Applied Energy 306 (2022) 118128

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Developing a benchmark model for renovated, nearly zero-energy, terraced dwellings

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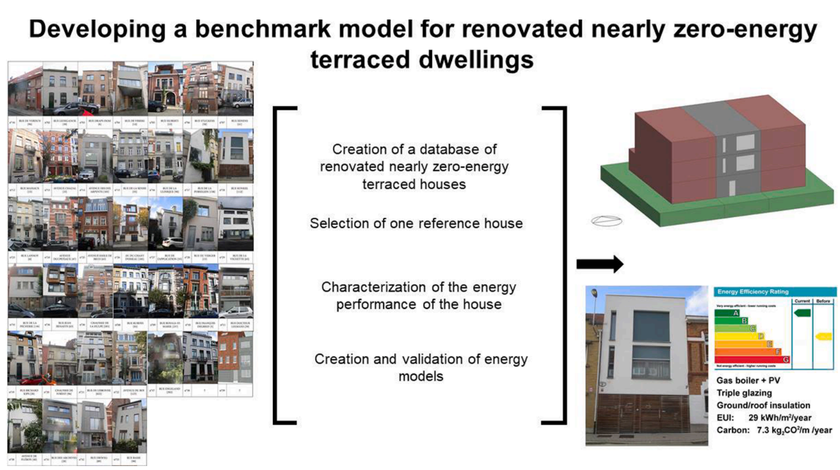
HIGHLIGHTS

- Development of a benchmark model for renovated nearly zero energy terraced buildings.
- The average energy use intensity per household was 29 kWh/m^2/year.
- Models validated with four-year monitoring data on energy consumption.
- Middle old families dominate households, and their occupancy profiles are presented.
- Findings on energy needs and use intensity are useful in temperate and continental climates.

GRAPHICAL ABSTRACT



Abbreviations: ANN, Artificial Neural Networks; BPIE, Building Performance Institute Europe; BMS, Building Management System; CAV, Constant Air Volume; CDD, Cooling Degree Days; CBECS, Commercial Buildings Energy Consumption Survey; CIBSE, Chartered Institution of Building Services Engineers; CO2, Carbon Dioxide; COP, Coefficient of performance; CV(RMSE), Coefficient of Variation of the Root Mean Square Error; DHW, Domestic Hot Water; EPBD, European Energy Performance of Buildings Directive; EPC, Energy Performance Certificates; EU, European Union; EUI, Energy Use Intensity; GDPR, General Data Protection Regulation; HDD, Heating Degree Days; HVAC, Heating, Ventilation and Air Conditioning; IAQ, Indoor Air Quality; IEQ, Indoor Environmental Quality; MBE, Mean Bias Error; MVHR, Mechanical ventilation with heat recovery; nZEB, nearly Zero-energy Building; nZE, nearly Zero-energy; nZES, nearly Zero-energy Schools; OCCuPANt, On the Impacts Of Climate Change on the indoor environmental and energy PerformAnce of buildiNgs in Belgium during summer; PC, Personal Computer; PHS, Passive House Standard; PHPP, Passive House Planning Package; PMP, Platform Masion Passive (Belgium); Pixii, Onafhankelijk Kennisplatform Energieneutraal Bouwen (Belgium); QZEN, Quasi Zero Energie; SHGC, Solar Heat Gain Coefficient; TABULA, Building Database Typology in the European Union; TMY, Typical Meteorological Year; UK, United Kingdom; USA, United States of America; VAF, Variable Air Flow; WWI, First World War; WWR, Window to Wall Ratio; ZEBRA 2020, nearly Zero-Energy Building Strategy 2020.

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https://doi.org/10.1016/j.apenergy.2021.118128
Received 20 April 2021; Received in revised form 22 October 2021; Accepted 23 October 2021
Available online 8 November 2021

ARTICLE INFO

Keywords:
Reference building
Terraced building
Row housing
Energy audit
Energy efficiency
Energy use intensity
Temperate climate

ABSTRACT

Brussels is one of the European cities with the most significant number of Passive House buildings on the continent. In the Brussels-Capital Region, the nearly zero-energy building obligations implemented is implemented since 2010. The Brussels-Capital Region has set up ambitious energy standards for new constructions. These standards target 'nearly zero' or 'very low energy consumption and are inspired by the 'passive house standard,' where high-energy performance is first achieved. Ten years after boasting this groundbreaking policy, many renovated, terraced houses are renovated to comply with the nearly zero-energy building requirements. Therefore, this study aims to develop an energy performance data set and one building performance simulation benchmark model for nearly zero-energy dwellings in Brussels. The study reports an inventory and field survey conducted on a terraced house renovated after the year 2010. An analysis of energy consumption (electricity and natural gas) and a walkthrough survey were conducted. A building performance simulation model is created in EnergyPlus to benchmark the average energy consumption and building characteristics. The estimate's validity has been further checked against the public statistics and verified through model calibration and utility bill comparison. The benchmark has an average energy use intensity of 29 kWh/m^2/year and represents terraced single-family houses after renovation. The paper provides a timely opportunity to evaluate the actual performance of nearly zero-energy terraced houses. The findings on energy needs and use intensity are useful in temperate and continental climates.

1. Introduction

Buildings account for 40% of Europe's energy use, and the residential sector accounts for 20% of the total energy use at the European level [1]. The introduction of the binding regulation for nearly Zero-Energy Buildings (nZEB) [2] by the European Commission (EC) has promoted the concept for the newly constructed and renovation of existing buildings [3]. The European Green deal states to cut carbon emissions to 55% of 1990 levels by 2030 by improving the energy performance of buildings [4]. Member states must increase their renovation rate from 2% a year to 3% annually before 2023 before stabilizing at least 2% in 2030. To achieve the new carbon reduction targets, [5] renovation gets remarkable attention in discussions about a decarbonized building stock. Yet, existing households exceed the number of newly built households in Europe [6]. The existing building stock will continue to dominate for the next 30 years. For example, in Belgium, the annual renovation rate of the existing building stock is <1% [7]. Deep renovations only occur sporadically. As shown in Fig. 1, dwellings are responsible for 14% of Belgium's greenhouse gas emissions. Awareness about the carbon emissions reduction potential of existing residential buildings is widespread among European governments, builders, housing associations, and building owners [8].

The EU 2030 target of climate-neutrality and the European Green Deal pivot on detailed knowledge of building stock properties and behavior. Detailed knowledge of building stock features and performance has the potential to positively advance policymaking and market design targeting nearly zero-energy, renovated buildings. While in North America and particularly the United States of America (USA), the benchmarking of existing buildings has acquired a consistent tradition [13,14,15,16,17,18], in Europe this research is gaining more and more importance [19]. The TABULA [10] building typology project and the EPISCOPE [20] building monitoring projects are the most structured and central depository of building stock models. An improved data set will enable a more accurate reflection of the building stock and mean deeper granularity in its analysis, potentially taking more aspects into accounts, such as nZEB, smart-readiness, and renewable energy generation. A shared data set will also support better comparability amongst modeling results. Modeling results in turn help decision-makers aggregate existing data and information by calculating potential results of their decision-making.

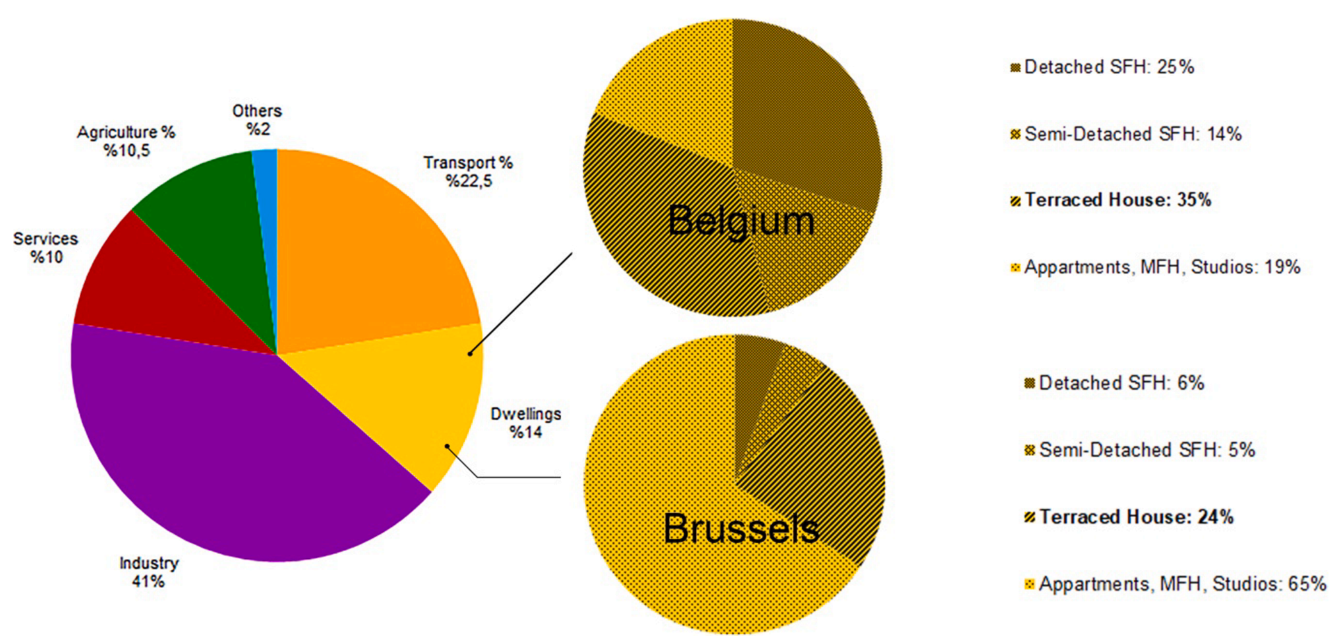

Fig. 1. Greenhouse gas emissions of Belgium in 2018 (%) [9] and the Distribution of Belgian dwellings by the period of construction [10–12].

The Energy Performance of Buildings Directive EPBD [21] requires the development of 'reference buildings' representing their building stock [22]. According to the EU Commission Guidelines [23], it is recommended that reference buildings are established representing the most typical building in a specific category (e.g., type of use and reference occupancy pattern or floor area or building envelope construction, etc.). Reference buildings-related data may include meteorological and socio-economic data, building characteristics (typology, thermophysical etc.), technical services and systems, renewables technologies, audits, indoor environmental quality, energy consumption, investments for operation, maintenance, and renovation, subsidies, energy market, and emissions. However, in Belgium, the creation of representative benchmark models based on field measurements is still in its infancy [24]. The Belgian residential building stock is relatively old, similar to most other Western European countries, and has a huge potential in energy saving and GHG emission reduction [25].

In this context, the development of building benchmarks allows to feed in or extract data for designing more effective building sustainability and renovation policies, programs, projects, and financing schemes. Thus, the development of a benchmark model requires characterizing building vintage and archetype. In Europe, one of the most underrepresented housing benchmarks is the terraced archetype or row houses [26]. In Belgium, Denmark, France, Germany, Ireland [26], the Netherlands, Scandinavian countries, and the United Kingdom (UK) [27], suburbanization after WWI encouraged the dwellers to live in single-family terraced housing in metropolitan and suburbia [28]. As shown in Fig. 2, terraced households often have two façade and a narrow plan, and a backyard. A large part of the European urban and suburban building stock does not comply with any energy efficiency requirements. Consequently, there is a lack of representative reference models of the average energy performance compared with the results of EPBD calculation models. A representative model of terraced houses in Europe is needed to assess this kind of scenario, as done in some EU projects to define target values for policy and regulatory implementation (e.g.

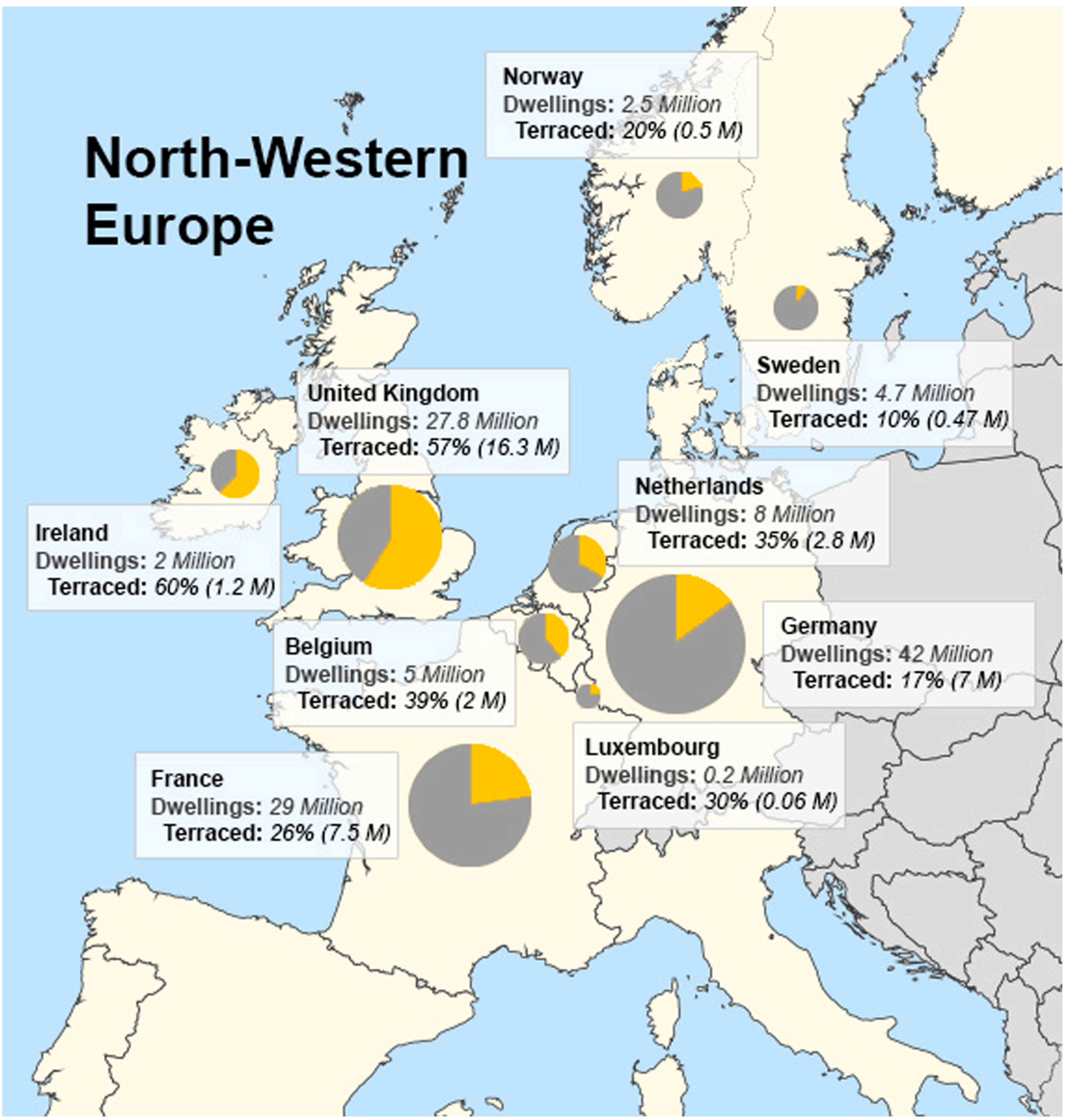

Fig. 2. The share of terraced housing archetype in North-Western Europe in 2020 [28].

energy consumption limits according to the EPBD. Bridging the knowledge gap on the real performance of renovated nearly zero energy buildings enables scientists and professionals to focus on the next step of carbon neutrality and healthy indoor environment of the non-historical residential building stock. (SEE Fig. 3.)

To create a new reference model for renovated, terraced buildings, we complied a new buildings database of renovated, nearly zero-energy, terraced buildings recently established to track the energy performance of buildings and other characteristics across Brussels. The Passive House concept was strongly promoted in Brussels and evolved to include nearly zero-energy buildings. The Brussels-Capital Region has put in place a “bottom-up” type energy efficiency policy for buildings, aimed at involving all citizens (all social classes combined) through various actions and incentives, reducing energy use in buildings. The BatEX (Batiment Exemplaire or Exemplary buildings) award was launched in 2007 [29]. Since 2007, four BatEX calls for projects have made it possible to select 156 projects of low energy and nearly zero-energy buildings constructed or renovated in an exemplary manner resulting in 9,359 m^2 of individual housing. In this study, we selected 39 renovated, terraced houses representing nearly zero-energy and characterized their energy performance by creating and validating a reference model.

Thus, this study aims to accelerate nearly zero-energy terraced houses’ renovation by creating validated benchmark models representing those buildings. The current study follows a cross-sectional study design where field surveys and auditing for more than thirty-nine households. The research directly engaged occupants who completed self-reported surveys and shared their energy bills compiled in a dataset about their buildings. The research methodology combines mixed research methods involving qualitative (e.g., literature review) and quantitative empirical and modeling (e.g., walkthrough audits, building performance simulation, calibration) research. Our study approach and methodology are similar to the work of Murphy et al. [30], Touchi et al. [31], Kragh, and Wittchen, and Attia et al. [24,32] aiming to develop two simulation reference models based on monitoring and analyzing 1320 households. The building performance simulation models are implemented in the EnergyPlus energy simulation program. A systematic and replicable approach for measurement and verification based on ASHRAE Guideline 14 was used to calibrate the building performance simulation models [33].

The study provides robust evidence of the extent of energy intensity use and the influence of occupant behavior in Belgium’s temperate climate. Simultaneously, its methodology and findings can be helpful across Northern and Western Europe (see Fig. 2). Characterizing the real energy performance of the renovated building stock has multiple benefits for various stakeholders such as reduced energy bills, carbon emissions, and improved level of indoor environmental quality for households. The main added value of this paper is that it will help achieve the EU carbon targets leading up to net-zero emission buildings by the middle of the country. Thus, the originality of the paper relies on defining the relationship between occupancy profiles and energy use of renovated nearly zero-energy residential buildings. The building energy models were created using a multizonal modeling approach distinguishing living areas, sleeping areas, and short presence spaces. On these bases, the paper presents a fundamental construct of a building energy model and its occupancy profiles that represent renovated, nearly-zero terraced residential buildings to predict future renovation potential. One of the reasons for the article’s originality is that the results report a significant change of the nature of energy needs of high-performance terraced dwellings towards electricity domination. Finally, the benchmark model can be used in other countries to compare better and verify the energy savings and support the modernization of high-performance buildings with smart technologies towards carbon neutrality of heating. The findings will inform the design, monitoring, and evaluation of the EPBD calculation method and energy efficiency policies. The factors and building characteristics that can lead to the energy performance gap of nearly zero-energy terraced houses are discussed.

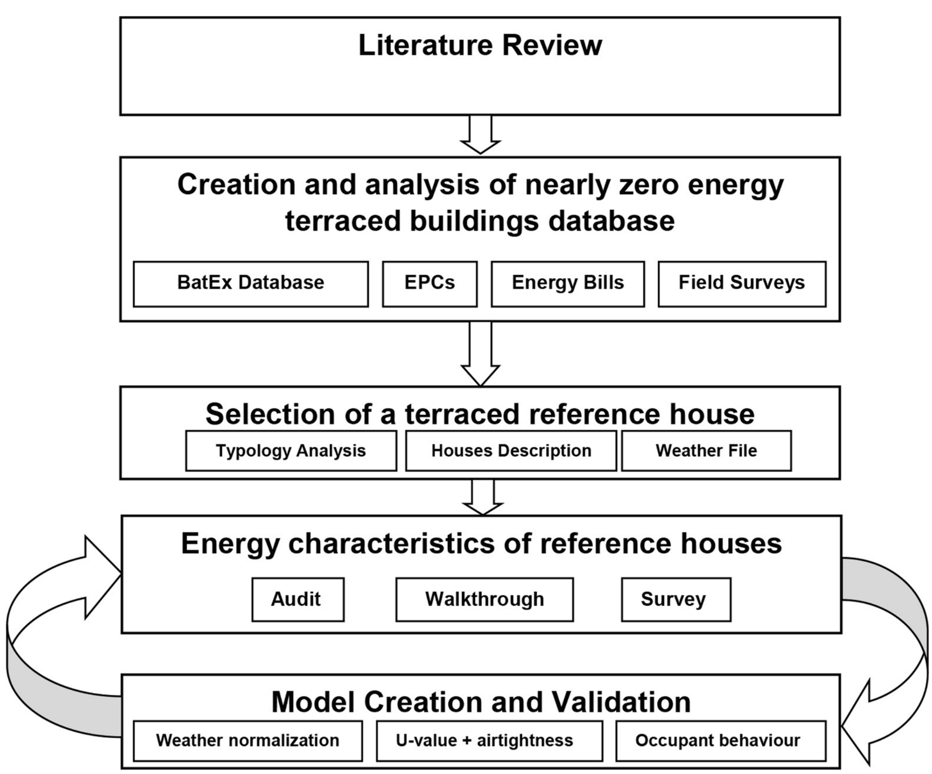

Fig. 3. Conceptual framework for the study methodology.

2. Methodology

The research methodology is based on a mixed-method comprising observational methods and modeling methods to create a representative reference model for renovated, nearly zero-energy terraced buildings in Brussels (Belgium). As shown in Fig. 2, the methodology started with a literature review to position the research and define the knowledge gap regarding nZEB benchmarking studies. Then, creating a database of renovated buildings took place to characterize the energy efficiency of terraced nZEB. Several databases were consulted, and information was compiled to form a dataset of high-performance terraced households. Next, field visits and walkthrough audits were conducted to characterize the building's performance and collect energy bills. Only the selected representative benchmark was modeled and validated. The research design was validated by modeling experts and was compared to previous similar studies of Attia et al. [72], Ben et al. [26], and Pagilano et al. [35] to refine its approach. The methodology is similar to the approach of Tereci (2013) [36], who defined a reference building and calculated their energy use for different German archetypes; and Ghajarkhosravi (2020), who developed an energy benchmark models for multi-unit residential buildings (MURBs) in Toronto, Canada [37]. The following sections describe in detail the steps undertaken in this research.

2.1. Literature review

The literature review analysis was performed by browsing through key references related to building benchmarks for high-performance residential buildings. More than sixty publications were reviewed in the Belgian content concerning residential building benchmarking and energy efficiency characterization. The review included residential benchmarking reports that were developed as part of the EU cost-optimality approach for the three regions of Belgium; Brussels [38], Flanders [39], and Wallonia [40]. An exhaustive list of the reviewed studies and their content analysis can be found in this study's technical report [24]. Moreover, vital international studies on benchmarking were reviewed and summarized in the introduction. The review focused on state-of-the-art benchmark model creation approaches [22] and their calibration techniques for model validation [41]. The study also covered the most well-known building archetype databases, such as the US Department of Energy's archetypes database for residential buildings [13] and the European Projects TABULA EPISCOPE [20] that aim to provide reference buildings for the European building stock.

2.2. Creation of a database for nearly zero-energy terraced buildings

An initial database of 44 households was created and updated. Several databases were consulted and used to compile a consistent dataset of nearly Zero-energy Terraced Buildings. Firstly, the BatEx platform for exemplary buildings was consulted [29]. BatEx platform and database result from a project set up by the Brussels-Capital Region to provide financial support for low and ultra-low energy residential buildings. BatEx project concerns all types of exemplary buildings: single-family housing, collective housing, and offices, commercial or industrial buildings both for renovations or new constructions [42]. Based on a set of inclusion and exclusion criteria, we selected terraced nZEB. The inclusion criteria of selected buildings included low energy and ultra-low energy buildings, including Passive House certified buildings. The inclusion criteria included archetypes such as terraced or row houses with single-family or individual dwellers occupying the building. The household had to be renovated or newly constructed after 2010 and has been occupied for at least three consecutive years. An optional criterion was to include households with smart meters. The exclusion criteria included households that did not include a mechanical ventilation system or were partially renovated. The search focuses mainly on carbon neutrality and circularity on building scales [27]. Secondly, Brussels Energy Performance Certificates (EPC) database was consulted [43] to inquire about the selected buildings' energy rating. In Brussels, EPC is valid for ten years. Therefore, we tried to track the difference between the EPC rating before and after renovation or construction. Thirdly, the Belgian Building Cadaster [44] was consulted to verify the buildings' construction dates. At the end of this first screening and selection round, 44 buildings are retained in the initial database.

Next, field visits were organized to visit the 44 households representing nZEB in Brussels. All houses were visually inspected to assess the building envelope characteristics. The field surveys also enabled identifying and characterizing the energy systems (air and water heating systems, ventilation, lighting, smart meter, etc.) of individuals who could submit the survey by mail or online. Households occupants were invited to sign a consent form to share their electricity and fuel bills (gas or fuel oil) via their energy providers. Once signed, it was possible to access their bills via the energy suppliers. The content of survey questionnaires and consent forms is discussed in detail in Section 2.4 and found in a separate technical report [24]. In addition, occupants were invited to fill in an online or paper survey that characterizes their building's energy efficiency. The consent form and survey content covered the building characteristics, domestic hot water, energy systems, and occupant behavior. Logbooks were also distributed to owners so that they could indicate their monthly consumption. In some dwellings, data loggers were installed to record consumption. Access to the forms and surveys can be found in the project report [24]. Finally, we accessed the EnergieID tool for monitoring energy use was consulted [45]. EnergieID is a community joint monitoring platform. The platform collects consumption data of families who received a subsidy from the BatEX project to allow users to compare their data and compete to reduce their energy use. *Bruxelles Environnement* (local government) provided the EnergieID tool for monitoring users' resource use (energy and water) to encourage occupants to track their buildings and avoid rebound effects [46]. Through EnergieID tool and BatEx, households' owners were contacted, as it was often easier to convince people to share their bills. The field visit excluded several cases that did not meet the inclusion and exclusion criteria explained earlier. Finally, the dataset was reduced to 39 buildings representing high-performance row housing in Brussels.

2.3. Selection of the representative reference terraced building

After creating the final dataset with 39 terraced households, a descriptive statistical analysis took place to select one representative building. The building architecture, occupancy, and energy efficiency characteristics were analyzed, including the building construction age. Middle-class families own more than 80% of the investigated households, and the original construction date is older than First World War (WWI). From 1700 to 1914, single-family dwellings constituted the most common housing type in Brussels. An overview of the different prewar housing types is available in the study of B^3-RetroTool project that aims to increase the retrofitting in the city [47]. We interviewed several house owners to understand the renovation's motives and the improvements of energy efficiency and comfort before and after the renovation [46]. Other influential factors that lead to selecting the representative reference terraced building were the demographics (number of occupants per family) and household surface area.

This dwelling's main characteristic is its small width of façade (around 6–8 m). The row houses' width results from the conjunction of two factors: - the dimensions of the wooden beams used in the roof wood-frame - the narrowness of the land plots during the 18th-century urban densification. In general, the middle-class house is organized around two types of spaces: - the main rooms or living spaces; - the secondary spaces, which group the building services and circulations. The distinction between these two spaces is made according to a longitudinal division that divides the house into two distinct spaces in the ratio of 2/3 – 1/3. The construction system is based on bearing walls with wood-frame structures. Internal walls are made from brick and are not load-bearing. The floors bear perpendicularly on the street façades and shear walls. Wooden joists are spaced from 35 to 40 cm. The thickness of the bearing walls is around 40 cm to ensure their stability [48].

Finally, one representative building was selected strategically. Plans and geometric forms of all houses were described and analyzed. Based on the typology analysis and classification, a theoretical reference model was created. The energy performance data compiled in the database (Section 2.2) allowed us to select a typical archetype to represent nearly zero-energy terraced households.

2.4. Energy characteristics of representative terraced building

Two levels of energy characterization are carried out for the selected houses based on the recommendations of Krarti [49]. An analysis of energy use intensity (electricity and natural gas) and a walkthrough survey is conducted between 2019 and 2020 for 39 households. Key informant interviews are conducted in Dutch, English, and French one-to-one with main stakeholders living in the selected households. The key informal interviews assured introducing the project to occupants. The walkthrough surveys allowed us to inspect the energy efficiency characteristics and energy use for 2016–2019 based on monthly bills. The walkthrough audits allowed us to understand the performance of the building and to identify the usage patterns. Monthly energy use was retrieved via private databases. Private companies such as Energy 2030, Octa, Engie, Lampiris, Brusol, and Luminus gave access to the consumption data based on the occupant's consent. The *Autorité bruxelloise de régulation dans les domaines de l'électricité, du gaz* (BRUGEL) database was also used as part of the study. The BRUGEL is the organism for the regulation of the electricity and natural gas markets in Brussels. This allows consumers to compare their current energy contract with the current market offer. It collects data on the production and consumption of electricity and gas in Brussels and reports on price trends. Finally, 39 audits were conducted via field visits and self-administered online and paper-based surveys.

The second type of energy characterization was highly detailed and involved several techniques to reduce the uncertainty of energy efficiency characterization parameters and occupancy patterns. The smartphone-based survey was developed to identify the occupancy density and profiles in the different households' thermal zones daily, weekly, monthly, and seasonal. With some modifications made to meet the current occupancy profiling exercise's objectives, the survey was replicated for different households' zones. The sampling design consisted of a random sample—a free, open-source application that allowed collecting the responses and compiling them on the server via the cloud. Open Data Kit open-source software was used to collect the data [50]. Once repetition of the answers patterns was found, the request for occupancy information input was stopped. Therefore, 25 household occupants participated in the occupancy surveys between 2019 and 2020. The collected data was compiled with the central project database and analyzed to describe the representative households' energy performance to serve later the building modeling stage.

The annual occupancy schedule has been set based on an average yearly schedule representing 2016–2019. The occupancy surveys and data loggers' data were used to determine households' heated thermal zones, size, composition, age, and occupants' presence. The survey involved information about water consumption and Domestic Hot Water (DHW) use. The number of vacation days was determined per household. The daily occupancy schedule has been established in line with ISO 18523 recommendations [51]. A special section in the energy audit involved characterizing artificial lighting, HVAC systems, and energy sources. The audit questionnaire included questions describing the mechanical ventilation systems and components. Mobile heating units and heating were checked. Visual inspection for all mechanical ventilation systems took place to trace and understand the ventilation strategy and heat exchangers' presence.

2.5. Development of the benchmark model

The representative simulation model was made based on the previously described selection process and building characterization. The simulations have been performed through the dynamic energy modeling software tool EnergyPlus [52]. All simulations were performed for the location of the Brussels-capital region in Belgium. Brussels falls under the Köppen-Geiger classification of temperate oceanic climate with no dry season and warm summer. Overall, Belgium's climate is mild-cold and humid, with significant rainfall during the year. Dwellings are typically heating-dominated [53] with an average of 2391 Heating Degree Days (HDD) and 36 Cooling Degree Days (2016–2020, base temperature 15 °C HDD and 24 °C CDD) [54]. Brussels meteorological weather data for 2016–2019 were requested from the Belgian Royal Meteorological Institute [55].

2.5.1. Calibration

The building simulation model input's validity has been further checked against the public statistics and verified through a model calibration and utility bill comparison. Calibration was done for evaluating the goodness of fit of the energy models according to ASHRAE Guideline 14 [56]. The ASHRAE Guideline 14 uses two indices to assess the goodness-of-fit of the building energy model. The Mean bias error, MBE, and the Coefficient of variation of the Root mean square error, CV (RMSE). MBE is a measure of the overall bias error between the measured and simulated data in a known time resolution:

$$MBE = \frac{\sum_{i=1}^{N_p} (m_i - S_i)}{\sum_{i=1}^{N_p} m_i} [\%] \quad (1)$$

where mi (i = 1, 2, …, Np) are the measured data, si (i = 1, 2, …, Np) are the simulated data at time interval i and Np is the total number of the data values.

CV(RMSE) represents how well the simulation model describes the variability in the measured data and is usually expressed as a fraction multiplied by 100. It is defined as:

$$CV(RMSE) = \frac{1}{m}\sqrt{\frac{\sum_{i=1}^{N_p} (m_i - S_i)^2}{N_p}} [\%] \quad (2)$$

where, besides the quantities already introduced in Eq. (1), m is the average of the measured data values. Evaluating a building energy simulation model's accuracy is made according to the model's conformity with the recommended criteria for MBE and CV(RMSE).

According to the ASHRAE Guideline 14, the simulation model is considered calibrated if it has MBE that is not larger than 5%. CV (RMSE) is not larger than 15% when the monthly data are used for the calibration.

To get reliable building energy models and increase the accuracy of estimating the building's performance, the models of detached single-family houses underwent two subsequent calibrations. The building model was first calibrated based on the building's measured monthly gas consumption. An uncertainty analysis was then performed to identify the most influential independent input variables, including the weather, building envelope, and occupancy [57].

2.5.2. Weather normalization

Weather normalization was applied to isolate weather changes on the archetypes' energy performance for 2016–2019 [58]. The degree-days method was used to represent the total positive or negative difference [59]. The degree-day is the difference between a base temperature and an average temperature of the place taken as a reference. This notion considers that the heat losses are proportional to the difference between the indoor T° and the outdoor T° of modeled building. This degree-days method, therefore, allows establishing the normalized consumption. The relationship between these two consumptions can be selected based on the equation below:

$$\text{Normalizedconsumption} = \frac{\text{monitoredenergyuse} \times \text{normaldegreedaysonsite}}{\text{observeddegreedaysonsite}} \quad (3)$$

2.5.3. Building envelope performance monitoring

The envelope airtightness and conductivity values were identified as influential modeling input parameters with high uncertainty. Despite the airtightness values found in several studies [60], including the earliest work of Bossaer et al. (1998) [61], we relied on the EPC audits values of envelope infiltration at 50 Pa [m^3/h.m^2] for the terraced houses renovated after 2010. Also, an airtightness test took place for one household using the pressure measuring device DG-700 and software TECTITE Express 5.1 and BlowerDoor® measurement according to EN 13,829 [62] and STS P 71–3 [63].

Moreover, a 21 day U-value monitoring took place on different envelope surfaces using gSKIN® KIT-2615C (U-Value Kit) according to ISO 9869–1:2014 [64]. The kits were installed to measure a representative brick cavity wall [65], the roof, and the attic (loft) floor. Most of the investigated attic slabs were insulated, and literature [10] did not provide accurate and representative values. Therefore, the conductivity and heat capacity of the attic slab required special attention. Airflow rates at the mechanical ventilation grille terminals (supply and extract) were measured in each dwelling using a hooded anemometer.

2.5.4. Occupancy behavior verification

Three data loggers, namely TESTO IAQ 160, were placed in the selected household with the house owners' consent. The data loggers uploaded five readings (temperature, humidity, CO_2, and pressure) every 15-minutes to the cloud. The field measurements took place in 2019 to refine residents' specific behavioral characteristics. With the help of the survey responses and the monitoring data, occupancy schedules were verified. Lighting, plug loads, and domestic hot water schedules were developed based on the energy and indoor environment monitoring data. The profiles were accordingly scaled to match the building energy modeling software's needs based on the work of Koupaei et al. 2019 [66]. After defining both daily and yearly heating (and cooling) and natural ventilation, using meteorological weather, the heating, cooling, and natural ventilation schedules were created. The EnergieID tool for monitoring energy use was useful during the repetitive occupancy behavior verification activities [45]. Energie ID provided information on the real monthly electricity and natural gas use and the expected energy use. The expected energy use was estimated by the tool based on a heating and cooling degree-day calculation that takes into account the annual energy use profile during the last three years. The tool process occupants' data into simple graphs and compare them with similar users through a benchmark module [45].The comparison graphs allowed to identify any discrepancy between the real use and expected monthly energy that exceeded more than ±10% resulted in questioning the occupants further. For example, during the summer of 2019 occupants left the house for 16 days for holidays.

3. Results

This section describes the dataset of nearly zero-energy terraced households and the selected reference building, its energy characteristics, and the validation results of the building simulation model.

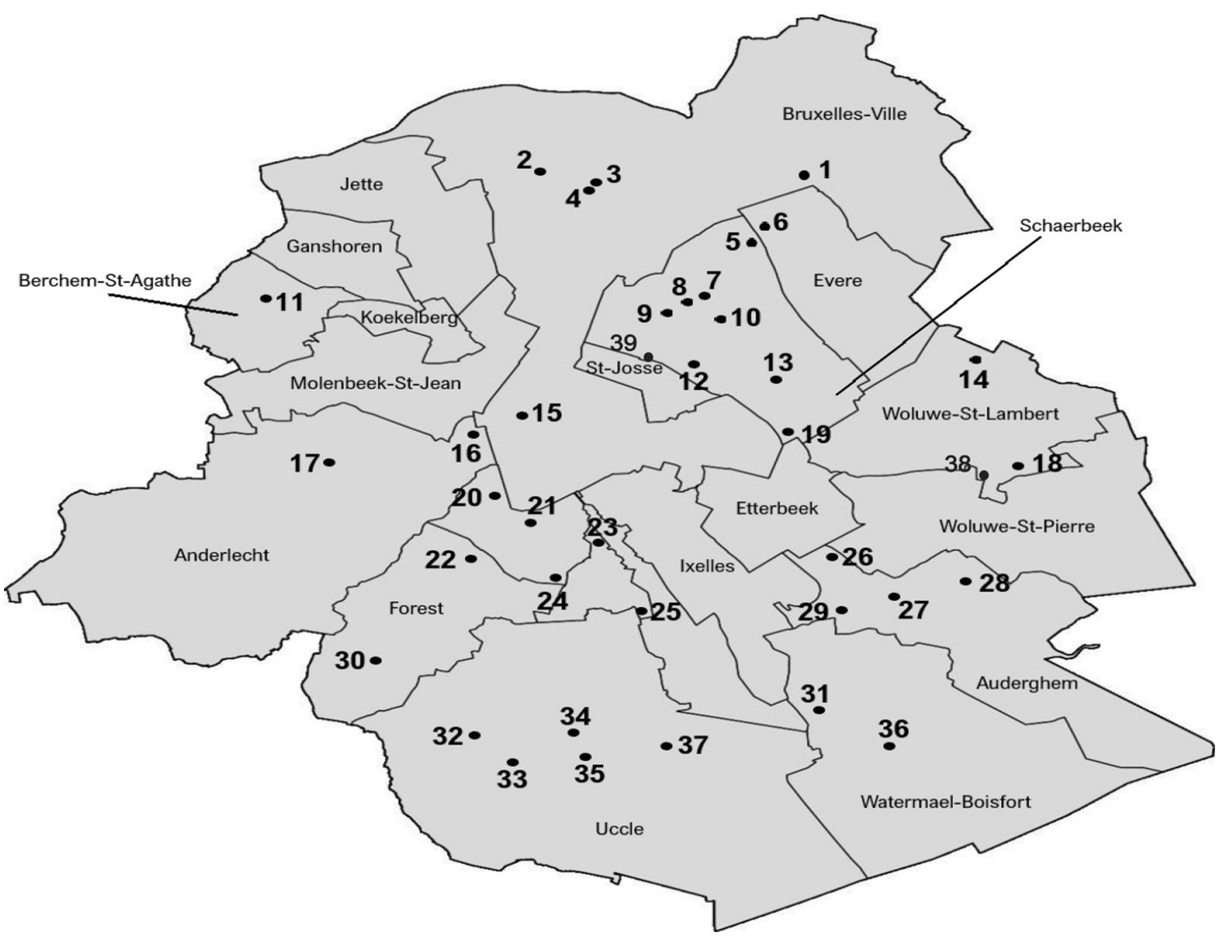

Fig. 4. Map of Brussels indicating the location of the nearly zero-energy, terraced households renovated after 2010 in Brussels.

Table 1
List of nearly zero-energy terraced buildings of the dataset.

Building no.	Archetype	Construction date	Surface [m^2]	Occupant (s)	Heating Energy Demand [kWh/m2*year]	Energy use intensity [kWh/m2/Year]	Airtightness	Compactness [V/S]
1	**Terraced**	1960	320	4	20.5	23.5	2.1	3.60
2		1935	171	4	29.0	47.0	1.5	2.95
3		1958	199	2	12.0	13.0	0.6	1.93
4		1950	106	2	5.0	33.0	0.4	4.23
5		1960	147	3	15.0	35.4	0.6	4.10
6		1954	266	2	30.0	39.0	1.7	6.48
7		1960	276	4	14.6	25.4	0.6	4.74
8		1966	271	4	39.0	50.1	2.1	5.94
9		1960	406	4	21.3	26.4	1.5	5.06
10		1960	320	2	30.0	31.0	3.0	3.90
11		1966	290	2	29.0	30.0	1.6	5.38
12		1954	194	2	26.0	28.0	1.2	4.91
13		1964	160	2	49.0	67.5	2.6	6.04
14		1950	306	4	20.0	23.8	0.6	4.31
15		1939	180	4	15.3	15.0	0.6	2.61
16		1948	196	2	27.0	42.3	1.1	5.72
17		1953	173	2	14.6	30.3	0.6	4.62
18		**1948**	**179**	**4**	**16.7**	**28.7**	**0.5**	**3.53**
19		1953	221	2	30.0	43.5	1.5	3.33
20		1970	259	2	21.0	30.0	0.9	3.41
21		1956	234	2	25.0	36.0	0.8	5.79
22		1957	381	4	30.0	37.0	0.8	3.32
23		1949	288	4	16.0	27.1	1.0	4.27
24		1955	282	2	43.6	44.0	1.5	3.16
25		1945	250	2	26.0	38.0	2.6	4.84
26		1950	275	3	29.8	39.5	1.5	4.06
27		1931	149	2	26.2	46.1	2.8	4.24
28		1930	160	2	16.0	34.8	1.0	2.81
29		1935	315	2	11.3	20.5	0.5	2.83
30		1968	271	4	23.0	30.0	0.8	1.86
31		1960	153	2	15.0	34.6	0.5	4.22
32		1939	199	2	15.0	30.1	0.6	5.31
33		1955	120	2	30.0	55.0	0.8	4.80
34		1935	221	4	38.0	51.0	1.6	4.08
35		1930	377	2	10.0	12.0	0.4	3.75
36		1965	272	2	37.8	48.0	2.6	4.83
37		1960	181	2	26.6	42.5	2.1	3.23
38		1899	290	2	15.0	30.0	1.0	3.30
39		1880	180	4	12.0	15.0	0.8	2.80

3.1. Database of nearly zero-energy terraced households

Fig. 4 illustrates the location of the investigated households. Table 1 lists thirty-nine selected projects that represent nearly zero-energy terraced households in Brussels. The table lists the most important energy performance indicators, including occupant density, heating energy use, and energy use intensity. All households' envelope (walls, roofs, and ground) conductivity values and air permeability were extracted from the EPC reports. Fig. 5 shows the facades of the 39 visited households.

As shown in Fig. 6, the selected buildings are heating-dominated. Some of the surveyed households had an air conditioning system installed, which justifies the high electricity use.

3.2. Selected reference building

Plans and layouts of thirty-nine configurations were analyzed. The most dominant layout form and orientation were long narrow rectangles with narrow gardens. As shown in Fig. 5, most houses have a tall and narrow façade of three floors. Based on the variance analysis of the thirty-nine households' energy use intensity indicated in Fig. 6 and Table 2, the reference building 18 presented in Fig. 7 was identified as representative. The selected building represented average values for energy use and occupancy values with a family of four occupants. By calculating the median of the values that are reported in Table 1 (by fitting a Gaussian Mixture Model onto the data), the closest sample to the mean (or the actual median) would be sample number 21. However, the building occupants of sample 21 did not represent the classical family composition found across the sample of two parents and two children. Moreover, many measurements of monthly energy use were missing in the EnergieID profile of sample 21. Therefore, we excluded this reference building and selected building 18, due to its representation of a young family represented in ISO 18523–2:2016 and the completeness of monthly energy use data.

The building represents typical terraced houses with a rectangular plan and an external thermal insulated construction system for the envelope (see Fig. 8). The building was renovated after 2010 and is labeled as a nearly zero-energy building with photovoltaic panels on the roof. The energy characteristics are further described in Section 3.3.

The building energy model has multizonal thermal spaces that are categorized as (1) living area (living, dining, and kitchen), (2) sleeping area (bedrooms), and (3) short-presence area (bathrooms and corridors. Fig. 9 illustrates the modeled archetype in 3D view. The external timber trellis is shown and the garage door in Fig. 7 was omitted to simplify the model and make sure that the garage space depends on artificial lighting. Removing the garage door from the model had a negligible effect on the energy use during the calibration process because the garage space was not heated (See section 3.4). The dataset that includes the model files in EnergyPlus and DesignBuilder format is available in open-access format [67].

3.3. Energy characterization of the reference building

The energy characteristics of the reference building simulation models are described in this section.

Fig. 5. Images of the 39 investigated nearly zero-energy terraced buildingsin Brussels.

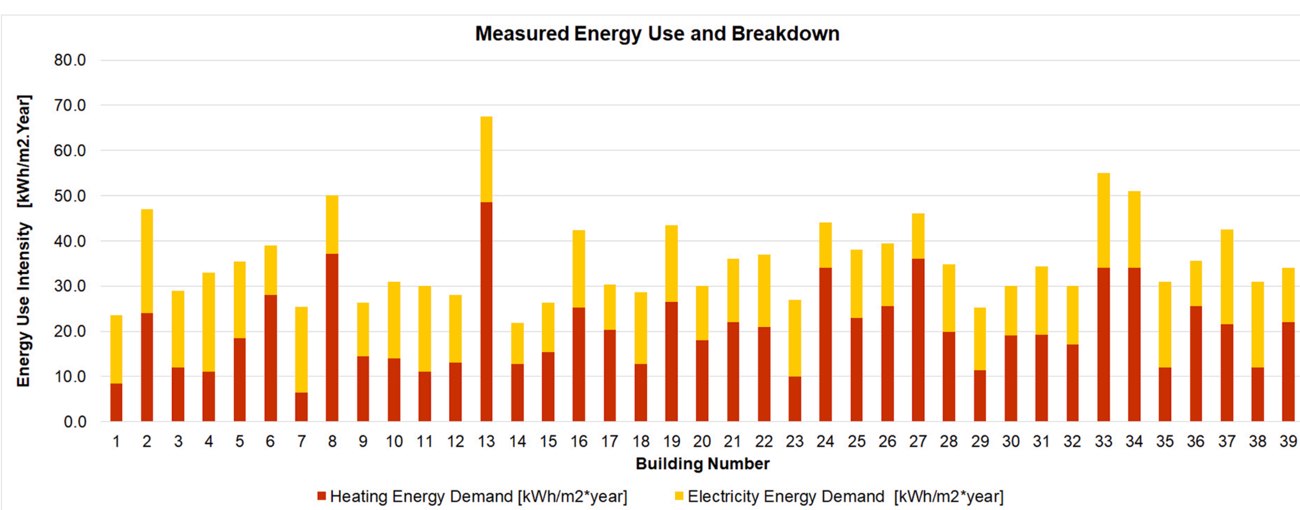

Fig. 6. Measured energy use and its breakdown.

3.3.1. *Energy use intensity*

As shown in Fig. 7, the EPC rating of terraced houses is A. The carbon emissions calculations are based on the assumptions proposed by Georges et al. [68]. The characterization of the thirty-nine households' energy use indicated that the average energy use intensity is 23.2 kWh/m^2/year for heating, including DHW and 11 kWh/m^2/year for electricity. Fig. 7 indicates that the selected reference building's average energy use intensity is 16.7 kWh/m^2/year for heating (including DHW) and 12 kWh/m^2/year for electricity (see Table 3).

3.3.2. *Occupancy density and schedules*

Almost all of the investigated occupants were second or third house owners. Families (<60 years old) dominated the terraced households where both adults work unless divorced. Overall, the occupancy was around 3.6 occupants per household. A family of two parents and two children occupies the selected benchmark building. The parents' age is

Table 2
General description of the benchmark.

Building description	Terraced house
Number of floors	3
Total area (m^2)	173
Occupants	4
Total volume (m^3)	873
External wall area	122
Roof area	91
Floor area	259
Windows area	41
Windows U-value	1.2
Windows G-value	0.6
Wall surface absorptance	0.9
Walls U-value (W/m^2K)	0.4
Roof U-value (W/m^2K)	0.3
Ground U-value (W/m^2K)	0.3
Attic Floor U-value (W/m^2K)	0.8

about 45, and the children are ten years and seven years old, respectively.

Based on the surveys and monitoring observations, the occupancy schedules were created with ISO 18,523 Part 2. ISO 18,523 Part 2 is developed for an average age category of 45-year old occupants. Fig. 10 presents the occupancy schedules for the three space categories as (1) living area (living, dining, and kitchen), (2) sleeping area (bedrooms), and (3) short-presence area (bathrooms and corridors. Since occupants were mainly seniors, we considered the same schedules for a weekday and the weekend. Tables 4 and 5 summarize the holidays and occupation periods used for the nearly zero-energy terraced building.

3.3.3. Lighting intensity and schedules

The data collected from the survey allowed us to define the most commonly used types and numbers of lamps. The dominant types of lamps used were LED lamps (79%) followed by compact fluorescent lamps (21%). Halogen lamps were found primarily in the dining and living areas. The average lighting power intensity for living areas was 12 W/m^2. For the bedroom, for example, the average lighting power density is 8 W/m^2, with an average variance of 6.1 W/m^2. Fig. 10 presents the lighting schedules applied to the three main space categories. Lighting schedules were modified during the winter period to extend the living areas 2 h after 08:00 and 1 h before 17:00. Several attempts to validate the lighting schedules were achieved by comparing the outcomes with the reports published by Flemish Energy Agency [69] and IP Belgium [70].

3.3.4. Plug load intensity and schedules

The penetration rates and saturation rates of house appliances were determined based on survey findings. Table 6 lists the most found house appliances in nearly zero-energy terraced buildings. The 20 listed appliances had a saturation rate higher than 70% in the surveyed sample. The national average of household appliances is 77 appliances per household [71]. The plugged appliances' unit capacity (standby and continuous) was estimated based on the running hours and power values. The average plug load power intensity is estimated at 8 W/m^2. Surprisingly, around 18% of households had an air conditioning unit (split), 19% had a dehumidification device, and 12% had mobile electric heating devices. Finally, the monthly and annual electricity use was used to validate the modeling assumptions.

3.3.5. Cooking and domestic hot water

Most visited households were connected to the district gas grid. Most households used lean gas, and some households had solid fuel heating stoves. The analysis of gas utility bills allowed defining the baseline of energy use for DHW and cooking. The water use per person was surveyed, representing an average of 45 m^3 per household (2 adults and 2 children), which stands for 62 L/person/day. The DHW hot water (of 60 °C) was calculated to reach 30 L/person/day. The cooking activities were assumed to reach 40–60 min per day.

3.3.6. HVAC and renewable systems and comfort setpoints

Natural gas condenser heaters heated more than 90% of households. A small number of households had a fuel oil boiler, a pellet, or a wood logs heating system. In 2012, Brussels encouraged pellet stoves because they are less polluting than open fireplaces. The city provided a subsidy for their purchase [73]. However, with the frequent air pollution waves with particulate matter during the winter of 2016 and 2017, the city discommended pellet stoves in 2017 [74].

More than 90% of households had a hydronic heating system with a hot water loop coupled to floor heating and/or radiators. Thermostatic valves control hot water flow in response to the local sensed setpoint temperature. Radiators are located in sleeping rooms, including children's rooms and low occupancy spaces. The thermostat average setpoint temperature was 21 °C in living areas, including the kitchen. The thermostat in the bathroom and short-presence areas were set to 16 °C

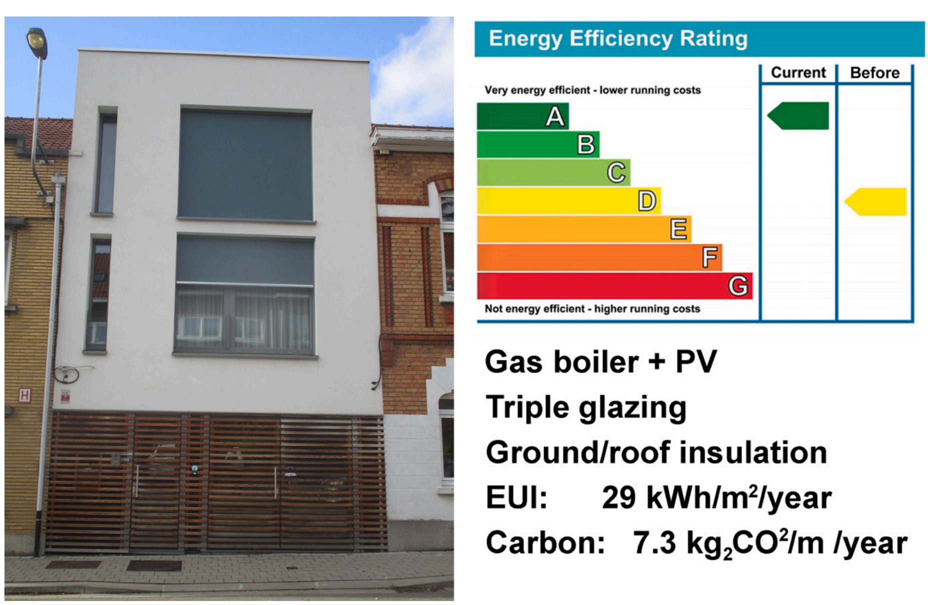

Fig. 7. Measured energy use intensity and carbon emissions according to the EPC.

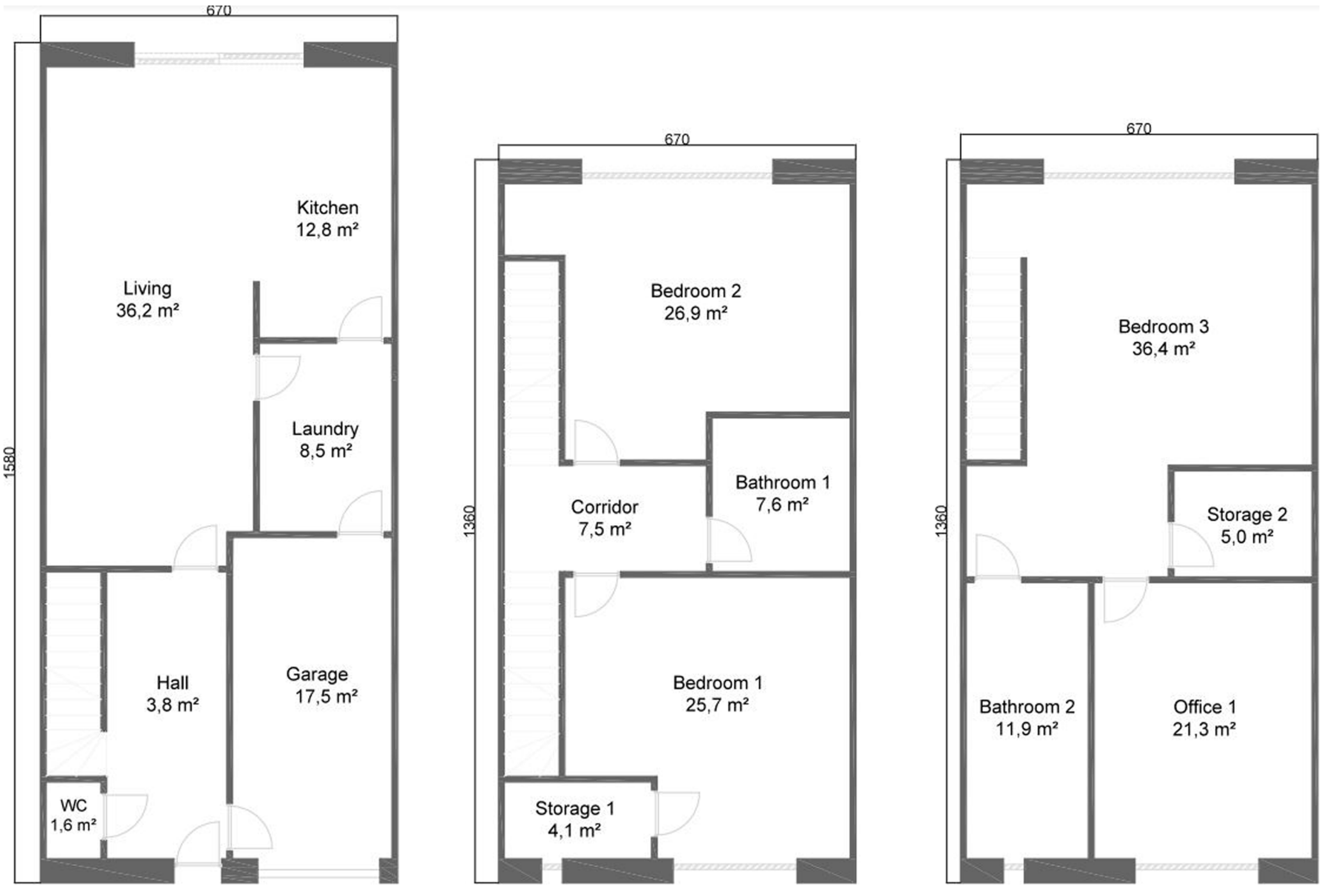

Fig. 8. Floors and plans for the reference building.

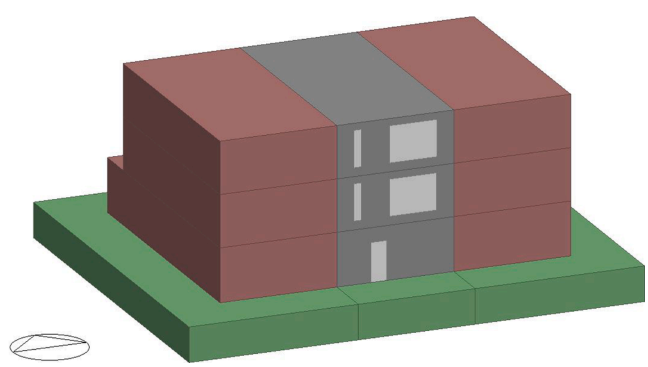

Fig. 9. Reference building model in 3D view.

Table 3
Heating demand, electricity demand, and energy use intensity.

Average heating energy demand [kWh/m^2/year]	Average electricity demand [kWh/m^2/year]	Average energy use intensity [kWh/m^2/year]
16.7	12	28.7

where radiators were left closed. Occupied bedrooms were set to 18 °C, where radiators were left half-open. The real measured setback temperature in both households was 12 °C when occupants were absent during holidays. Therefore, the thermal comfort setpoint criteria complied with ISO 17772–1,2 requirements (Category II) for normal comfort expectation in the new building and renovation [75] and [76].

Almost all of the investigated households had mechanical ventilation with a heat recovery (MVHR) unit. Results from airflow rates measurement confirmed that the air supply and balance were balanced. MVHR units are sized based on the proposed treated floor area, occupancy levels according to NBN D 50–001[77]. The Passive House Standard state a fresh air requirement of 30 m^3/h per person (equivalent to 8.33 L/s/p) is to be provided for adequate indoor air quality conditions. As shown in Table 9, the airflow rates were in an acceptable range. However, many interviewed house owners in Uccle and Forrest's districts complained about the mechanical ventilation systems that extract polluted air. The use of wood stoves among upper-class household users increases the air pollution outdoor during winter. Despite high-efficiency particulate air filters, mainly occupants complained about the use of system D for mechanical ventilation.

Furthermore, the row house generates electricity onsite of 3000 kWh/year, which is almost covering the annual electricity needs of 3600 kWh/year. The owners had a contract with an electricity supplier and producer that relies 100% on renewable resources.

Finally, several attempts to validate the heating energy use and schedules were achieved by comparing the outcomes with the reports found in the literature [78,79] and published by the Brussels government [80–84].

3.4. Numerical model calibration

Several iteration rounds took place based on several input validation measures. The MBE and CV(RMSE) values of monthly energy use were calculated and are presented in Table 7. The obtained values are in acceptable ranges. Fig. 11 shows the estimated gas and electricity use of the representative building. The calibration was done over four years and involved several reviews from peer modelers.

Table 8 indicates the normalized energy use intensity after weather

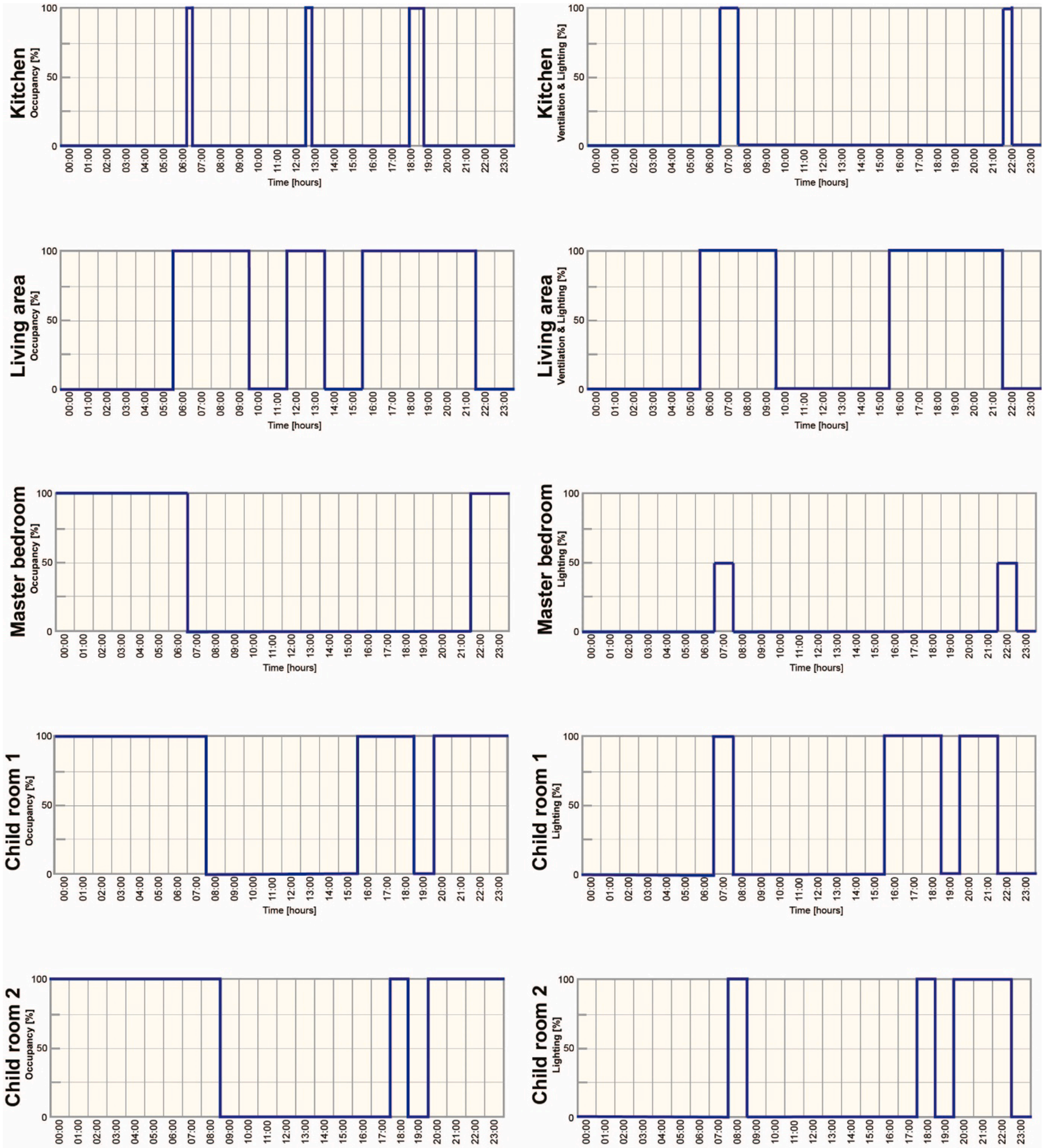

Fig. 10. Occupation, ventilation, and lighting schedules.

normalization. Brussels' HDD days were extracted from the Eurostat website for 2016–2019 [54]. The archetypes' energy use was compared with the observed energy use intensity extracted from the energy bills. The difference between the heating degree values lies between -4° and $+3.5^{\circ}$ HDD—the weather normalization allowed to neutralize the effect of weather and validate the results presented in Table 3.

Moreover, the envelope input parameters were refined through U-value monitoring and airtightness measurements. The final U-values of the building envelope and internal floors are presented in Table 9. In addition, the blower door test results are indicated in Table 9. Despite the difficulties in testing the three floors as one volume, the overall envelopes' airtightness value was very good (see 2.6.3). The replacement of the windows and the insulation increased the airtightness. Also, our findings are close to the assumptions reported by the Flemish [51,52], and Walloon [73] studies. The in-situ blower door test allowed verifying the main sources of air leakages around fenestration apertures, ducts, and electrical devices. The reported values reduced the uncertainty of the building energy model remarkably.

In a final attempt to validate, the multizonal energy model, household occupancy profiles were refined. The repetition of the surveys

Table 4
occupation status of terraced building with four family members.

2018/2019	Member	Parent1	Parent2	Child 1	Child 2
Days at home weekday	Occupancy	Employed	Employed	Student	Student
	06:00–08:00	Regularly	Regularly	Regularly	Regularly
	08:00–12:00	Seldom	Seldom	Seldom	Seldom
	12:00–15:00	Seldom	Rarely	Rarely	Rarely
	15:00–18:00	Seldom	Often	Rarely	Often
	18:00–23:00	Regularly	Regularly	Regularly	Regularly
	23:00–06:00	Regularly	Regularly	Regularly	Regularly
Days at home weekend*		Regularly	Regularly	Regularly	Regularly

Table 5
Holidays schedules for the year 2019.

Name	Start date	End date	Number of days
Easter holidays	30/03/2019	05/04/2019	7
Summer holidays	01/08/2019	15/08/2019	15
All saints'day holidays	28/10/2019	05/11/2019	7
Christmas holidays	24/12/2018	01/01/2019	7

Table 6
Appliances found in typical renovated nearly zero-energy terraced houses.

Appliance	Watt-hour	Daily operating hours	Appliance	Watt-hour	Daily operating hours
Furnace fan	50	1.5	HD Television	50	5
Coffee machine	600	0.2	Deep Fryer	1500	0.05
Microwave	1500	0.2	Washing machine	680	0.8
Mobile charger	5	24	Refrigerator (2 doors)	95	24
Phone charger	3	3	Kettle	1500	0.2
Built in Oven	300	0.1	PC/ Laptop/ Tablets	150/ 60/40	2
Electric Iron	1100	0.1	Freezer	15	24
Vacuum cleaner	330	0.05	Radio	15	0.1
Clothes Dryer	561	0.8	Dishwasher	720	1
DVD/CD Player	40	0.05	Electric Stove	650	0.9

Table 7
MBE and CV(RMSE) of the monthly energy heating and electricity consumption.

Statistical indices	MBE (%)	CV(RMSE) (%)
Monthly calibration (natural gas)	3,8	9.5
Monthly calibration (electricity)	2.7	5.6

allowed us to reach a high agreement on the most probable profiles. Some of the household occupants reported improved winter thermal and increased setpoint temperatures in living areas compared to the older comfort habits before renovation [46]. In households dominated by children or females, respondents indicated mobile electric heaters in study or sleeping areas. In addition, a significant part of respondents reported the problem of overheating during summer. 92% of survey respondents indicated opening windows for natural ventilation during summer.

4. Discussion

Brussels is one of the European capitals that seek energy neutrality of its building stock. Brussels has one of the largest Passive House complying households due to the regional government's 2009 decision to embrace passive constructions [74]. Hence, benchmarking allows characterizing the newly renovated buildings, evaluating them as high-performance buildings, and closing the performance gap. This section discusses the study findings and positions them regarding the state-of-the-art of renovated, nearly zero-energy housing.

4.1. Summary of the main findings

The selected reference model represents thirty-nine renovated and terraced, nearly zero-energy households in Brussels. The model was created and validated through walkthrough audits, in-situ measurements, and four years of energy use bills. The benchmarking of newly, renovated row houses allowed us to evaluate the real energy performance of nearly zero-energy buildings over time and share learned lessons. Benchmarking allowed us to understand the actual building's performance and nature of occupancy [46]. As shown in Table 9, the average energy use intensity of 29 kWh/m^2/year and represents single-family row houses built before 1945, thus before any building energy efficiency requirement. The pre-retrofit energy need is assumed approximately 300 kWh/m^2 per year, corresponding to label D. This gives savings of 7,3 kg CO_2 eq./yr per household, offering both an important contribution to achieving climate objectives as well as increasing long-term housing renovation rates (see Fig. 7). The buildings almost comply with the criteria of the nearly zero-energy building. Several investigated cases comply with the Passive House requirements. The heat gains are low due to the small size of windows (see WWR values) and external roller shutters in most households. However, the heat losses are remarkably low, as indicated by the low U-value of the envelope and good airtightness. The air change rate at 50 Pa pressure was 1.58 ACH. We used the Sherman model [85] to convert the 31.6 at 50 Pa m^3/h-m^2 and assign the value of 5.89 m^3/(h.m^2) in the EnergyPlus model. In addition, the internal gains are medium due to the occupancy density of 42 m^2/person.

The result of the benchmarking of the reference model is summarized in Table 9. The most important and tangible outcomes of the building performance characteristics are described below:

- Thirty-nine representative single-family terraced households have been selected from the Brussels database of exemplary buildings.
- A multizonal energy benchmark model was created in EnergyPlus based on the representative building stock performance and was calibrated based on the ASHRAE BESTEST requirements.
- A dataset of thirty-nine nearly zero-energy buildings characterizes the physical and thermal characteristics that have been created.
- The average annual energy use intensity after calibration and weather normalization is 29 kWh/m^2/year.
- The EPC rating for the benchmark is A, and the average heating use intensity is 17 kWh/m^2/year.
- The building envelope air permeability was very good, with an average of 1.58 vol/h at 50 Pa, and the building envelope is well insulated after renovation. The envelope conductivity is around 0.4 W/m^{2}K for walls and 0.3 W/m^{2}K for roofs.
- Most windows are triple glazed due to window retrofits that took place after the year 2010. The overall windows performance is high, with a low conductivity value ranging around 1 W/m^{2}K.
- The households are dominated by adult families and couples (<65 years old) and have an average occupancy density with an average household area of 150–300 m^2.

4.2. Strengths and limitations of the study

Building benchmarking is the basis for energy performance assessment approaches to reduce energy consumption and align with minimum performance requirements [86]. In this study, an essential vintage

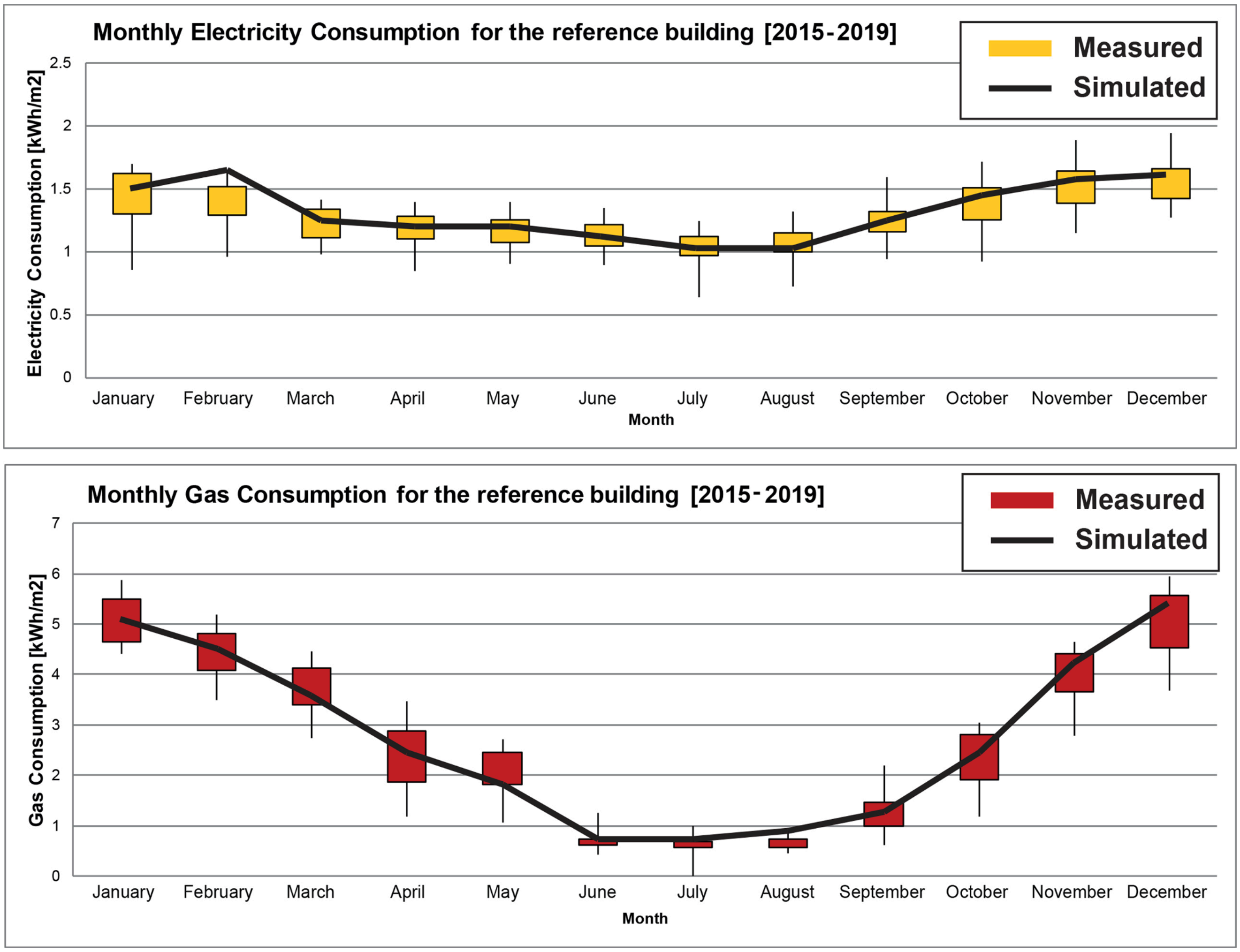

Fig. 11. Surveyed and simulated monthly electricity and gas use of the reference model.

Table 8
Normalised energy use intensity for archetypes A and B between 2016 and 2019.

	2016	2017	2018	2019
Energy use intensity in kWh/m^2/year	30.1	29.9	27.1	28.7
HDD base temperature 15 °C [51]	2556	2448	2383	2379
The difference compared to the average 2442 HDD (2016–2019)	−4%	+0%	+2.5%	+3.4%
Normalized energy use intensity (kWh/m^2/year)	**28.8**	**29.9**	**27.8**	**29.6**

of single-family row households was characterized by real monthly energy use data for natural gas and electricity with four years of monitoring (2016 and 2019). The study identified a type of owners and age group that are not often studied in the literature [87]. Also, we are not aware of a West European study that characterized such a sample size of recently renovated, nearly zero-energy, terraced houses using fieldwork data collection techniques. Most of the existing studies found in the literature are based on statistical methods to create theoretical benchmark models [20]. The study results present a representative and accurate characterization of energy efficiency and occupant behavior that can be used in Belgium and in Western Europe (see Fig. 2).

With the help of a mixed methodological approach, previously used [46], the study was able to survey house owners, collect energy bills, perform walkthrough audits and more importantly, perform in-situ blower door test and conductivity monitoring. The presence of smart meters in many households due to photovoltaic installation helped verify the monthly energy profiles. Furthermore, data from the EnergieID platform [22] allowed the validation of the energy use and users' profiles. We strongly recommend allowing occupants to share their monitoring data, track their buildings' performance and avoid the rebound effect through a comparative behavioral change tool [46]. The BatEX project achieved a shift in the parties' mindset involved in the renovation of their terraced households. The high ownership rate of the renovated row houses (almost 95%), the young age of owners (around 45 years old), and the support (financial, technical, and logistical) from the Brussels government made the idea of renovation financially attractive and encouraged owners to invest. Our observation is aligned with previous studies [88] found in the literature [89]. At the same time, occupants committed to behavioral changes and adopted several innovations to decrease their investment payback period.

A systematic and structured data collection approach with a team of 15 participants allowed triangulating the data sources. The triangulation approach allowed revealing insights on the occupancy behavior and building energy efficiency. Despite the long investigation period that covered 4-years, the results are valuable, and the dataset will be further analyzed and exploited. Therefore, a detailed comfort characterization is still underway. The reported overheating problems, air conditioners, and mobile electric heaters are a consequence of winter and summer discomfort problems. A thermal comfort assessment paper shall deal with the indoor thermal quality issues and investigate the potential impacts of climate change, similar to previous studies [90].

The representativeness of the selected reference building with external

Table 9
Summary of input parameters for the benchmark model after calibration and weather normalization

Model input measures		Terraced nZEB
Envelope	Window to Wall Ratio (WWR in %)	19%
	Openings conductivity [W/m^{2}K]	1.2
	Solar Heat Gain Coefficient (SHGC)	0.6
	Light transmittance (LT)	0.80
	Solar protection (External)	Roller Shutters
	Walls U Value = [W/(m^{2}K)]	0.4
	Roof U Value = [W/(m^{2}K)]	0.3
	Airtightness (at 50 Pa m^3/h-m^2)	31.6 (=1.58 ACH)
	Airtightness (at 4 Pa m^3/(h-m^2)	5.89 (=0.3 ACH)
Heating system, ventilation, and air conditioning	COP Heating system	0.88
	Temperature set point [°C] for heating	21
	Set back temperature [°C] for heating	12
	Ventilation rate (Living / open kitchen) (m^3/h)	supply:25 / extract:30
	Ventilation rate (Bedrooms) (m^3/h)	supply: 25
	Ventilation rate (Bathroom) (m^3/h)	extract:25
	Mechanical ventilation heat recovery efficiency	92%
	Heating system	Gas-fired boiler
	Heating fuel	Natural gas
Lighting	Lighting power density [W/m^2]	8–10
Occupancy	Number of people	4
	Occupancy Density [m^2/person]	43
	Occupancy schedule	See Fig. 10
	Window opening	during summer
Total	**Average consumption [kWh/m^2/year]**	**29**

*A division by 25 between the flow rates at 50 Pa and the flow rates in average condition.

façade insulation (ETICS) is considered a study limitation. The pre-world war II and 19th-century brick facades of Brussels with balconies, bays, and decorations do not allow for insulating the façade externally [91]. The rich façade styles, including the neo-gothic, art-deco, and art-nouveau facades, row houses in Brussels, leading to internal insulation in many cases, as shown in Fig. 5. Consequently, the presence of thermal bridges increased the overall U-value and airtightness properties of facades in several investigated buildings in our dataset. However, the influence of internal insulation on energy use intensity remains slight. Also, our sample of 39 households had a rate of 90% of ownership. In other words, 90% of occupants owned the renovated households, while the average rate of ownership in Brussels is 39%. The high rate of ownership is strongly influenced by the BatEX funding scheme that encourages house owners to renovate towards nZEB.

4.3. Implication for the practice and future research

The implication of our work on practice feeds the discussions on the importance of updating the knowledge about the building stock inventory of nearly zero-energy buildings and the efficiency of new renovation activities. There is a need to exchange benchmarks related data around Europe. Building stock energy models are essential tools for technology RD&D strategy development [92]. Our benchmark model [67] can become part of existing nZEB databases and tools developed by the PHPP [93] or EC [20,94]. It can help the EPBD future recasts to estimate the requirements for carbon–neutral renovations and to support the modernization of nearly zero-energy buildings with smart technologies such as heat pumps and photovoltaic for heating decarbonization. And make a clearer link to clean mobility through batteries integration in renovated households. Most of the renovated households exceeded the EPBD energy efficiency requirements and complied with the PassiveHouse requirements. Because at that time, there was a remarkable gap between the Passive House and the EPBD requirements. However, the gap in 2021 is almost closed. On the other hand, the energy performance gap remains the central challenge to achieve high-performance and energy-neutral buildings [95].

In this context, the EPBD calculation method should be further developed to encourage real reference models. Multizonal models and dynamic simulation are essential ways to eliminate the discrepancy between the assumed modeling input and actual occupancy and operation conditions concerning mechanical ventilation systems and heating systems. Also, the current EPCs requirements for renovation in Brussels do not encourage or inform owners how to reach the nZEB target. As a consequence the renovation rate in Brussels is low. Brussels has more than 550.000 households with more than 46 million m^2 [96]. The current renovation rate is 5% for households occupied by their owners and 2.6% for rented households [96]. The renovation rate requires to be accelerated, despite the challenging pressure to find qualified labor in the field of building renovation.

Future research should also explore cost-effective renovation strategies and solutions based on the European Cost Optimality approach [97]. The impact of the BatEX project has been proven through this study to transform the existing building into zero-energy households. The terraced houses can generate their own (renewable) energy needed for both the homes and tenants each year. The potential of full electrification of heating, hot water, and cooking should be further explored in the short term. The replacement of gas condensing boilers shall be mandatory after 2030. Heat pumps should be the main solution, and district heating to decarbonize heating in row houses [98]. The increase of electric energy generation by photovoltaic should be further promoted to reach energy and carbon neutrality. In the long term, the reduction of energy use intensity should not be used as the sole criteria for a building's energy efficiency. The overall energy use intensity per occupant should be considered as an additional criterion to improve over energy efficiency [46]. This can help the city achieve its objective to approach carbon neutrality by 2050 lowering the average EUI to 100 kWh/m^2/year for the city's buildings [96].

Finally, we invite international researchers to develop new benchmark models for other newly constructed and renovated, nearly zero-energy archetypes. Benchmark models for nearly zero terraced housing should be tested in different climates than in Belgium's temperature oceanic climate. Future detailed audits should focus on airtightness measurement tests and focus on the assumptions of mechanical ventilation systems. Further research to validate and generalize the proposed models for nearly zero-energy dwellings can mitigate climate change effects concerning cities' urban heat island effects in Belgium and other Western European countries.

5. Conclusion

The energy characterization of thirty-nine renovated, nearly zero-energy, terraced houses located in Brussels took place based on four-year measurement data (2016–2019). The energy use characterization indicated that the average energy use intensity of the reference building is 29 kWh/m^2/year. Our research methodology combines mixed research methods involving qualitative (e.g., literature review) and quantitative empirical and modeling (e.g., walkthrough audits, building performance simulation, calibration) research. One representative single-family row house was identified and modeled in EnergyPlus software after several iteration rounds. The model was calibrated according to ASHRAE Guideline 14 using two indices to evaluate the goodness-of-fit of the building energy model. Rigorous validation measures consolidated the model input assumptions, namely (1) weather normalization, (2) envelope conductivity and airtightness, and (3) occupancy behavior observations. On such a basis, the study provided an accurate energy model representing nearly zero-energy, renovated row houses. Such benchmark models are vital to predicting energy use intensity and energy efficiency of row houses. It supports the efforts towards an energy transition based on the decarbonization of heating energy use. The concept of nearly zero-energy buildings shall be developed to become zero-emission buildings by 2050.

The choice of external insulation and high-performance windows improved the overall envelope performance. The compact geometry of row houses, comprising three floors, allowed for natural thermal zoning and reduced the heated house volumes/spaces with the help of the preset thermostat. Thermal zoning and heating control appeared to be the most influential factor to the low energy use intensity. The households were dominated by families of two to four occupants under the age of 65. However, thermal discomfort problems are reported during extreme winter or summer days, resulting in the reliance on personalized plugged electric heating or air conditioning units. We expect the proliferation of nearly zero-energy rows households and the out phasing of gas boilers in the short term. The full electrification of nearly zero-energy households coupled with electric vehicles is the next logical step towards zero carbon emission households. Further research aiming to characterize other renovated archetypes better and develop multi-objective renovation scenarios appears necessary to tackle carbon neutrality issues in existing households.

CRediT authorship contribution statement

Shady Attia: Conceptualization, Supervision, Methodology, Validation, Visualization. **Théophile Canonge:** Investigation, Software, Data curation. **Mathieu Popineau:** Investigation, Data curation. **Mathilde Cuchet:** Investigation, Data curation.

Declaration of Competing Interest

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

Acknowledgment

The authors express their thanks to all survey respondents. The Walloon Region partially funded this research under the call 'Actions de Recherche Concertées 2019 (ARC)' and the project OCCuPANt, on the Impacts Of Climate Change on the indoor environmental and energy PerformAnce of buildiNgs in Belgium during summer. The authors would like to acknowledge the Walloon Region and Liege University for funding gratefully. We would also like to recognize the Sustainable Building Design Lab to monitor equipment in this research and the valuable support during the experiments and data analysis.

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