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A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale

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ABSTRACT

Zero-energy buildings (ZEBs) are attracting increasing interest internationally in policies aiming at a more sustainably built environment, the scientific literature and practical applications. Although "zero energy" can be considered at different scales (e.g., community, city), the most common approach adopts only the perspective of the individual building. Moreover, the feasibility of this objective is not really addressed, especially as far as the retrofitting of the existing building stock is concerned. Therefore, this paper aims first to investigate the opportunity to extend the "zero-energy building" concept to the neighbourhood scale by taking into account two main challenges: (1) the impact of urban form on energy needs and the on-site production of renewable energy and (2) the impact of location on transportation energy consumption. It proposes a simplified framework and a calculation method that is then applied to two representative case studies (one urban neighbourhood and one rural neighbourhood) to investigate the feasibility of zero-energy in existing neighbourhoods. The main parameters that act upon the energy balance are identified. The potential of "energy mutualisation" at the neighbourhood scale is highlighted. This paper thereby shows the potentialities of an integrated approach linking transportation and building energy consumptions.

1. Introduction

1.1. Zero-energy at the building scale

The building sector is a major consumer of energy worldwide [1–3]. For example, it represents over 40% of the overall energy consumed in the European Union [1–3]. In the current context of growing interest in environmental issues, reducing energy consumption in the building sector is an important policy target. Politicians, stakeholders and even citizens are now aware of the issue of energy consumption in buildings, especially as a result of the passage of the European Energy Performance of Buildings Directive and its adaptation to the Member States. Its main aim was to establish minimum standards for the energy performance of new buildings and existing buildings larger than 1000 m^2 subject to major renovation [4]. Another major trend commonly proposed to reduce the energy consumption of the existing building stock is the improvement of the thermal performance of the envelope of existing buildings (sometimes in combination with more efficient heating/ventilation systems) [1,3]. As a result, new construction and renovation standards ((very) low-energy standards, passive house standards) [5–7] have been developed to drastically minimise the energy consumption of new and retrofitted buildings and the associated greenhouse gas emissions. During the last few years, "zero-energy buildings" have aroused increasing interest internationally in the scientific literature (e.g., [8–14]), policies aiming at a more sustainable built environment and even concrete applications.

In the literature, the "zero-energy" objective is most often considered on the building scale. Although existing definitions are commonly articulated around an annual energy balance equal to zero (the energy demand of the building is compensated by its renewable production) [10,11], numerous differences exist and several definitions coexist [8,12] depending on such elements as specific local conditions, political targets, connection (or not) to the grid and measures to address energy efficiency before using renewable energy sources. The "zero-energy building" (ZEB) is presented as a general concept that also includes autonomous buildings not connected to energy grids. The term "net zero-energy building" (nZEB) "*underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year*" [8, p. 220]. The concept of a "nearly zero-energy building" is presented by the European Directive on the energy performance of buildings [15] as a "*building that has a very good energy*

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performance. The nearly zero energy or very low amount of energy required should be supplied to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

Other derived concepts are also found in the literature based on various balance metrics [9]. For example, Torcellini and Crawley [9] defined four net zero-energy building balances (net zero primary energy, net zero site energy, net zero energy cost and net zero emissions) and Mohamed et al. [16] investigated them for a single-family house with different heating alternatives. For Voss et al. [10,17], a clear definition, standardised balancing method and international agreements on the meaning of "zero-energy building" (ZEB) are lacking.

To address this issue, Marszal et al. [12] recently proposed a review of the existing ZEB definitions and various calculation methodologies. They highlighted seven main issues to be addressed in further definitions: the metric of the balance, the balancing period, the type of energy use included in the balance, the type of energy balance, the acceptable renewable energy supply options, the connection to the energy infrastructure and finally the requirements for the energy efficiency, the indoor climate and, in the case of grid-connected ZEB, the building-grid interaction. Amongst the more complete existing approaches, Sartori et al. [8] developed a systematic, comprehensive and consistent definition framework for "net zero-energy buildings". They considered "*all the relevant aspects charactering net ZEB and aims at allowing each country to define a consistent (and comparable with others) net ZEB definition in accordance with the country's political targets and specific conditions*" [8, p. 221]. This framework is articulated around two types of annual balances: the import/export balance (balance between delivered and exporter energy) and the load/generation balance (balance between load and generation). The monthly net balance can also be determined according to the same philosophy [8]. Voss et al. also [10] proposed a harmonised terminology and balancing procedure that takes into account the energy balance as well as the energy efficiency and load matching and highlighted that "*it is the optimisation and not the maximisation of electricity exported to the grid that is an essential planning goal for net zero-energy buildings, in addition to the reduction of energy consumption*" [10, p. 55]. These authors proposed a new label (ZEB *x*) allowing the distinction between the need for seasonal compensation (the lower the "*x*" value, the lower this need for compensation). In the same vein, Srinivasan et al. [18] introduced a "renewable emergy balance" as a tool to ensure that buildings are optimised for the reduced consumption of resources and that the use of renewable resources and materials is optimised over the entire lifecycle of the building. Pless and Torcellini [11] ranked the renewable energy sources used in a building to propose a classification grading system for ZEB, based on renewable energy supply options. The goal of this work is to encourage, first, the utilisation of all possible energy-efficient strategies and, then, the use of renewable energy sources and technologies located on the building [19]. Attia et al. [20] developed one of the only decision support building simulation tools that can be used as a proactive guide in the early design stages of residential net zero-energy building design. This tool is designed for a hot climate (Egypt) and allows for the sensitivity analysis of possible variations of nZEB design parameters and elements to inform the decision-making process by illustrating how these variations can affect comfort and energy performance.

As far as policies are concerned, the ZEB is currently receiving an increasing amount of attention in several countries [12–14]. In Europe, the recasting of the European Performance of Buildings Directive (EPBD) requires all new buildings, built in Member States, to be "nearly zero-energy" buildings (nZEB) by 2020. As a consequence, Member States are currently implementing this objective into their own national regulations [14]. The zero objective will then be extended to existing buildings undergoing major retrofitting works [15]. In the United States of America, the Energy Independence and Security Act (2007) [21], which concerns the energy policy of the entire country, aims to create a nationwide net zero-energy initiative for houses built after 2020 and commercial buildings built after 2025. The Asia-Pacific Partnership on Clean Development and Climate, a public-private partnership of seven countries (Australia, Canada, China, India, Japan, South Korea and the United States of America), aims also at promoting the development of net zero energy homes [13].

In practice, several buildings have recently been built that prove that "zero energy", at the building scale, is feasible. Most of these existing zero-energy buildings are (small or large) residential buildings and office buildings [17,22]. Fong and Lee [23] showed that the net zero-energy target seems not to be possible for high-rise buildings in Hong Kong. However, they note that it is feasible for low-rise residential buildings in this subtropical climate.

1.2. Zero energy at the neighbourhood/community scale

Generally speaking, most papers investigating energy issues at the neighbourhood/community scale focus on either the impact of urban form on energy consumption in buildings [e.g., 24–26] or the potential of solar energy utilisation for active and passive solar heating as well as photovoltaic electricity production, lighting and related energy supply and demand [e.g., 27–30]. Hachem et al. [31] studied and compared the electricity generation potential of neighbourhoods and their energy performance in terms of heating and cooling and found out that a significant increase in total electricity generation can be achieved by the building integrated photovoltaic systems of housing units of certain shape-site configurations, as compared to their reference case. They also highlighted that the energy load of a building is affected by its orientation and shape. The impact of urban form on transportation energy consumption has also be widely highlighted in the literature, but it is considered either alone [e.g., 32–36] or, in a few studies, in comparison with building energy consumption [e.g., 37–39].

Studies and reports dealing with zero energy at the neighbourhood/community scales are few in number. The framework proposed by Sartori et al. [8] can also be applied to a cluster of buildings. Kennedy and Sgouridis [40] addressed the question of how to define a zero-carbon, low-carbon or carbon-neutral urban development by proposing hierarchical emissions categories. Todorovic [41] investigated the role of simulation tools in the framework of zero-energy urban planning. The National Renewable Energy Laboratory [19, p. 4] defined, in a technical report, a "zero net energy" community (ZEC) as "*one that has greatly reduced energy needs through efficiency gain such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy*". They highlighted [19, p. 1] that "*community scenarios could link transportation, home and the electric grid as well as enable large quantities of renewable power onto the grid*". They also applied the ZEB hierarchical renewable classification proposed by Pless and Torcellini [11] to the concept of community to focus on the mode and location of production of renewables. A community that met the zero energy definition thanks to renewable energies produced within its built environment (or in brownfields) is at the top of the classification (rank A) whereas a community that met the definition through the purchase of renewable energy certificates is ranked C.

Although not specifically dedicated to the "Zero-energy" objectives, several neighbourhood sustainability assessment tools have recently been developed [42]. Examples of these NSA tools are, amongst others, the STAR Community Rating System (Sustainability Tools for Assessing and Rating Communities) [43] and the US Green Building Council's LEED-ND (Leadership in Energy and Environmental Design—Neighbourhood Development) [44] in the

United States, BREEAM Communities (BRE Environmental Assessment Method) in the United Kingdom [45], HQE2R (Haute Qualité Environnementale et Économique dans la Réhabilitation des bâtiments et le Renouvellement des quartiers) in France [46] and CASBEE-UD (Comprehensive Assessment System for Built Environment Efficiency–Urban environment) in Japan [47]. These tools aim to assess and rate communities and neighbourhoods against a set of defined criteria and themes. They propose a checklist of criteria (mainly optional) and a range of various guidelines to help local stakeholders, designers and citizens move towards more sustainability. Although they all include a large theme dedicated to energy, they neither allow a quantitative assessment of energy consumption or GHG emissions nor the evaluation of the energy efficiency of retrofitting scenarios.

As far as concrete projects are concerned, the West Village is a net zero-energy community, including 662 apartments and 343 single-family homes, under construction in Davis, California [48,49]. Another interesting development at the neighbourhood scale is the Beddington Zero (fossil) Energy Development (BedZED) sustainable neighbourhood, which was intended to be the UK's largest mixed-use zero-carbon community. However, the zero objective was not achieved. Others examples of very low energy neighbourhoods include Hammarby Sjosjad, Augustenborg and BO01 in Sweden, Vauban and Kronsberg in Germany, Eva-Lanxmeer in the Netherlands and Vesterbro in Denmark [50]. Finally, IEA-EBC (International Energy Agency's Energy in Buildings and Communities Programme) has currently a few Annexes/projects on zero-energy communities [22].

1.3. Aim of the paper

This paper aims to complete the existing approaches relating to "zero energy" by developing and investigating the opportunities linked to a new simplified framework dedicated to "zero-energy neighbourhoods" and articulated around the following three main challenges:

(1) The major challenge of the adaptation and retrofitting of the existing building stock (especially in the large part of Europe in which the renewal rate of the existing building stock is quite low), in complementarity with the numerous studies dealing with the production of new optimised buildings and communities, and the concrete feasibility of zero-energy in retrofitting.
(2) The impacts of parameters linked to the urban form on the energy efficiency of single buildings as well as on the choice and efficiency of on-site renewable energy sources (e.g., the possible mutualisation of energy supply and demand between individual buildings).
(3) The impact of the location of residences, work places and services on daily mobility patterns and their related energy consumption, which are considered together with building energy consumption because building or retrofitting very efficient buildings could be counterproductive if its location does not allow alternatives to private cars for daily mobility (travel to work, school, shops, etc.) and imposes long travel distances.

As architects and urban planners, we are particularly interested in investigating the possibilities to adapt the existing building stock in order to reach an annual zero-energy balance, at the neighbourhood scale, and in highlighting the main urban and architectural parameters that act upon the energy balance of a neighbourhood. Thus, in the following, we will take into account three main themes directly related to the urban form of existing neighbourhoods: building energy consumption, the on-site production of renewable energies and transportation energy consumption of inhabitants (in order to take into account the location of activities on the territory in the balance).

1.4. Content of the paper

To this extent, Section 2 proposes a simplified framework and a calculation method to assess zero-energy neighbourhoods. An application of the proposed framework is then developed in Section 3 to test its applicability, investigate the feasibility of zero-energy in retrofitting neighbourhoods and highlight key parameters in the annual energy balance of two representative neighbourhoods (in Belgium). Section 4 discusses key challenges to be addressed and perspectives to be investigated in future research. Finally, the research findings and strengths and weaknesses of the proposed framework are summarised in Section 5.

2. A simplified net "zero-energy neighbourhood" framework: method and assumptions

The net "zero-energy neighbourhood" framework (nZEN) proposed in the scope of this paper aims to articulate the three main energy uses (building energy consumption, the production of on-site renewable energy and transportation energy consumption for daily mobility), at the neighbourhood scale. A neighbourhood is understood here as an "urban block" (that is to say the smallest area of a city that is surrounded by streets) or a group of several "urban blocks". We only consider residential neighbourhoods although the general methodology could be extended to industries, shops, etc. Also note that public services energy uses in a neighbourhood (e.g., street lighting, traffic lights) are not assessed. A previous research [38] namely showed that street lighting energy consumption is minimal in comparison with building and transportation energy consumptions.

The nZEN is here described as a neighbourhood in which the annual energy consumption for buildings and transportation of inhabitants is balanced by the production of on-site renewable energy. The main balance is annual, but monthly, daily or hourly balances could also be studied according to the same definitions to better capture the gaps between energy consumption and production by renewable sources. As far as the metric of the system is concerned, the balances are proposed in terms of primary energy. The conversion factors used to convert gross energy into primary energy are 1 for natural gas and petrol and 2.5 for electricity, as stated in the Walloon regulation on the energy performance of buildings [51]. Only the use phase of the neighbourhood is taken into account in these balances (construction and deconstruction phases are not assessed). Note also that a net zero-energy neighbourhood implies interactions among the buildings in the neighbourhood and between the building and transportation energy consumptions. The zero-energy balance is thus considered as a whole, and each building is not necessarily a zero-energy building. Finally, we assume that the neighbourhood has an electric grid that can provide energy to the neighbourhood when on-site generation from renewables is lower than the load. If greater, the on-site production can be sent to the grid.

2.1. Energy consumption in buildings

The methodology used to assess building energy consumption takes into account the annual energy consumption for space heating (E_{SH}), space cooling (E_{CO}), ventilation (E_V), appliances (E_A), cooking (E_C) and domestic hot water (E_{HW}). The neighbourhood's annual energy consumption for buildings (E_B) is calculated using Eq. (1).

$$E_B = E_{SH} + E_{CO} + E_V + E_A + E_C + E_{HW} \quad (1)$$

2.1.1. Energy consumption for space heating, cooling and ventilation

The method developed to assess energy consumption for space heating, cooling and ventilation was extensively presented in a previous paper [38]. This method combines a typological classification of buildings and neighbourhoods and thermal dynamic simulations. This typological approach classified the residential building stock of Belgium and was based on the following factors: common ownership (detached, semi-detached or terraced houses, apartments), the heated area of the dwelling in square meters (m^2), the heating and ventilation systems, the date of construction and the level of insulation, including retrofitting works performed by the owners (e.g., insulation of the roof and/or replacement of the glazing, change of the heating and/or ventilation systems). Thermal simulations were performed for all of the dwelling types of this typological classification of buildings. The results of these energy simulations (E_{SH} and E_V) are stored in a database comprised of the energy consumption of approximately 250,000 buildings. In these thermal simulations, Brussels meteorological data (temperate climate) are used. The minimum temperature in the dwellings is 18 °C, and internal gains are defined according to the surface area of the dwelling. A correction factor is applied to available solar gain according to the neighbourhood type to take into account the reduction of solar gains with increased built density. The net and gross energy consumption and primary energy consumption for space heating, cooling and ventilation at the neighbourhood scale are finally calculated by adding the results from the energy consumption analysis for each type of house according to their distribution in the neighbourhood and the neighbourhood type. Cooling (E_{CO}) is not taken into account in the case studies presented in Section 3, in accordance with regional yearbooks [52]. Moreover, the overheating indicator defined in the European Energy Performance of Building Directive [4] as the ratio between the solar and internal gains of a building to transmission and ventilation losses was calculated by [38] for Walloon residential buildings. It remains under the threshold value proposed in the Directive (29.8% under the threshold value for the worst cases), which indicate that the overheating is not unacceptable and does not require the installation of cooling system [4].

2.1.2. Energy consumption for appliances, cooking and domestic hot water

The annual energy consumptions related to appliances (E_A), cooking (E_C) and domestic hot water (E_{HW}) are assumed to depend on the number of inhabitants in the building. In the following application, regional mean values, gathered by a regional institute in charge of environment (the "Cellule Etat de l'Environnement Wallon" [53]), are used; however, in situ surveys could also be implemented in the model. The energy consumptions related to appliances and cooking are 1048 kWh per person per year and 170 kWh per person per year, respectively [53]. The energy consumption for heating water is obtained by multiplying the volume of hot water needed annually at the neighbourhood scale (m^3) by the difference in temperature between cold and hot water and a conversion factor, used to convert kilocalorie into watt-hour. This factor is worth 1.163 kWh/m^3 °C [54]. We consider each inhabitant to need 100 l of cold water (10 °C) and 40 l of hot water (60 °C) per day, in accordance with the regional trends [53].

2.2. Energy consumption for daily mobility

The annual energy consumption for daily mobility (E_{DM}) is assessed using a performance index introduced by Boussauw and Witlox [55] and adapted by Marique and Reiter [56]. This index is expressed in kWh/travel per person and represents, for a territorial unit, the mean energy consumption for travelling for one person living within a particular neighbourhood. This index takes into account the distances travelled, the means of transportation used and their relative consumption rates, as expressed by Eq. (2). In the equation, i represents the territorial unit; m the means of transportation used (diesel car, gasoline car, train, bus, bike, walking); D_{mi} the total distance travelled by the means of transportation m in territorial unit i; f_m the consumption factor attributed to the means of transportation m; and T_i the number of persons in the territorial unit i. The consumption factors depend upon the consumption of the vehicles (litres of fuel per kilometre) and their occupation rate. In the Belgian context [56], these values are 0.56 kWh/person per km for a diesel car, 0.61 kWh/person per km for a non-diesel car, 0.45 kWh/person per km for a bus, 0.15 kWh/person per km for a train and 0 for non-motorised means of transportation, as the latter do not consume any energy [56].

$$\text{Energy performance index } (i) = \sum_{m} \frac{D_{mi} f_m}{T_i} \quad (2)$$

The energy consumption for daily mobility (E_{DM}) is obtained using Eq. (3) by multiplying the energy performance index by the number of people (N) and the number of trips (T) in the neighbourhood.

$$E_{DM} = \text{Energy performance index} \times NT \quad (3)$$

In our nZEN framework, we attribute all travels to and from work and to and from school to the neighbourhood (rather than the portion that is really consumed within the neighborhood) to focus on the impact of residential locations on transportation energy consumption.

Data used in the following case studies come from a national census carried out in Belgium (the General Socio-Economic Survey 2001 [57]). Note that these data only concern home-to-work and home-to-school travel; however, we could use the same methodology with data from an in situ survey account for all travel purpose.

2.3. On-site energy production by renewable sources

On-site energy production via photovoltaic panels (E_{PV}), thermal panels (E_{TH}) and small wind turbines (E_{WT}) are considered when accounting for renewable energy sources. The annual renewable energy produced in the neighbourhood (E_{RP}) is calculated using equation 4.

$$E_{RP} = E_{PV} + E_{TH} + E_{WT} \quad (4)$$

2.3.1. Photovoltaic panels (electricity)

The potential of neighbourhoods for active solar heating and photovoltaic electricity production is obtained using numerical simulations performed with Townscope software [58]. Only photovoltaic panels on roofs are considered because those on facades are less effective in Belgium [59]. Townscope allows the calculation of the direct, diffuse and reflecting solar radiation reaching a point and the radiation distribution on a surface. As calculations are performed under clear-sky conditions, the software is used to determine a first correction factor M (the difference between the values calculated for the assessed neighbourhood and the clean site) to apply to the mean solar radiation MSR for the considered latitude (MSR = 1000 kWh/m^2·year for Belgium [60]). A second factor F is applied to take into account the roof orientation and inclination (Table 1) [61].

The solar energy received by the considered surface is obtained using Eq. (5). The potential of roofs for photovoltaic electricity production (E_{PV}, in kWh per year) is obtained by Eq. (6). In Eq. (6), S represents the surface area of the considered roofs, C the percentage of the roofs covered by panels (maximum 0.80), η_{pv} the efficiency of the photovoltaic panels, η_{inv} the efficiency of the inverter and

Table 1
Values of the correction factor *F*, which accounts for roof orientation and inclination [61].

		Inclination				
		0°	15°	25°	35°	50°
Orientation	East	0.88	0.87	0.85	0.83	0.77
	Southeast	0.88	0.93	0.95	0.95	0.92
	South	0.88	0.96	0.99	1	0.98
	Southwest	0.88	0.93	0.95	0.95	0.92
	West	0.88	0.87	0.85	0.82	0.76

λ a correction factor taking into account electricity losses. In the following case studies, the efficiency of the photovoltaic panels is fixed at 0.145, the efficiency of the inverter at 0.96 and the electricity loss correction factor at 0.2; in accordance to the technical characteristics of the most used type of panels in Wallonia [62].

$$E_{sol} = \text{MSR} \times FM \,(\text{in} \quad \text{kWh/m}^2\text{year}) \quad (5)$$

$$E_{PV} = E_{sol} SC\eta_{pv}(1-) \quad (6)$$

2.3.2. Thermal panels (hot water)

The solar energy received annually by the roof is obtained using Eq. (5), where correction factor *M* is calculated with Townscope and correction factor *F* is defined according to Table 1. Eq. (7) allows the determination of whether the roofs of the houses of the neighbourhoods are adapted to the production of hot water. In Eq. (7), E_{sol} represents the solar energy received by the roofs, *S* the surface area of the panel and η_{th} the efficiency of the thermal panels. We consider that 55% of the production of hot water of each household must be covered through thermal panels (from a technical-economic viewpoint, the optimum is often considered to be between 50% and 60%). Under these conditions, the efficiency of the system is 0.35.

$$E_{TH} = E_{sol} S\eta_{th} \quad (7)$$

2.3.3. Wind turbines

The approximation used to evaluate the annual electricity production of wind turbines (E_{WT}) consists of multiplying the rated power of the wind turbine by the number of operating hours at this rated power, as in Eq. (8), in which *P* is the rated power of the wind turbine and OH the number of operating hours. This value is fixed at 1000 h for a small wind turbine [63].

$$E_{WT} = P \cdot \text{OH} \quad (8)$$

2.4. Annual balance at the neighbourhood scale

The annual energy consumption of the neighbourhood (E_N) is calculated by adding the building energy consumption (E_B) and transportation energy consumption (E_{DM}) and subtracting the on-site renewable energy production (E_{RP}), as shown in Eq. (9).

$$E_N = E_B + E_{DM} - E_{RP} \quad (9)$$

The monthly balances can also be studied according to the same type of equation by replacing the annual energy consumption and production by the corresponding monthly values.

3. Results

3.1. Presentation of the case studies

The case studies chosen are two common archetypes of neighbourhoods (understood as urban blocks, that is to say the smallest area of a city that is surrounded by streets) and are representative of the building stock in Belgium [64]. The two neighbourhoods

Table 2
Main characteristics of the two case studies.

	Case 1	Case 2
Type	Urban	Suburban
Surface area	0.97 ha	12.02 ha
Population	180 inhabitants	150 inhabitants
Buildings	57	55
Detached houses	7%	75%
Semi-detached houses	17.5%	19.6%
Terraced houses	75.5%	3.6%
Apartments	0%	1.8%
Density	60 dw/ha	5 dw/ha
% of the surface area occupied by buildings	29%	5%

contain essentially the same number of buildings but in a very different urban form. Each urban form presents its own specificities and characteristics, especially as far as the built density and the types of buildings are concerned, as highlighted on Table 2, and requires personalised solutions regarding the energy efficiency in the building and transportation sectors and the on-site production of renewable energy.

The first case study (Fig. 1) is a dense neighbourhood (60 dwellings per hectare) representative of an old compact industrial urban fabric. This neighbourhood is located close to good transportation networks (trains and buses), work places, schools, shops and services. Buildings are very poorly insulated, because the neighbourhood was built in the 19th century.

The second case study (Fig. 2) is a low-density suburban neighbourhood (5 dwellings per hectare) located in the suburbs (18 km) of the city centre. It is representative of the urban sprawl that began in Belgium in the 1960s. Public transportation is minimal, and car dependency is high. The neighbourhood is comprised of detached houses built between 1930 and 2010. Some retrofitting works (changing of the glazing, roof insulation) has been performed by the owners.

3.2. Annual energy balance

In the current situation, the energy consumption for space heating is quite large in both neighbourhoods (184 kWh/m² per year in case 1 and 235 kWh/m² per year in case 2), and the annual zero-energy balance cannot be achieved (Table 3). A clear difference is observed between the heating energy requirements of the two neighbourhoods because the first is made up terraced houses, which consume approximately 25% less energy for heating than the less compact urban form. Similarly to the building scale, to

Fig. 1. Case study 1—a representative urban residential neighbourhood (Belgium).

Table 3
Results of the application of the "zero-energy neighbourhood" framework to the two case studies.

		Case study 1	Case study 2
Consumption (kWh)	Space heating and ventilation: *E*SH + *E*v	1,421,694	2,754,341
	(*E*SH + *E*v—low-energy retrofitting)	(463,595)	(703,235)
	(*E*SH + *E*v—passive retrofitting)	(143,156)	(214,074)
	Appliances: *E*A	161,139	155,485
	Cooking: *E*C	26,277	25,355
	Hot water: *E*HW	152,950	127,458
	Daily mobility: *E*DM	339,696	441,072
Production (kWh)	Photovoltaic elec.: *E*PV	139,945	314,669
	Hot water heating: *E*TH	80,417	67,170
	Wind turbine: *E*WT	0	50,000

Fig. 2. Case study 2—a representative suburban residential neighbourhood (Belgium).

achieve a net zero-energy balance at the neighbourhood scale, the energy demand (heating in these case studies herein) must be reduced using energy efficiency measures (a major retrofitting of the envelope of the building). The result must satisfy the (very) low, passive or net zero-energy standards. Moreover, the results show that the zero-energy neighbourhood objective also needs to minimise the energy needs for appliances, cooking and hot water. It is important to emphasise the influence of less energy-consuming devices as well as adapted user behaviours and lifestyles, parameters that have already been studied in detail in other references (e.g., [65–67]).

Energy consumption for daily mobility is also higher (approximately 30%) in the suburban neighbourhood, which is highly dependent on private cars and for which travel for work and school is across large distances. Taking into account energy consumption from daily mobility, as highlighted in our assumptions, the impact of the location of the neighbourhood can be included in the annual balance. This is crucial to avoid simply proposing building or retrofitting zero-energy buildings and neighbourhoods as the optimal solution to create a more sustainable built environment, regardless of their location and the impact of this location on transportation energy consumption. Moreover, the results show that the zero-energy neighbourhood objective also requires the minimisation of the energy needs for daily mobility, even in urban areas.

In contrast, as far as on-site renewable energy production is concerned, the photovoltaic production is higher in the suburban neighbourhood (case 2) because simulations performed with Townscope to calculate solar radiation on roofs (see Section 2.3.1, above) have shown that the shadowing effect is much lower in this area than in the dense neighbourhood (case 1). Quite interestingly, parametric variations show that if photovoltaic panels are only located on roofs that receive over 90% of the maximum solar energy and if the electricity production is mutualised at the neighbourhood scale, the efficiency (kWh produced per m^2 of panel) increases significantly (+10.7% in case 1 and +5.0% in case 2). The same amount of photovoltaic electricity can thus be produced by installing fewer panels than reported in Table 3, where photovoltaic panels were installed on each building. Thermal energy production is higher in case 1 thanks to the surface areas of the roofs but simulations performed to assess solar radiation on roofs (see Section 2.3.1, above) have shown that the shadowing effect is much lower in the suburban area.

The use of wind turbines in the first case study was not assessed because of the dense context in which it is located. In the suburban case, a small wind turbine produces approximately 50,000 kWh annually. This wind turbine could be located in the centre of the neighbourhood because this location is sufficiently far from existing houses (based on the noise produced by the turbine and the existing regulations); however, this solution would prohibit the future densification of the neighbourhood, which is a possible solution to increasing the sustainability of existing suburban blocks.

In comparison with building and transportation energy consumption, and for the considered climate and context, the on-site generation of renewable energy is often limited, especially in the dense case study. The zero-energy balance cannot be achieved, even if buildings are retrofitted to the passive standard. Therein, intermediate levels of performance (the [very] low, passive or net zero-energy neighbourhoods) could also be promoted, especially as far as interventions in existing neighbourhoods are concerned. Rather than the respect of a zero-energy annual balance, it seems important to promote, above all, the minimisation of building and transportation energy consumptions and the maximisation of renewable energy production.

3.3. Monthly energy balances

An annual balance was used first in this paper. Yearly balances account for the succession of the four seasons and their particularities. However, it is also interesting to investigate shorter periods of time. Monthly production and consumption curves highlight the shift between the production and consumption peaks and between supply and demand, particularly for solar energy (highest in summer) and heating consumption (highest in winter), as highlighted in Fig. 3.

4. Discussion and perspectives for further research

Achieving a net zero-energy balance in the two existing neighbourhoods is very difficult, namely because the building stock

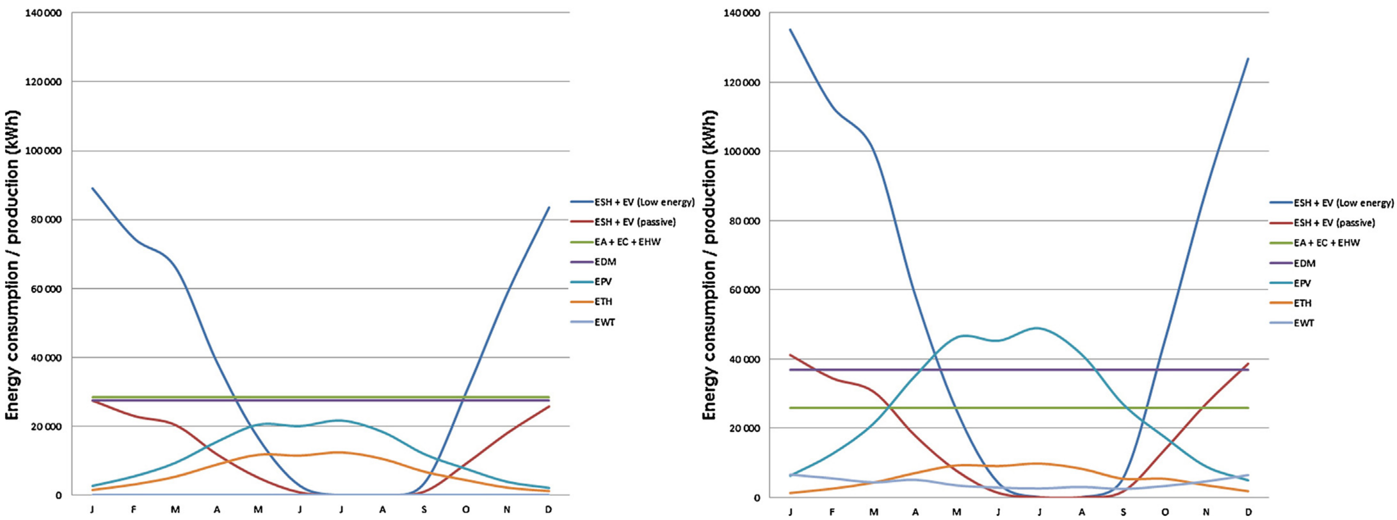

Fig. 3. Monthly production and consumption curves for the two case studies (case study 1 on the left and case study 2 on the right).

is poorly insulated. Intermediate milestone and targets could be proposed to help local communities to move towards more sustainability:

1. Improve the energy efficiency of the building stock (e.g., retrofitting to the passive house standard).
2. Minimize energy demand for buildings and for transportation through occupant behaviour (e.g., adapting the inner temperature of the dwellings, promoting car sharing).
3. Maximise on-site renewable energy production (e.g., installing PV panels).
4. Use off-site renewable energy production (e.g., using district heating and imported renewable energy).

As we highlighted significant differences between the urban and the suburban case studies, these milestones should be differentiated, according to the local opportunities in each neighbourhood.

In this course to reach sustainability in existing neighbourhoods, one of the main advantages of the neighbourhood scale is the potential for an “energy mutualisation” for both energy production and energy consumption. We have namely highlighted the interest of producing photovoltaic electricity at the neighbourhood, rather than at the individual scale. Another example was the pooling of the built envelope in dense urban neighbourhoods that allows to reduce energy needs of terraced houses, in comparison with detached houses. This concept of “pooling”, at the neighbourhood scale, provides numerous avenues to increase energy efficiency in our built environment. In the same vein, it should be noted that this “energy mutualisation” or “pooling” at the neighbourhood scale offers interesting perspectives for the compensation of the monthly peaks (as well as hourly peaks) between supply and demand between individual buildings, especially in neighbourhoods presenting a wide variety of functions with different and shifted energy needs (offices, schools, etc., versus residences).

As far as perspectives for further research are concerned, the connection to the grid, the use of smart grids and the storage of energy should be investigated in the future. Cost optimisation should also be considered based on current discussions related to the European Directive on the Energy Performance of Buildings. Finally, we recommend extending the balance to the entire lifecycle of a neighbourhood by including the energy and CO_2 embodied in materials and technical installations (including transportation infrastructure).

5. Conclusions

The goal of this paper was to contribute to the existing literature on the “zero-energy” objective in the building sector by investigating the feasibility of this objective at the neighbourhood scale. The paper presented a simplified framework and a calculation method related to the “net zero-energy neighbourhood”, which included building energy consumption and the on-site renewable energy at the neighbourhood scale as well as the impact of urban form and the location of the neighbourhood on transportation energy consumption for daily mobility. These developments were applied to two case studies (one urban neighbourhood and one suburban neighbourhood in Belgium) to highlight the main parameters that act upon the annual energy balance of a neighbourhood and to propose concrete steps to improve the sustainability of existing neighbourhoods. This work highlighted the opportunities for and interest in extending the boundaries of the existing frameworks from the building to the neighbourhood, which mainly concern the impact of urban form and daily mobility. The proposed nZEN framework allows to consider building energy consumption, renewable production and transportation energy consumption as an integrated system, rather than separated topics.

In a more general perspective, this works calls for a better integration of the individual building into its context in policies dealing with energy efficiency. Promoting the building and retrofitting of energy-efficient buildings is a good step towards increased energy efficiency in our built environment (i.e., by imposing mandatory minimum requirements on the energy efficiency of buildings that are crucial to reach a net zero energy balance); however, it is not sufficient. It is also crucial to consider parameters and interactions linked to a larger scale, the urban planning scale, to more effectively achieve the aims of these policies. To this end, the location of new buildings and developments appears to be crucial in the total balance, which includes both building and transportation energy consumption.

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