insulating double glazing	1.4 W/m²K
Triple glazing	0.5 W/m²K
Weighted average value (<1990)	2.75 W/m²K

3.6. 2030 horizon

The 2030 horizon is particularly important for electricity and gas suppliers for mid-term planning and estimation of the global modification of the residential sector energy demand. 2030 prospective study could also give HVAC manufacturers indications about the potential introduction of an innovative system on the market. Moreover, this horizon is particularly suitable for the determination of an energy policy at a national level.

The final tree-structure of 2012 was turned into a so called "evolutionary" tree-structure to simulate possible evolutions of the building stock by taking into account a yearly demolition rate, a yearly construction rate, a yearly heavy retrofit rate and a yearly light retrofit rate.

The first step consists in creating a tree-structure by only taking into account the constructed and the demolished buildings between 2012 and 2030. The total number of building for the year 2030 can be deduced from Equation 3:

$$N_{2030} = N_{2012} * (1 + (x_{con} - x_{dem}))^{t} \qquad (3)$$

with:

- N_{2012}, the total number of building in 2012;
- N_{2030}, the total number of building in 2030;
- x_{con}, the yearly construction rate;
- x_{dem}, the yearly demolition rate;
- t, the number of year considered (i.e. t = 18 years).

Table 6: Coefficient of heat transmission.

Conduction coefficient of heat transmission		U_{wall} [W/m²K]		$U_{windows}$ [W/m²K]		U_{roof} [W/m²K]		U_{floor} [W/m²K]		U_{door} [W/m²K]
Insulation		NI**	WI**	NI	WI	NI	WI	NI	WI	Mean
Source		Tabula (value before renovation), LEHR (added insulation thickness for renovated elements of houses constructed before 1990), EPB 2010 (for renovated elements of houses constructed after 1990)								
YOC*	< 1945	2.25	0.59	5	2.75	4.15	0.44	3.38	0.77	3.3
										3.3
	45–70	1.56	0.53	5	2.75	3.33	0.43	3.38	0.77	3.3
	70–90	0.98	0.44	3.5	2.75	0.77	0.3	1.14	0.43	3.3
	90–07	0.49	0.4	3.5	2	0.43	0.3	0.73	0.4	3.3
	> 08	0.4		2		0.3		0.4		3.3

* YOC: year of construction

** NI/WI: not insulated/with insulation

Table 7. Elements total thermal capacity.

Capacity		K_{wall} [kJ/m^2-K]		K_{roof} [kJ/m^2-K]		K_{floor} [kJ/m^2-K]	
Insulation		NI	WI	NI	WI	NI	WI
Source		Tabula (wall composition), LEHR (added insulation thickness for renovated elements of houses constructed before 1990)					
	< 1945	453.6	472.1	30.9	43.8	235.2	236.4
	1945–1970	483.9	502.4	42.6	55.5	235.2	236.4
YOC	1970–1990	394.2	412.7	44.7	57.5	347.5	348.7
	1990–2007	396.2	414.8	46.7	50.9	348.1	349.2
	< 2008	397.3		50.3		348.4	

Table 8: Infiltration rate at 50Pa per time period and type of dwelling [9].

Infiltration rate at 50Pa [m^3/hm^2]					
	Initial walls				**Walls insulated after retrofit**
Time period	**Freestanding house**	**Semi-detached house**	**Terraced house**	**Apartment**	**All type**
<1971	18	18	14.9	14.9	6
1971–1990	17.1	16.3	14.1	14.1	6
1991–2007	12	12	10	10	6
2008–2002	6.1	6.3	6	6	6
>2012	/	/	/	/	2.5

Concerning the repartition, the total amount of constructed houses is added to the tree structure. Conversely, the total amount of demolished building is removed from the tree structure. When removing these cases, the assumption made is that priority is given to the totally not insulated buildings before 1945, then between 1945 and 1970... This assumption may not realistically represent the real estate market, since it may imply the destruction of historically classified buildings for instance.

The second step consists in introducing the heavily refurbished buildings in the tree structure. Heavy renovation corresponds to the insulation of all the elements of the buildings (walls, windows, roofs and floors) according to EPB 2010 [20]. Priority is given to the totally not insulated buildings constructed before 1945, then to those with only windows insulated and constructed before 1945. Once all these buildings built before 1945 have been refurbished, retrofit of buildings built between 1946 and 1970 can be considered, and so on.

The third step focuses on the introduction of the lightly refurbished building. Light renovation corresponds to the insulation of roofs and windows according to EPB 2010.

The fourth step consists in defining the new occurrence of each building based on the updated absolute number of buildings.

4. Results

As already mentioned, the proposed hybrid approach is thought more accurate for the building stock consumption predictions than approaches previously presented in the literature. Combination of data coming from several studies allows for a better representation of the heterogeneity of the current Belgian building stock. The developed tool can be freely downloaded by the bottom-up modeling community.

The so-called "evolutionary" tree-structure can be used for a quick assessment of a wide variety of evolution scenarios of the residential building stock and to assess the impact on the energy consumption of different penetration rates for various HVAC technologies. For instance, the tree-structure can be used to estimate the impact of retrofit strategies on the whole building stock consumption. A forecast of the required installed heating capacity can be provided. Penetration rates for heat pumps and μ-CHP or their possible evolution by 2030 can also be obtained.

For the sake of clarity, it is important to note that the results presented in the sections below are expressed per average dwelling, i.e. a weighted average of the results obtained for each typical dwelling. To obtain numbers for the overall residential building stock, this average value should be multiplied by the number of dwellings (4 675 433 for the year 2012). This number is assumed to evolve by 2030, depending on the imposed construction and demolition rates.

4.1. Final tree-structure of 2012

The final tree-structure is illustrated in Figure 3 for the particular case of semi-detached houses constructed between 1946 and 1970. The entire housing stock is divided in 992 cases: the number of investigated cases is 282 for freestanding, semi-detached and terraced houses and 146 for apartments. Used references are also given in Figure 3.

Based on this tree-structure description, average U-values for walls and windows and their relative share in the building stock is illustrated in Figure 4 for walls and windows.

4.2. Impact of retrofit strategies of the building stock

An estimation of the average annual heating needs per dwelling can be obtained by the “Heating Degree Day” (HDD) method. For the Belgian context, the latest are defined on a 15°C/15°C base and assumed identical for all types of buildings. This means that, for an average daily outdoor temperature below 15°C, indoor air is assumed to be heated up to 15°C, given that external and internal gains bring it to reach thermal comfort of 18°C. A supplementary condition is introduced to determine the beginning and end of the heating season, based on the maximum temperature of the day (respectively above or below 18°C) and whether a minimum of 2 HDD have been counted for the day [29]. 1914 real Heating Degree Days were reported for Uccle (Belgium) for year 2012.

In addition to the reference year 2012, two evolution scenarios up to horizon 2030 are investigated:

- A “Business-as-Usual scenario” (BAU): expected demolition and construction rates are set respectively to 0.075% and 0.9% per year, and the renovation rates to 0.8%/year for light renovation and 0.5%/year for heavy renovation.
- An optimistic retrofit scenario: expected demolition and construction rates are set respectively to 0.075% and 0.9% per year, and the renovation rates to 0.5%/year for light renovation and 1.5%/year for heavy renovation.

It should be noted that, given the assumption chosen for the destruction of existing buildings, the results presented hereafter give optimistic views in terms of energy savings.

Global heat transfer losses through building envelope (H_{total}) combine transmission losses (H_{tr}) and ventilation losses ($H_{infiltrations\ \&\ ventilation}$). Transmission losses are obtained by multiplying the average heat transfer coefficient by the heat transfer area, whereas the ventilation losses are the product of the ventilation mass flow rate by the air thermal capacity. Values for the different scenarios are listed in Table 9.

Based on these data, the average space heating needs (i.e. not including the production system efficiency) reached 18.8 MWh per average dwelling. This value is in agreement with the average values for space heating consumption provided by [12] for example. Domestic hot water needs are estimated to 50 liters at 50°C per day per adult equivalent ([29] & [30]) which represents 1.67 MWh per year per dwelling for 1.97 adult equivalents. In 2030, a business-as-usual scenario leads to annual total energy needs for space heating and domestic hot water of 14.4 MWh per dwelling. In the optimistic scenario, the average annual total energy needs for space heating and domestic hot water per dwelling is 12.1 MWh. The respective shares of free-standing houses, semi-detached houses, terraced houses and apartments are illustrated in Figure 5-left. It can be noted that the relative share of domestic hot water in the energy needs increases (Figure 5-right).

The same analysis can be presented in terms of primary energy consumption per energy vector for the whole building stock (Figure 6). Average production systems efficiencies, expressed based on lower heating values (LHV), are now taken into account (values are given in Table 10 [31]) as well as final to primary energy conversion factor. The final to primary energy conversion factor for electricity is 2.5 for Belgium in 2012, and is assumed unchanged in 2030. Energy savings per average dwelling reach up to 22%. With the imposed destruction and construction rates, the number of dwellings increases up to 5.2 million in 2030, leading to 13% reduction in terms of primary energy consumption at the residential building stock scale for the business as usual scenario.

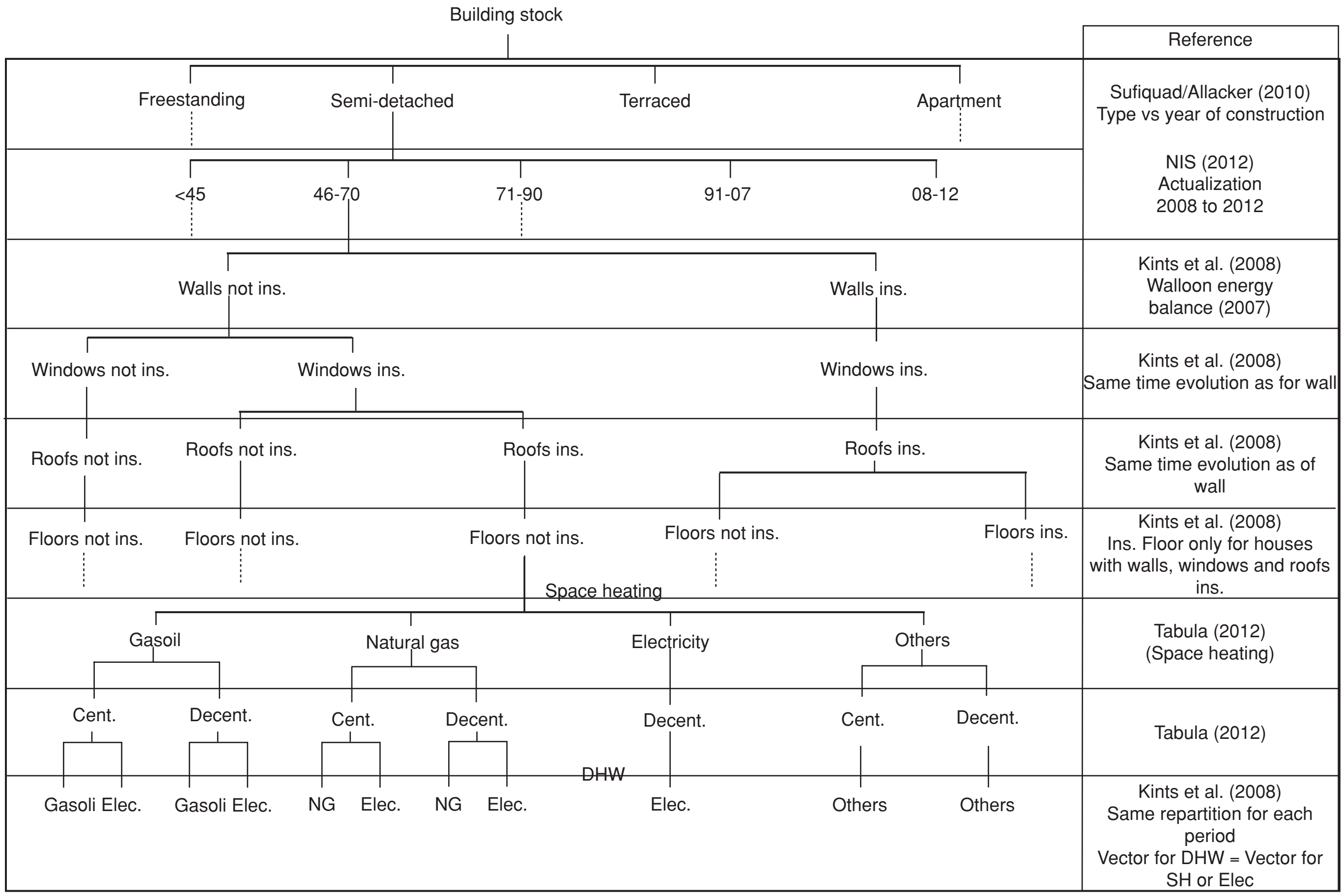

Figure 3: Belgian building stock tree structure.

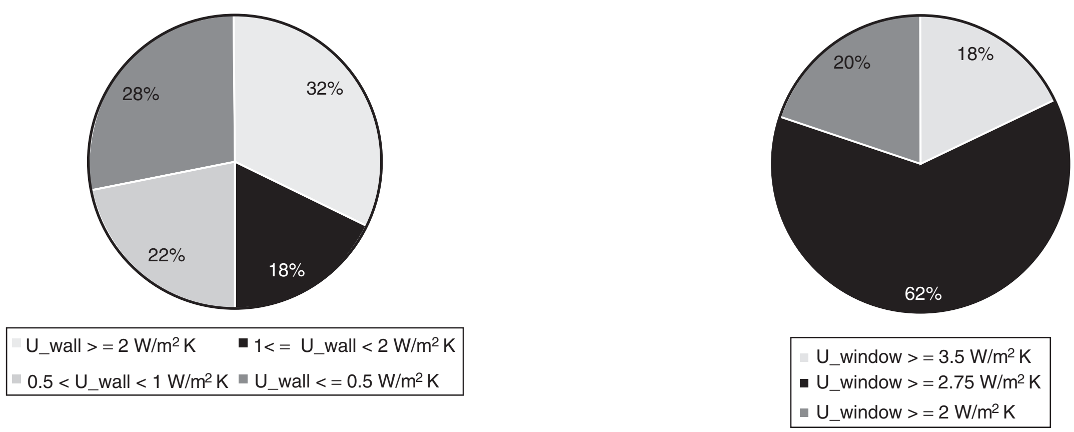

Figure 4: U values repartition for walls and windows.

4.3. Forecast of the required installed heating capacity

The tree-structure also allows to determine the required installed heating capacity according to the type, age and envelope characteristics of the buildings. Sizing of the heating system can be carried out at –10°C outdoor temperature and an air change rate of one volume per

Table 9: Transmission and ventilation losses coefficient for 2012 reference case, 2030 BAU scenario and an optimistic retrofit scenario by 2030.

	2012	2030 – BAU	2030 – Optimistic
$H_{tr,\ without,\ thermal,\ bridging}$ [W/K]	279	195	151
$H_{tr,\ with,\ thermal,\ bridging}$ [W/K]	290	205	161
$H_{infiltrations,\ ventilation}$ [W/K]	82	72	65
H_{total} [W/K]	372	277	226

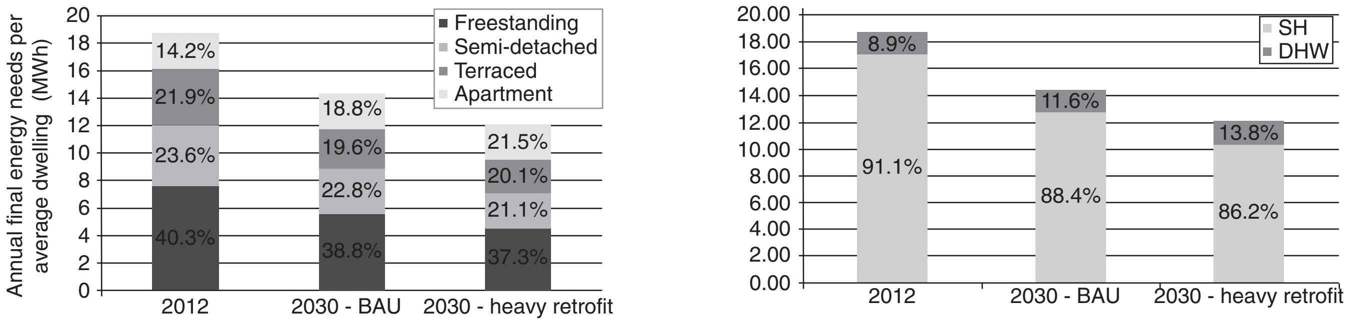

Figure 5: Annual energy needs per average dwelling for space heating and domestic hot water.

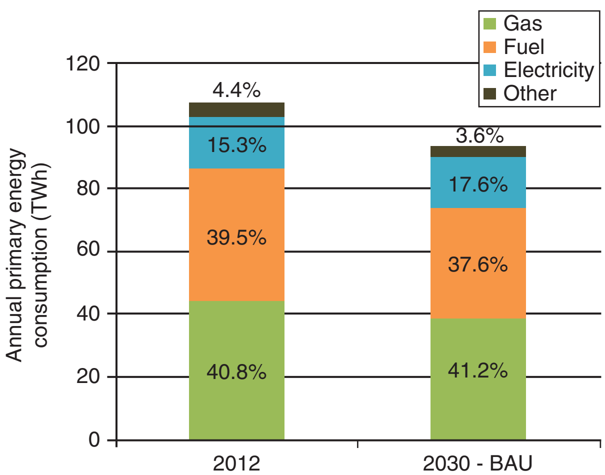

Figure 6: Annual primary energy consumption for Belgian residential building stock by energy vector for space heating and domestic hot water.

hour. Figure 7a represents the required installed capacity as a function of the cumulative distribution in the building stock for three different scenarios: 2012 situation, the BAU scenario and a heavy renovation scenario defined above. In 2012, the average largest installed capacity is around 31 kW. For the BAU scenario, this number only drops to 30 kW. In the optimistic scenario for 2030, contrariwise, the largest consuming houses are either demolished or heavily retrofitted, leading to a decrease of the maximum installed capacity to 20.5 kW. Indeed, Figure 7b shows that houses with the largest installed power are those constructed before 1970. The latter are retrofitted in priority as explained in the section devoted to the methodology of implementation of the 2030 scenarios. This Figure also points out that newly constructed houses (>2007) require in average an installed capacity of 8 kW.

The same analysis can be carried out per type of building. Indeed, the required installed capacities are rather different for single family and multi-family buildings. In 2012, around 45% of the heating systems of single family houses present an installed power higher than 15 kW, whereas all the apartments require installed capacities below 9 kW, and 50% below 4.5 kW.

4.4. Assessment of the penetration rate of heat pumps and μ-CHP

Other potential uses of the developed tree-structure are:

- The assessment of the maximum penetration rate of a given HVAC technology (available power, technical constraints...)

Table 10: Production system efficiency based on lower heating values (LHV) [31].

	Construction year	Energy vector SH	Energy vector DHW	Efficiency SH [–]	Efficiency DHW [–]
Centralheating system	<2007	Gas	Gas	0.85	0.85
		Fuel	Fuel	0.8	0.8
		Gas	Electricity	0.85	1
		Fuel	Electricity	0.8	1
		Other	Other	0.8	0.8
	>2007	Gas	Gas	1	1
		Fuel	Fuel	0.97	0.97
		Gas	Electricity	1	1
		Fuel	Electricity	0.97	1
		Other	Other	0.97	0.97
Decentralized system	/	Gas	Gas	1	0.9
		Gas	Electricity	1	1
		Fuel	Fuel	1	0.9
		Fuel	Electricity	1	1
		Other	Other	1	0.9
		Electricity	Electricity	1	1

- The assessment of the impact of a given penetration rate of HVAC technology on the overall building stock energy use.

The latter scenarios can be considered for the year 2012 or for the 2030 horizon.

As a first illustration, a heat pump manufacturer could compute the maximum penetration rate on the residential market of a given heat pump technology and maximum installed power. The latest has been defined as required installed power to cover 80% of heating needs for -10°C outdoor temperature, 20°C indoor temperature and an air change rate of 1 volume per hour at 2Pa. For example, in 2012, a single 10 kW heat pump could potentially be installed in 57% of the dwellings. This number rises to up 75% and 85% respectively for BAU and optimistic scenarios in 2030.

If indeed 57% of air-to-water heat pumps were installed, the impact on the electricity consumption for the entire building stock would correspond to the share represented in Figure 8(right). Assuming an average seasonal Coefficient of Performance (COP) of 2.75 for space heating and 2.62 for domestic hot water production [32], the annual primary energy savings reach only 5% per average dwelling. The reason for such a small decrease can be found in the fact that, with the aforementioned assumptions, the dwellings likely to be equipped with heat pumps are amongst the least consuming of the overall stock.

These numbers can provide useful information for heat pump manufacturers, regarding the current and future expected heat pump markets.

A similar analysis can be conducted for μ-CHP units. In this case, two criteria have been used to determine if a μ-CHP of 1kW electrical power (kWel) could be installed in a specific building. The first one is related to the actual energy vector. It was chosen that μ-CHP could only be installed in buildings supplied by gas. The second is based on an economic criterion: the user can enter a given thermal power and a number of working hours required to be cost-effective. For this example, the number of hours was set to 4000 [33], including part-load working periods, leading to a maximum penetration rates of 10.3% for 2012, 3.8% for BAU scenario and 1% for the optimistic retrofit scenario. These figures only account for single separated housing equipped with their own μ-CHP (1kWel). Deeper investigations should also consider bigger units for apartment's buildings and cluster of dwellings.

5. Discussions

As for any simulation model, the results are strongly dependent on the assumptions made. As emphasized by

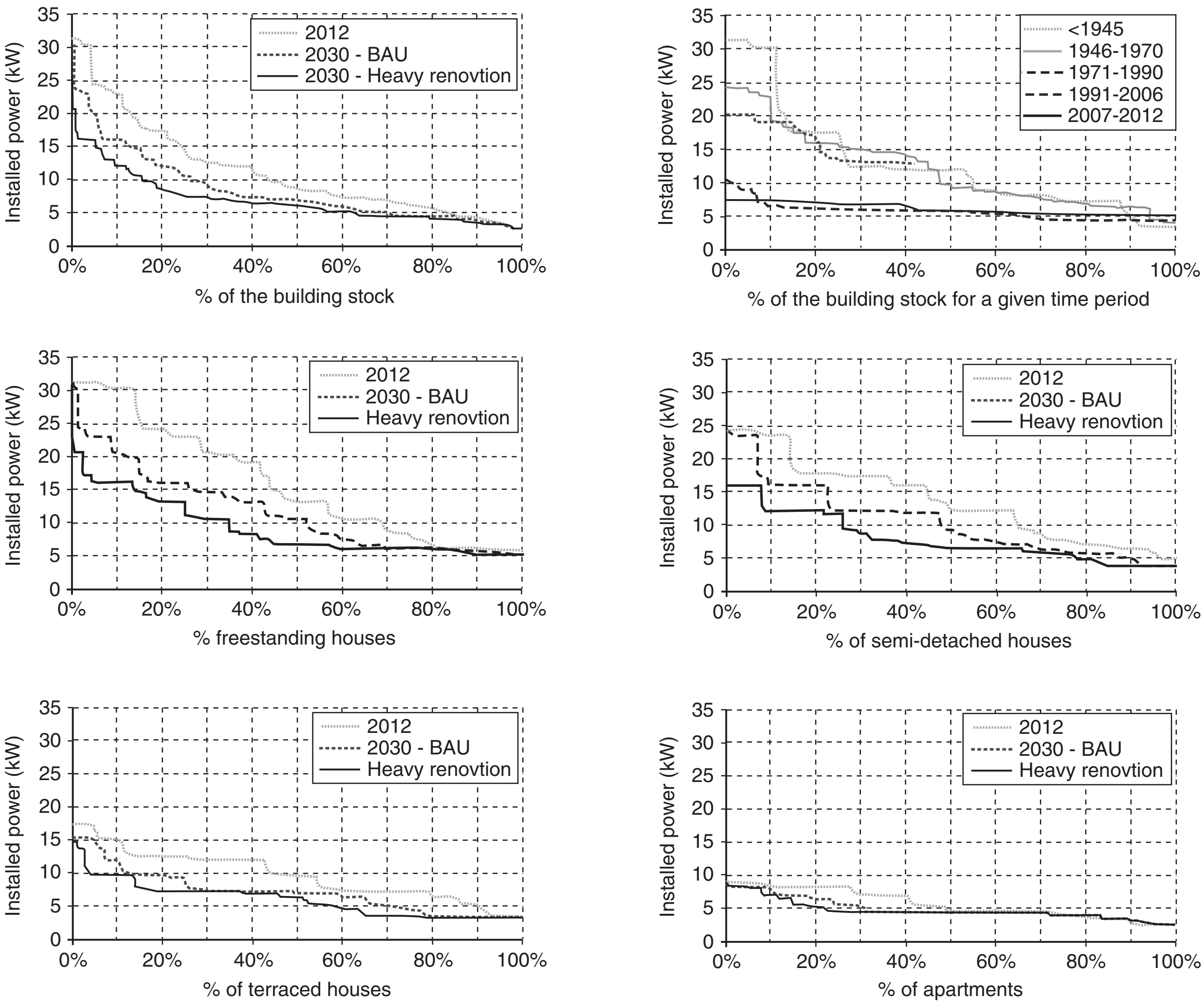

Figure 7: a) Installed capacity for heating needs for 2012, 2030 BAU scenario and 2030 heavy renovation scenario for the Belgian residential building stock – b) Installed capacity for heating needs for 2012 building stock according to the construction age of the buildings – c) Installed capacity for heating needs for 2012, 2030 BAU scenario and 2030 heavy renovation scenario for freestanding houses – d) Installed capacity for heating needs for 2012, 2030 BAU scenario and 2030 heavy renovation scenario for semi-detached houses – e) Installed capacity for heating needs for 2012, 2030 BAU scenario and 2030 heavy renovation scenario for apartments.

the results presented in section 4, the developed tree-structure constitutes a powerful and flexible tool. First, the analysis devoted to envelope retrofit confirms the large potential for energy savings through improvement of building envelope insulation level. In a business-as-usual scenario by 2030 horizon, primary energy savings at the national scale reaches 13%, taking into account the simultaneous increase in the number of dwellings. More optimistic scenarios have to be implemented to meet European energy policy roadmaps by 2030. Secondly, a massive introduction of heat pumps (57%) amongst low-consuming houses in 2012 (installed thermal power inferior to 10 kW in design conditions) brings only 5% primary energy saving for the current electricity production energy mix. The share of electricity consumption increases from 15 to 40%. In the coming years, this electricity consumption increase could be satisfied by renewable energy sources. The

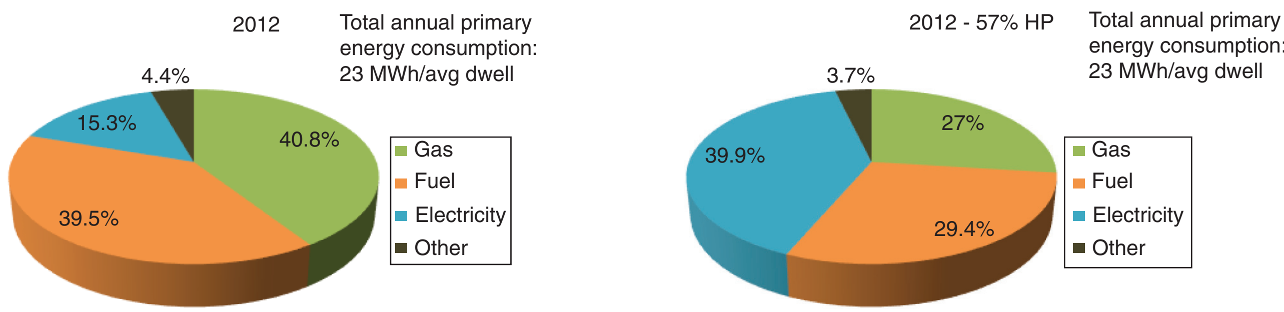

Figure 8: Impact of introduction of 60.02% heat pumps on the total annual primary energy consumption per average dwelling.

impact of such high penetration rate on the electricity grid has to be investigated. For example, increase in peak power demand should be quantified, which is possible by combining this tool to dynamic building simulation models.

6. Conclusions and perspectives

The present paper proposes a tree-structure of the Belgian residential housing stock. The first part presents the state of art in the field of the characterization of the Belgian residential housing stock and introduces some concepts related to the creation of a housing typology and more precisely the Belgian housing typology. The final tree-structure for the period up to 2012 presents 992 typical buildings, each of them being characterized in terms of age, type, building envelope characteristics and used energy vectors. The tree-structure is then extended for the period 2012–2030.

Scenarios of envelope retrofit have been investigated for 2030 horizon: a business-as-usual scenario (0.5 % heavy renovation/year) and an optimistic scenario (1.5% heavy renovation/year, 0.5% light renovation/year). Reductions of respectively 23% and 36% in final energy needs per dwelling for space heating and domestic hot water production were obtained compared to year 2012. Conclusions differ in terms of primary energy savings at the national scale; business-as-usual scenario leads to 13% overall reduction. The developed tree-structure also allows quick estimations of the cumulative frequency of the required installed power according to the type, age and envelope characteristics of the buildings, up to year 2030. In 2012, around 45% of the heating systems of single family houses present an installed capacity higher than 15 kW. Newly constructed houses (>2007) require in average an installed capacity of 8 kW. Finally, the impact of the penetration of innovative technologies such as heat pumps on the electricity consumption can be assessed. If for example 57% or the housing stock was equipped with air-to-water heat pumps of maximum 10 kW thermal power, the annual primary energy savings reach only 4% per average dwelling.

In a future work, this tree-structure will be coupled to a dynamic building simulation model, allowing the derivation of aggregated gas and electricity load profiles of the Belgian residential building stock for a given time step (quarter hour, hour). The impact of the penetration of different HVAC technologies on these profiles will be assessed. This simulation model represents a valuable tool for grid management system operators in the context of integration of decentralized renewable energy sources. Indeed, buildings can potentially become key systems for smart energy management at the distribution grid level. Modulation strategies of the load profiles for demand side management purposes will be investigated.

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List of abbreviations

ACH:	Air Changer per Hour
BAU:	Business As Usual
COP:	Coefficient Of Performance
DHW:	Domestic Hot Water
HDD:	Heating Degree Day
HVAC:	Heating, Ventilation and Air Conditioning

LHV: Lower Heating Value
μ-CHP: micro Combined Heat and Power
SH: Space Heating

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