From Zero Energy Building to Zero Energy Neighbourhood.
Urban form and mobility matter.

ANNE-FRANCOISE MARIQUE[1], MARINE PENDERS[1], SIGRID REITER[1]

[1]LEMA (Local Environment: Management & Analysis), University of Liege, Liege, Belgium

ABSTRACT: Zero-Energy" Building (ZEB) is arousing more and more interest internationally, both in policies aiming at a more sustainable built environment (such as the European Directive PEB that will require, for example, all new buildings to be "nearly Zero-Energy" Buildings (nZEB) by 2020) and in the scientific literature. Although Zero-Energy can be considered at different scales, this approach only adopts the perspective of the individual building and neglects phenomena linked to larger scales. Therefore, this paper aims at investigating the "Zero-Energy Neighbourhood" concept. It proposes a calculation method that takes into account three main topics: the energy consumption of buildings, the impact of the location on the energy consumption for daily mobility and the use of renewable energies. An application of this calculation method to two representative case studies (one urban neighbourhood and one suburban neighbourhood) is proposed. Main parameters that act upon the energy balance are highlighted and combined to propose concrete results to improve our built environment and move towards more sustainability. Hourly and monthly balances, the potential of "energy mutualisation" and smart grids are keys challenges that are of crucial importance in the scope of a Zero-Energy objective at the neighbourhood scale.

Keywords: Zero Energy Building, Zero Energy Neighbourhood, urban form, mobility, renewable energy

INTRODUCTION

The building sector is a major consumer of energy worldwide. It represents, for example, 37% of the overall energy consumed in the European Union. In the current context of growing interest in environmental issues, reducing energy consumption in the building sector appears thus as an important policy target. Politicians, stakeholders and even citizens are now aware of the issue of energy consumption in buildings, namely through the passing of the European Energy Performance of Buildings Directive and its adaptation to the Member States. Another major trends 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). New construction standards ((very) low energy standard, passive house standard) were thus developed to drastically minimize the energy consumption of new and retrofitted buildings and minimize the associated greenhouse gas emissions.

During last few years, the « Zero-Energy Building», in particular, has aroused more and more interest internationally, both in policies aiming at a more sustainable built environment and in the scientific literature. As far as policies are concerned, the recast of the European Performance of Buildings Directive (EPBD) requires, for example, all new buildings to be "nearly Zero-Energy" Buildings (nZEB) by 2020 and will be extended to existing buildings undergoing major retrofitting works [1]. In the United States of America, the Energy Independence and Security Act (2007) [2], that concerns the energy policy of the whole country, aims to create a nationwide net Zero Energy initiative for commercial buildings built after 2025.

More concretely, several buildings have recently been built and prove that Zero Energy, at the building scale, is feasible. These buildings, which do not contribute to climate change, bring together architectural design, energy efficiency and the local use of renewable energies to reach an equalised annual energy balance [3]. Most of these existing Zero Energy Buildings are (small or large) residential buildings and office buildings [4,5]. Renovations to Zero Energy and Zero Energy at larger scales remain still quite rare. One interesting development, at the neighbourhood scale, is the BedZED sustainable neighbourhood that aimed to be the UK's largest mixed use Zero Carbon community. However, the Zero Carbon objective was not achieved.

In the literature, the Zero Energy objective is most often considered at the building scale. Several papers propose thus definitions of Zero Energy Buildings [3,6], calculation methodologies [7] or support tool for early stages of design [8]. These definitions are commonly articulated around an annual energy balance equal to zero. But, in spite of its huge interest in terms of energy efficiency in buildings, the "Zero Energy Building" concept still considers the individual building as an autonomous entity and neglects the importance of phenomena linked to larger scales as far as energy performances of buildings, the efficiency of renewable energies and the impact of the location of the building on transport energy consumption are concerned. Research and papers dealing with Zero Energy at larger scales are not numerous: a few papers study the Zero Energy City [9] or the role of simulation tools in the ZEB objective, at the city scale [10]. A prospective vision at an intermediate scale between the whole city and the building is lacking.

To our point of view, coming from an analyse of numerous previous research dedicated to the impact on urban form on energy consumption both in the building [e.g. 11,12,13] and in the transportation [e.g. 14,15,16] sectors, six main challenges seem important to be considered to complete the existing approaches dedicated to “Zero Energy” :

(1) The neighbourhood scale is particularly interesting from an operational point of view and allows to take into account numerous interactions that occur at a scale larger than the building one.
(2) The major challenges of both developing new efficient urban forms and buildings and retrofitting the existing building stock (in particular in Belgium, where the renewal rate of the existing building stock is quite low).
(3) The huge impacts of parameters linked to the urban form on the energy efficiency of single buildings and on the choice and the efficiency of renewable energy sources.
(4) The impact of the location of residences, work places and services on daily mobility patterns and their related energy consumption.
(5) The significant increase in energy needs at the horizon 2040, given the demographic growth (+600,000 inhabitants in the Walloon region of Belgium) and the increase of consumption peaks.
(6) The significant increase of energy produced by renewables sources and associate constraints (storage, connection to grids, gap between consumption and production peaks, etc.).

In this context, this paper aims at articulating these challenges through the investigation of the concept of “Zero Energy” at the neighbourhood scale. It proposes a framework and a calculation method to assess Zero Energy Neighbourhoods in a comprehensive systemic approach allowing to take into account and assess the numerous interactions at the neighbourhood scale. An application of the proposed framework is then developed to test its applicability and highlight key parameters in the annual energy balance of two representative neighbourhoods. Key challenges to be addressed and futures perspectives to investigate in further research are finally highlighted.

A “ZERO ENERGY NEIGHBOURHOOD” FRAMEWORK: METHOD AND ASSUMPTIONS

The “Zero Energy Neighbourhood” concept is described, by analogy with the Zero Energy Building, as a neighbourhood in which annual energy consumption for buildings and transportation of inhabitants are balanced by the local production of renewable energy. The balance is annual but monthly balances are also studied to capture the gaps between energy consumption and production by renewable sources. Energy consumption and production, in the neighbourhood, can be evaluated thanks to the following method. For each part of the general framework (energy consumption in buildings, energy consumption for daily mobility and energy production by renewable sources), the calculation methodology and the main assumptions are presented.

Energy consumption in buildings

The methodology combines a typological classification of buildings, thermal dynamic simulations and statistical treatments of national censuses in order to assess the annual energy consumption for space heating (E_{SH}), for space cooling (E_{CO}), for ventilation (E_{V}), for the appliances (E_{A}), for cooking (E_{C}) and for domestic hot water (E_{HW}). Energy consumption and primary energy consumption for space heating, cooling and ventilation at the neighbourhood scale are calculated by adding the results from the energy simulations for each type of house according to their distribution in the neighbourhood [17]. The annual energy consumption related to appliances (E_{A}) and cooking (E_{C}) are assumed to be independent on the building type and are based on regional statistics or in situ surveys. 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 to obtain kWh.

In the framework of this paper application, a typology of dwellings classifying the residential building stock of the Walloon region of Belgium is used. This typological approach was based on the following factors: common ownership (detached, semi-detached, terraced house, apartments), the heated area of the dwelling in square meters (m^2), the heating and ventilation systems, the date of construction and the related level of insulation. Three additional categories are added for houses built according to standards higher than the European Energy Performance of Buildings Directive (EPBD). These are the low-energy standard, the very low-energy standard and the passive standard which respectively correspond to annual heating requirements lower than 60 kWh/m^2.year, 30 kWh/m^2.year and 15 kWh/m^2.year. Each parameter can be adapted to capture, for example, retrofitting works (e.g. insulation of the roof and/or replacement of the glazing, change of the heating and/or ventilation systems, etc.).

Results of energy simulations of all the types of dwellings of this typology (E_{SH} and E_{V}) are stored in a huge database that comprises the energy consumption of around 180,000 buildings. In these thermal simulations, Brussels meteorological data (temperate climate) are used. The minimum temperature in the dwelling is 18°C and internal gains are defined according to the surface area of the dwelling. Energy consumption and primary energy consumption for space heating and for ventilation at the neighbourhood scale are thus calculated by adding the results from the energy consumption analysis for each type of house according to their distribution in the neighbourhood. Note that heating represents about of 75% of the consumption of buildings in Belgium [18]. Cooling is not taken into account in our case studies because cooling is rare in residential buildings in Belgium.

The energy consumption related to appliances and cooking are respectively evaluated at 2,827 kWh per household and per year and 461 kWh per household and per year in Belgium [19]. The energy consumption related to domestic hot water (E_{HW}) is assumed to be dependent on the number of inhabitants. We consider that each inhabitant need 100 litres of cold water (10°C) and 40 litres of hot water (60°C) per day, in accordance with the regional trends [19].

Energy consumption for daily mobility

The annual energy consumption for daily mobility (E_{DM}) is assessed thanks to a performance index [20,21]. This index is expressed in kWh/travel.person and represents, for a territorial unit, the mean energy consumption for travels for one person living within a particular neighbourhood. This index takes into account the distances travelled, the means of transport used and their relative consumption rates, expressed by equation (1). In the equation, *i* represents the territorial unit; *m* the mean of transport used (diesel car, fuel car, train, bus, bike, on foot); *Dmi* the total distance travelled by the means of transport *m* in the district *i*; *fm* the consumption factor attributed to means of transport *m* and *Ti* the number of persons in the territorial unit *i*. Consumption factors depend upon the consumption of the vehicles (litres of fuel per kilometre) and their occupation rate. There are worth 0.56 kWh/person.km for a diesel car, 0.61 kWh/p.km for a fuel car, 0.45 kWh/p.km for a bus, 0.15 kWh/p.km for a train and 0 for non-motorized means of transportation because these do not consume any energy.

$$(1)\text{Energy performance index } (i) = (\textstyle\sum_m D_{mi} * f_m) / T_i$$

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

$$(2)\ E_{DM} = \text{Energy performance index} * N * T$$

Data used to calculate annual energy consumption for daily mobility can come from different sources: national censuses, “in situ” surveys carried out in the assessed neighbourhoods or mean values (travelled distances and means of transportation) representative of the type of neighbourhoods. In the framework of this paper application, we will use data from a national census carried out in Belgium in 2001. Note that these data only concern home-to-work and home-to-school travels but we could use the same methodology with data coming from in situ survey to take into account all the purposes of travel.

Energy production by renewables sources

The potential of urban and suburban neighbourhoods for active solar heating and photovoltaic electricity production is obtained thanks to numerical simulations performed with Townscope software [22]. In this paper application, only the roofs will be considered because photovoltaic panels on facades are less effective in Belgium. Townscope allows to obtain direct, diffuse and reflecting solar radiation reaching a point and radiation distribution on a surface. As calculations are performed under a clear sky which is not representative of the Belgian climate, the software is used to determine a correction factor M (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 = 1,000 kWh/m².year for Belgium). A correction factor F is applied to take into account the orientation and the inclination of the roofs (tab.1).

Table 1: Correction factor F, depending on the inclination and the orientation of the roof, for Belgium

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

Solar energy received by the considered surface is obtained thanks to equation 3.

$$(3)\ Esol = MSR * F * M \text{ (in kWh/m}^2\text{.year)}$$

The potential of roofs for photovoltaic electricity production (E_{PV}, in Kwh per year) is obtained by equation 4. In the equation *S* represents the surface area of the considered roofs, *C* the percentage of the roofs covered by panels (maximum 0.80), ηpv the efficiency of the photovoltaic panels, ηinv the efficiency of the inverter and 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 electricity losses at 0.2.

$$(4) E_{PV} = Esol * S * C * \eta pv * \eta inv * (1-\lambda)$$

The potential of roofs for heating hot water through thermal panels cannot be assessed through the equation used for photovoltaic electricity because both systems are quite different. Solar energy received annually by the roof is obtained thanks to equation 3, where the correction factor F is defined according to tab.1 and the correction factor M is calculated with Townscope. Equation 5 allows to determine if the roofs of the houses of the neighbourhoods are adapted to the production of hot water. In equation 5, *Esol* represents the solar energy received by the roofs, *S* the surface area of the panel and ηth 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 point the view, the optimum is often considered to be comprised between 50% and 60%). In this condition, the efficiency of the system is worth 0.35.

$$(5) E_{TH} = Esol * S * \eta th$$

The approximation used to quickly evaluate the annual electricity production of wind turbines (E_{WT}) consists in multiplying the rated power of the wind turbine by the number of operating hours at this rated power, according to equation 6, in which *P* is the rated power of the wind turbine and *OH* the number of operating hours. This data is fixed at 1,000 hours for a small wind turbine and is comprised between 1,800 and 2,200 for a big onshore wind turbine.

$$(6) E_{WT} = P * OH$$

For the moment, only photovoltaic panels, thermal panels and wind turbines are considered in the balance. The production of heating and/or electricity through cogeneration, biomass and other renewable energy sources will further be investigated to complete the approach presented in this paper.

Annual balance at the neighbourhood scale

The annual "Zero Energy" balance, at the neighbourhood scale, is given by equation 7.

$$(7) E_{SH}+E_{CL}+E_{V}+E_{A}+E_{C}+E_{DM}+E_{HW}-E_{PV}-E_{TH}-E_{WT}=0$$

The annual balance is proposed in primary energy. Conversion factors used are 1 for natural gas and petrol and 2.5 for electricity. Monthly balance can also be studied according to the same type of equation, by replacing annual energy consumption and production by monthly values.

APPLICATION TO TWO REPRESENTATIVE NEIGHBOURHOODS

Presentation of the case studies

The chosen case studies are two common archetypes of urban blocks and are representative of the building stock in the Walloon region of Belgium. The two neighbourhoods present more or less the same number of buildings but are arranged in a very different urban form. There both present their own specificities and characteristics (tab. 2) and need personalized answers as far as both the energy efficiency in the building and in the transportation sectors and the production of renewable energy are concerned.

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 not, or very poorly, insulated because the neighbourhood was built in the 19th century. Inhabitants are mainly poor people and do not have money enough to retrofit and insulate their houses.

Figure 1: Case study 1-a representative urban residential neighbourhood (Belgium), © maps.google.be

The second case study (fig. 2) is a low-density suburban neighbourhood (5 dwellings per hectare) located in the suburbs (18 kilometres) of the city centre. It refers to the urban sprawl that has touched our territories from the sixties. Public transportation is very low and car dependency high. The neighbourhood is made up detached houses built between 1930 and 2010.

Some retrofitting works (changing of the glazing, insulation of the roofs) were performed by the owners.

Figure 2: Case study 2 - a representative suburban residential neighbourhood (Belgium) © maps.google.be

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	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%

Results: Annual Energy balance

In the current situation, the Zero Energy balance cannot be achieved, especially because energy consumption for space heating is quite huge in both neighbourhoods (184 kWh/m².year in case 1 and 235 kWh/m².year in case 2). A clear difference is observed between the heating energy requirements of the two neighbourhoods because the first one is made up terraced houses, that consume around 25% of energy for heating less than less compact urban form. As already highlighted in the literature, the Zero Energy objective, at the building or at the neighbourhood scale, needs first to drastically minimize the energy needs for heating thanks to a major retrofitting of the envelope of the building to reach the (very) low or the passive standard. Energy consumption for daily mobility is also higher (about 30%) in the suburban neighbourhood that is very dependent about private car and where distances to travel to go to work and to school are huge. Taking into account energy consumption from daily mobility allows, as highlighted in our assumptions, to include the impact of the location of the neighbourhood in the annual balance. This is crucial to avoid simply proposing to build or retrofit Zero Energy Buildings and Neighbourhoods as the optimal solution to draw a more sustainable built environment, regardless of their location and the impact of this location on transport energy consumption. Moreover, the results show that the Zero Energy Neighbourhood objective needs also to minimize the energy needs for daily mobility, even in urban areas. As far as renewable energy production is concerned, the photovoltaic energy production is better in the suburban neighbourhood (case 2) because shadowing effect are quite low, in comparison with the dense neighbourhood (case 1). The use of wind turbine 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 allows to produce around 50,000kWh annually. This wind turbine could be located in the centre of the neighbourhood, because distance to existing houses is sufficient enough (according to noise produced by the turbine and the existing regulations) but this solution avoid the future densification of the neighbourhood, that could be a possible solution to increase the sustainability of existing suburban blocks [23].

Table 3: Annual energy balance (kWh) in the two case studies

		Case 1	**Case 2**
Consumption	Space heating and ventilation: E_{SH} +E_V	1,421,694	2,754,341
	(E_{SH} +E_V – low energy retrofitting)	(463,596)	(703,236)
	(E_{SH} +E_V – passive retrofitting)	(142,059)	(222,017)
	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
Prod.	Photovoltaic elec.: E_{PV}	139,945	314,669
	Hot water heating: E_{TH}	80,417	67,170
	Wind turbine: E_{WT}	0	50,000

Discussion and perspectives

The main advantage of the neighborhood scale is the potential “mutualisation” of energy production. For example, if photovoltaic panels are only located on the roofs that received more than 90% of the maximum solar energy and if the electricity production is mutualized at the neighborhood scale, the efficiency (kWh produced per m² of panel) increase (+10.7% in case 1 and +5.0% in case 2). The same amount of photovoltaic electricity can be produced by installing fewer panels than in tab.3, where all the individual roofs were used. Others examples of mutualisation that will be further investigated are the use of common ownership to reduce space heating needs, the use of electrical vehicle to store electricity production, etc.

As far as monthly production and consumption are concerned, it is interesting to highlight the gap between the production and consumption peaks, namely for solar energy (max in summer) and heating consumption (max in winter). This challenge (as well as hourly curves) are of crucial importance in the scope of a Zero Energy objective and will be addressed in further research. The third challenge to further investigate to operationalize the Zero Energy Neighborhood is the connection to the grid, the use of smart grids and the storage of energy.

CONCLUSION AND PERSPECTIVES

This paper aimed at completing the existing papers relating to “Zero Energy” by investigating the feasibility of this objective at the neighbourhood scale. The paper presented a general framework and a calculation method related to the new concept of “Zero Energy Neighbourhood”. These first developments were applied to two case studies to highlight main parameters that act upon the annual energy balance of a neighbourhood and help to propose concrete results to improve our built environment and move towards more sustainability. This work opens numerous future research perspectives that should be investigated to develop more widely the “Zero Energy Neighbourhood” concept and to concretely operationalize it. The methodological framework will be extended and completed, namely to take into account others sources of renewable energy, embodied energy, operational and embodied CO_2, etc. The potential of “energy mutualisation”, hourly and monthly balances, energy storage and smart grids are keys challenges that are of crucial importance in the scope of a Zero-Energy objective at the neighbourhood scale. They will be investigated in a further three-year research program.

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