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Assessing household energy uses: An online interactive tool dedicated to citizens and local stakeholders

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ABSTRACT

This paper presents the SOLEN integrated online tool, dedicated to citizens and local authorities. This methodology, developed to allow precise energy assessment (heating, cooling, ventilation, lighting, appliances, and cooking but also local production of renewable energy) of household energy uses, is firstly introduced. SOLEN uses a typological classification of buildings and thermal simulations. Many parameters are defined and taken into account to capture the specificities of numerous types of buildings exhaustively (e.g. type of buildings; number of floors; common ownership; orientation; thermal performances of the walls, floors, roofs, and windows; and ventilation type). These results related to building energy consumption are then crossed, in an integrated approach, with several indicators of urban sustainability, to take into account in the balance of the impact of the location of buildings on transportation energy consumption or the impact of the urban form on the production of solar renewable energy. This tool makes accessible to a large non-specialized audience the results of a three-year scientific research study in Wallonia (Belgium) and was awarded an Energy Globe Award (Belgium) in 2014. The first feedback from users is presented to conclude this contribution.

1. Introduction

There is an urgent need to reduce energy uses in our built environments, including cities, suburban areas, as well as rural settlements. In Europe, energy consumption in the building sector accounts for more than 40% of the final energy supplied to the customers [1], representing the most important sector, above transportation and industry. Buildings are thus considered as major contributors to climate change because of the release of carbon dioxide and others greenhouses gases, and promoting energy efficiency in buildings is often presented as a viable approach to the mitigation of climate change. Energy efficiency in the building sector has thus been the focus of extensive worldwide research over the past decades. Numerous research efforts have highlighted the need to produce more efficient buildings, but also to retrofit the existing building stock, especially in Europe where the renewal rate of buildings is quite low [2–4], thus the existing building stock should be the main target to significantly reduce energy consumption.

The use of mathematical models and simulation tools is often presented as the most credible approach to model the behaviour and to predict the energy consumption of a system [5,6]. Most of these existing models focus on the heating requirements of residential or tertiary buildings, at the individual building scale. More recently, the role that urban form plays in influencing the energy consumption of individuals buildings has also been studied extensively [7–9]; the importance of the location of a building and the characteristics of the neighbourhood in which it is located (density, diversity of function, access to amenities, etc.) on the generation of mobility patterns and quality of life has been highlighted. In fact, it seems counterproductive to produce or retrofit efficient buildings without any concern for the location of the building and its impact on the mobility of its inhabitants. Amongst their numerous advantages, the approaches based on mathematical models and simulation tools can account for a large number of parameters that are known to act upon the energy consumption of a system and can utilize parametric variations to test the impact of energy efficiency strategies.

Last but not least, several research and empirical results have demonstrated the significant impact of the lifestyles and behaviours of housing occupants on energy consumption [10,11]. Citizens and local authorities must be considered as the first actors that can concretely alter the energy consumption in buildings and

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in cities. The rate of private ownership in the residential building sector is high in most European regions (especially in Belgium where almost 70% of household occupants are owners of their own dwellings [12]). Private owners have a central role in the retrofitting of the building stock. Small adaptations to individual behaviours (e.g. thermostat, heated area, etc.) can help to reduce energy consumption drastically. However, research methods and tools that allow precise quantification of energy uses in buildings and energy savings related to various actions (insulating the roof, changing the glazing, behavioural changes, etc.) remain dedicated mostly to trained professional users [13–15], thus neglecting the huge potential energy savings linked to individual actions undertaken by citizens in their dwellings. Moreover, although an increasing number of household occupants are paying attention to their energy consumption and are motivated to undertake light or heavy renovation, they do not know what actions to undertake and are unaware of the impacts of renovation in terms of comfort, energy savings, costs, etc. Raising public awareness of the impact of citizens on energy efficiency is crucial and could quickly lead to significant reductions in the total energy consumption of a territory.

The dissemination of academic research to the public (citizens, local authorities, policy makers, etc.) is crucial to ensure more sustainable development of our territories and to reduce energy consumption in buildings. Thus, the main aim of this research was to encourage positive changes in the energy efficiency of the building stock, by providing an online interactive tool that will help citizens and local stakeholders to assess energy uses in their houses and neighbourhoods, starting at the individual scale. This tool was intended to transfer the main results of a three-year study to a non-specialized audience. The need for this type of research lies in the fact that its dissemination is for people that do not have specific knowledge in the energy field, but for them to have the necessary information to conduct themselves in their homes and neighbourhoods more energy efficiently.

In this context, this paper presents the SOLEN tool, a novel integrated urban tool, developed within the "Solutions for Low Energy Neighbourhoods" project and dedicated to citizens and local authorities. The aim of this tool is to address the previously highlighted main challenges, in an integrated approach, by allowing the user to perform an entire assessment of energy uses from residential buildings and daily mobility, as well as to quantify the energy efficiency of several types of retrofits and changes in daily habits. This tool is based on a previous version, developed to assess only suburban houses and neighbourhoods [16]. Major updates and complements were developed to strongly improve and enrich the first version and are presented, especially:

- The methodology to assess energy uses in buildings was strongly improved to also consider lighting, appliances, and cooking;
- The updated version of the tool allows the local production of renewable energy, such as PV panels, solar heating, etc. to be taken into account;
- The impact of the neighbourhood in which the building is located is taken into account;
- The methodology used to assess transportation energy uses was modified to include all types of travel, including chained trips;
- Several sustainability indicators were developed and crossed with energy consumption in buildings; and
- It is now also possible to obtain financial gains related to energy consumptions and potential energy savings.

The SOLEN interactive tool was built upon numerous methods, tools, and data that cannot be presented extensively in a single paper. As this paper focuses on the presentation of the interactive tool, enabling the transfer of scientific methods and results to a non-specialized audience, the interested reader can refer to several previous scientific papers in which all parts of the methods and related assumptions have been extensively presented [10,16–18,29,33–36]. The methods that have been developed to build the SOLEN tool are summarized in the two following sections. Section 2 briefly presents the methodology that enables a precise assessment of energy uses in buildings (heating, cooling, ventilation, lighting, appliances, cooking, and production of local renewable energy). This methodology was applied to the Walloon (Belgium) building stock and a huge database including more than 250,000 individual results was produced. Then, Section 3 presents several indicators of urban sustainability that were developed to be taken into account in the online interactive tool, including the impact of the location or urban form on energy production and consumption. In Section 4, the SOLEN online integrated urban tool, developed based on previous methodologies and their application, is presented. This tool, especially dedicated to citizens and local

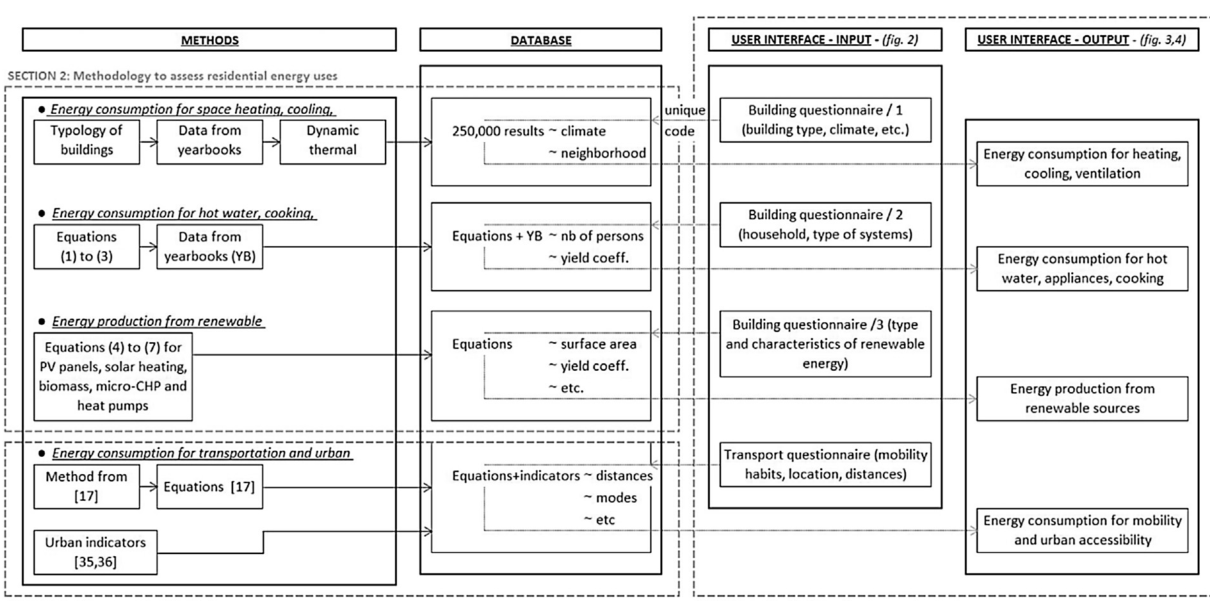

Fig. 1. Articulation between the components of the research (methods – database – user interface).

stakeholders, makes accessible to a large non-specialized audience the results of a three-year scientific research study that combined numerous scientific tools. The main findings and suggestions for further research are finally summarized in Section 5.

Fig. 1 illustrates the articulation between the different components of the research.

2. Methodology to assess residential energy uses

A methodology was developed to assess residential energy uses (energy requirements for space heating, cooling, ventilation, electrical appliances, cooking, and domestic hot water) and the local production of renewable energy, based on a "bottom-up" approach. It allows for precise assessment of energy uses at the individual building scale, but also for the drawing of trends, at the neighbourhood, city, and regional scales, by aggregating individual results. This methodology is based on several components and related assumptions that have already been extensively presented in previous papers (referenced in the following sections). The main elements and assumptions of these components are summarized and referenced below, as they are the basis on which the interactive tool was built. The new insights and assumptions are also presented.

2.1. Energy uses in buildings

This methodology combines several research methods and tools [16–18], including a typological classification of buildings, dynamic thermal simulations, and surveys carried out by the regional institutes in charge of energy yearbooks [19]. The energy consumption levels related to heating, cooling, and ventilation are derived from dynamic thermal simulations. The energy consumption levels related to domestic hot water, electrical appliances, and cooking are based on regional empirical surveys and are linked to the number of inhabitants in each dwelling. This methodology was applied to the Walloon building stock. However, this work is reproducible for other territories. For territories with similar building stocks, building construction techniques, and heating systems (such as France, Luxemburg, and the Netherlands), the climate conditions (degree-days) and mean consumption for hot water, cooking, and appliances can be adapted. For territories with very different types of buildings, construction techniques, and heating/cooling systems, the methods are reproducible but the typology of buildings and neighbourhoods must be redefined. The proposed results define energy consumption in kW h/m^2 year, primary energy consumption in kW h/m^2 year, and CO_2 emissions in kg CO_2/m^2.

2.1.1. Energy consumption for space heating – ESH, cooling – ECO, and ventilation – EV

Based on a typological approach, 60 main types of dwellings were defined to represent the Walloon residential building stock, based on the main characteristics of Walloon dwellings [18,20,21]. The typology comprises houses and apartments. For houses, the characteristics that were taken into account to build the typology are the orientation (B.1, see Table 1), the number of floors (B.2) (one and half, two, three, or four), the common ownership (B.3) (detached, semi-detached, or terraced house), and the orientation (B.4) of the building. For apartments, the characteristics are the plan configuration (B.1) (wide crossing, narrow crossing, three fronts, one front, or corner apartment), the position (B.3) of the apartment in the building (ground floor, intermediate floor, or top floor), and the orientation (B.4) of the building (north, east, south, or west). For all types of dwellings, the ceiling height was deemed 2.4 m; no attachments were modelled with such, but they can be taken into account by including them in the total area of the dwelling. Each of the 60 types was modelled with several different heated areas. As far as the thermal performances of the housing are concerned, two types of wall (C.1) are defined (solid or cavity). The insulation material considered in the method has a thermal conductivity (λ-value) of 0.040 W/m K. The insulation in the slabs and the walls (C.2 and C.3) can vary from 0 to 30 centimetres, and that in the roofs (C.4) can vary from 0 to 35 centimetres. The glazing type (C.5) may be simple (U-value = 5.8 W/m^2 K), double-old (typical from the 1970's and the 1980's, U-value = 2.83 W/m^2 K), double-new (new generation of double-glazing, U-value = 1.05 W/m^2 K), or triple (U-value = 0.6 W/m^2 K). The glazing surface area on each façade is defined according to the housing type, using a typical window-to-wall ratio for each type, as developed in [22] for the Walloon building stock. Three ventilation modes (C.6) are defined: natural ventilation (type A), ventilation with mechanical extraction (type C), and double-flow ventilation with heat recovery (type D). For ventilation of type A, the windows are opened for an internal temperature higher than 25 °C and are closed when this temperature drops down to 23 °C [39–41]. In the case of ventilation of types C and D, airflows are defined according to the Belgian requirements [23]. The heat recovery system efficiency is set at 85%. Three types of set points (C.7) are defined according to Belgian regulations [26] and norms [42]: 18 °C during day and night, 20 °C during day and night, and 20 °C with a reduction to 16 °C in a daily work pattern and during night. These three types of set points are defined to ensure thermal comfort. Because of the number of simulation to proceed and to the numerous energy performance studied (very low to very high energy performance that correspond to very long to very short heating seasons), no annual profile has been defined. A couple of rules of combinations were finally defined to eliminate non-realistic cases (for example, a building with 20 cm of insulation and simple glazing). In all, 250,000 types of buildings were defined.

The TRNSys thermal simulation software was then used to automatically perform an energy consumption analysis of space heating needs (ESH) and electricity needs for ventilation systems (EV) for each of the 250,000 cases in a standard context (the climate of Brussels without any surroundings buildings). Because of the temperate climate in Belgium (mean temperature in July from 1981 to 2010 = 18.4 °C [24]), cooling was not considered in this analysis because cooling needs are very low in Belgium and mainly concern office buildings. In these simulations, internal gains were defined according to Massart and De Herde [25] as 70 W/person for occupation and 6 W/m^2 and 4 W/m^2 for nominal power lighting and appliances, respectively. They are functions of the dwelling's surface and of the number of occupants which are set in the function of the type of housing. Internal gains are also set according to a daily and weekly schedule. In addition to the simulation results, three energy standards defined by the European Energy Performance of Buildings Directive (EPBD) were added in the database: the low-energy standard, the very low-energy standard, and the passive standard, which correspond to annual heating requirements lower than 60 kW h/m^2 year, 30 kW h/m^2 year, and 15 kW h/m^2 year, respectively.

Next, energy consumption for space heating (ESH) and ventilation (EV) were obtained by applying to the simulation results (energy needs), a conversion factor, depending on the efficiency of the heating system (production, distribution, and emission) and the type of fuel used; eight types of heating systems (C.8) and 11 types of fuel (C.9) were taken into account. For each type, the conversion coefficient that was used comes from Belgian regulations [26,27] (see also Appendix A).

Finally, two correction factors were defined and applied to the previous simulation results, to take into account the local climate (adaptation of degree-days in comparison with the Uccle-Brussels climate, A1 in Table 1) and the impact of the neighbourhood in which the building is located (density, shadows, A2 in Table 1). As far as the local climate is concerned, 1347 possibilities were

Table 1
Parameters related to (A) the environment in which the building is located, (B) the characteristics of the building, and (C) the thermal performances of the envelope and the systems which are taken into account to calculate the annual energy consumption for space heating.

A. ENVIRONMENT		B. TYPOLOGY				C. THERMAL PERFORMANCES AND SYSTEMS								
1. Climate	2. Neighbourhood	1. Housing type	2. Number of floor	3. Joint ownership	4. Orientation	1. Wall type	2. Slab insulation [cm]	3. Wall insulation [cm]	4. Roof insulation [cm]	5. Glazing	6. Ventilation	7. Thermostats	8. Heating system	9. Fuel type
Choice amongst 1347 locations	Dense downtown	Wide house	1.5	Detached or semi-detached	North	Solid	0	0	0	Simple, double-old or double-new	A	18 °C or 20 °C or 20 °C(day)–16 °C (night)	Hot water boiler condensing	Natural gas
				Terraced	North or East				16					
	Continuous urban		2	Detached or semi-detached	North		3	3	3				Hot water boiler non condensing	Gazole
				Terraced	North or East				16					
	Semi-continuous urban	Narrow house	1.5	Detached or semi-detached	North		6	6	6				Electric resistance heating	Propane
				Terraced	North or East				16					
	Homogeneous semi-continuous or social district		2	Detached or semi-detached	North		10	10	10	Double-new or triple	C ord D		Heat pump	Butane
				Terraced	North or East				20	Double-old, double-new or triple				
	Village or rural core		3	Semi-detached	North	Cavity	15	15	15	Double-new or triple			Heat pump water	LPG
				Terraced	North or East				30	Double-old, double-new or triple				
	Suburban area		4	Terraced	North or East		20	20	20	Double-new or triple			Micro combined heat and power	Coal
		Wide crossing apartment	1	Top, intermediate, ground	North or East				30	Double-old, double-new or triple				
	Isolated rural	Narrow crossing apartment	1	Top, intermediate, ground	North or East		25	25	25	Double-new or triple			Stove	Wood
		Three fronts apartment	1	Top, intermediate, ground	North				35	Double-old, double-new or triple				
	"Great sets"	One front apartment	1	Top, intermediate, ground	North, East, South, West		30	30	30	Double-new or triple			Radiator or electric heater	Wood (3 variants)
		Comer apartment	1	Top, intermediate, ground	North, East, South, West				35	Double-old, double-new or triple				
2 EPBD requirements (according to Umax)													Electric storage heater	Electricity
3 EPBD thermal standards (low energy – very low energy – passive)														

Table 2
Correction factors defined according to the type of neighbourhood.

Type of neighbourhood	Correction factor for roofs	Correction factor for facades
1. Dense urban core	0.72	0.42
2. Continuous urban neighbourhood	0.82	0.69
3. Semi-continuous urban neighbourhood	0.96	0.78
4. Homogeneous semi-continuous neighbourhood	0.95	0.79
5. Villages and rural core	0.98	0.85
6. Suburban neighbourhood	0.98	0.90
7. Isolated rural area	1.00	1.00
8. Great sets	0.96	0.60

defined, based on the heating degree-days (15/15) provided by the National Meteorology Institute (diffused through [32]) to cover the variation of the climate in every municipality of Wallonia, in comparison with the representative climate of Brussels. A coefficient based on degree-days was attributed to each location and then applied to the thermal simulation results (performed with the representative Brussels' climate). It is worth mentioning that the differences between the different locations remained small, as Belgium is a small country with a temperate climate (Northern Europe).

To account for the impact of the neighbourhood (urban form) in which the building is located, eight main types of residential neighbourhoods were defined based on the typological classification of the Walloon building stock [29]. These eight types are the dense urban core, continuous urban neighbourhood, semi-continuous urban neighbourhood, homogeneous semi-continuous neighbourhood (including social housing), villages and rural cores, suburban neighbourhoods, isolated rural areas, and great sets.

Three representative cases of each neighbourhood category were selected in Walloonia. Simulations were performed on these 24 selected neighbourhoods with Townscope, a software developed via [30] to assess direct, diffused, and reflected solar radiation easily as well as thermal comfort within built environments, based on 3D models. On the facades and roofs of each neighbourhood, 500 points were randomly defined, and an assessment of solar gains was performed in order to define correction factors to apply, according to the density of the neighbourhood and shadowing effects. A solar factor, M, was calculated for each type of neighbourhood to reflect the impact of solar masks and urban form on the solar resource, and this factor was also used to assess the local production of solar energy (see below). These correction factors according to the type of neighbourhood are listed in Table 2.

The correction factors relating to climate and to the type of neighbourhood were finally stored in the database and then applied to the results of the thermal simulations of buildings, in order to take into account, respectively, the local climate and the diminution of solar gains on facades and roofs, according to the built density of the neighbourhood in which the considered building was located.

2.1.2. Energy consumption for electrical appliances (EEA) and energy consumption for cooking (ECK)

EEA (Eq. (1)) and ECK (Eq. (2)) are calculated based on data from regional yearbooks. The Walloon Institute for energy and sustainable development (ICEDD) [19] highlights that each household uses 2.827 kW h annually for electric appliances and 461 kW h per year for cooking. Therefore, the consumption for electrical appliances and cooking are calculated using statistics from the ICEDD but weighted according to the number of people (N) per household and the corresponding yield coefficient (Yea and Yck).

$$EEA = (-40\,N^2 + 550\,N + 1765)\,Yea \quad (1)$$

$$ECK = (200\,N)\,Yck \quad (2)$$

2.1.3. Energy consumption for domestic hot water (EHW)

Annual EHW is obtained (Eq. (3)) by multiplying the volume of water (L) needed annually by all the inhabitants (N), the difference in temperature (ΔT) between the hot and cold water, and the heat capacity of water (C). It is estimated, based on regional averages, that an occupant uses 40 L of hot water and 100 L of cold water per day. The temperatures of the hot and cold water are set respectively at 60 °C and 10 °C. Finally, as for heating, 11 systems producing hot water were used to reflect the performance of the system (Yhw).

$$EHW = N\,L\,\Delta T\,C\,Yhw \quad (3)$$

2.1.4. Storage of the results in the database

The results of the energy assessments (space heating, cooling, ventilation, appliances, cooking, and hot water) were stored in a huge database comprised of seven parts: Part 1 is dedicated to the based degree-days coefficient, Part 2 stores the solar factors depending on the built density of the neighbourhood in which the building is located, Part 3 is dedicated to space heating requirements and electricity needs for the ventilation system, Part 4 relates to the characteristics of the heating systems, Part 5 addresses domestic hot water requirements, Part 6 relates to cooking requirements, and Part 7 is dedicated to electrical appliance requirements.

Part 3 (space heating energy needs and electricity needs for the ventilation system) is comprised of seven columns, as illustrated in Table 3. The first column includes a unique numeric code that allows one to identify the corresponding building and its characteristics directly and easily: each item of the code corresponds to a specific variation of a coefficient and provides the identity card of the tested case.

Columns 2 and 3 are used to store the slope (m_q) and the intercept (p_q), respectively, of the linear extrapolation used to generalize space heating energy needs obtained through thermal simulations to any similar building that presents a different heated surface area. Columns 4 and 5 (m_s and p_s, respectively) store coefficients related to solar gains. The two last columns (m_v and p_v) are used to calculate the electrical needs of the ventilation's fans.

The coefficients that are used to transform energy needs into fuel consumption, primary energy consumption, and CO_2 emissions into an estimation of the annual cost are also stored in the database. Coefficients related to primary energy and CO_2 emissions come from the current thermal regulations [26,27]. A mean energy price is proposed for each type of energy and can be changed by the user in the online tool.

2.2. Local production of renewable energy

2.2.1. Electricity production from photovoltaic panels – EPV

The potential of urban, suburban, and rural buildings for active solar heating and photovoltaic electricity production is obtained via numerical simulations performed with Townscope software [30]. Townscope allows for the attainment of direct, diffuse, and reflecting solar radiation reaching a point and radiation distribution on a surface, under a clear sky, which is not representative of the Belgian climate. A correction factor M (difference between the values calculated for the assessed neighbourhood and the same site without any buildings) is thus calculated and applied to the mean solar radiation (MSR) for the considered latitude (MSR = 1000 kW h/m^2 year for Belgium). A correction factor F is then applied to account for the orientation and inclination of the roofs [31]. Solar energy received by the considered surface (Esol) is obtained using Eq. (4).

$$Esol = MSR\,F\,M \quad (4)$$

The potential of roofs for photovoltaic electricity production (EPV, in kW h per year) is obtained using Eq. (5). In Eq. (5), S represents the surface area of the considered roofs, C the percentage of

Table 3
Example of the database for the space heating and ventilation needs (Part 3).

Code	m_q [kW h/m^2]	p_q [kW h]	m_s [kW h/m^2]	p_s [kW h]	m_v [kW h/m^2]	p_v [kW h]
1_3_2_1_c_l_g_3_2_1	41.9	38.6	8.1	486	2.2	−23.1
1_3_2_1_c_l_g_3_2_2	54.1	142.3	13.9	768.9	2.2	−23.1
1_3_2_1_c_l_g_3_2_3	49.1	105.5	8.1	486	2.2	−23.1
1_3_2_1_c_l_g_3_3_1	24.7	558.9	8.1	486	6.9	−73
1_3_2_1_c_l_g_3_3_2	32.4	792.5	11.3	646.2	6.9	−73
1_3_2_1_c_l_g_3_3_3	30.2	681.6	8.1	486	6.9	−73

the roofs covered by panels (maximum 0.80), Ypv the yield of the photovoltaic panels, Yinv the yield of the inverter, and λ a correction factor taking into account electricity losses. In the online tool, the yield of the photovoltaic panels is fixed at 0.145, the yield of the inverter at 0.96, and electricity losses at 0.2.

$$EPV = Esol\,S\,C\,Ypv\,Yinv\,(1\text{-}\lambda) \quad (5)$$

2.2.2. Solar heating – ETH

The potential of roofs for heating hot water through thermal panels cannot be assessed through the equation used for photovoltaic electricity because the systems are quite different. Solar energy received annually by the roof is determined via Eq. (4). Eq. (6) allows for the determination if the roofs of the houses of the neighbourhoods are adapted to the production of hot water. In Eq. (6), Esol represents the solar energy received by the roofs, S the surface area of the panel, and Yth the yield of the thermal panels. It is assumed that 55% of the production of hot water of each household must be covered through thermal panels (from a technical-economic point of view, the optimum is often considered to lie between 50% and 60%). Under this condition, the yield of the system is 0.35.

$$ETH = Esol\,S\,Yth \quad (6)$$

2.2.3. Biomass – EBIO

The use of biomass as a renewable energy source is taken into account by choosing a heating system using biomass as fuel (see Appendix A). In this case, the space heating energy consumption is not equal to zero but CO_2 emissions are. In fact, in accordance with EU legislation [32], biomass is considered carbon neutral, based on the assumption that the carbon released when solid biomass is burned will be reabsorbed during vegetative growth.

2.2.4. Micro-cogeneration – ECHP

A micro-CHP is a heating system able to produce thermal and electrical energy. Therefore, following a space heating demand DSH, an amount of electricity is produced and can be considered renewable energy. This production of electricity ECHP can be calculated using Eq. (7), where Ysyst is the yield of heat distribution and emission systems, λ is the portion of space heating that needs to be converted by the micro-CHP, Ychpé is the electrical yield of the micro-CHP, and Ychpth is the thermal yield of the micro-CHP.

$$ECHP = (DSH/Ysyst)\,\lambda\,(Ychpé/Ychpth) \quad (7)$$

2.2.5. Heat pump – EHP

Heat pumps allow for the use of renewable energy in our environment. The use of this energy is recognized through high efficiency heating systems, and the consumption of electricity is the energy consumption for space heating ESH calculated using a specific system yield for heat pumps (see Appendix A).

2.2.6. Wind turbines – EWT

As numerous political uncertainties still exist, regarding wind turbines in Walloon, the electricity production of wind turbines EWT is not considered in the online tool.

3. Other sustainability indicators related to residential energy uses

Energy consumption in buildings is a major contributor to the (un)sustainability of our built environment. However, previous studies have also highlighted the huge impact of other parameters related to urban form, location, and transportation habits of inhabitants [33,34]. To include these challenges in the energy balance provided in the SOLEN tool, results related to building energy uses can be compared to other sustainability indicators. Amongst the indicators developed during the research and provided in the SOLEN tool, the following are highlighted in particular.

3.1. Transportation energy uses

Based on a quantitative methodology previously developed by the authors and extensively presented in [17], transportation energy uses for daily mobility of inhabitants can be assessed and compared to building energy uses and production of renewable energy (in kW h, Fig. 3). The previously developed method was improved to allow for the accounting of chained trips and to precisely represent the mobility of the users. Mode of transportation, travelled distance, type of vehicle, consumption of the vehicles, number of people, etc. can be defined by the user of the tool, to adapt to each particular situation.

3.2. Urban accessibility

To complete the quantitative approach presented in Section 3.1, other indicators related to accessibility and potentialities of the urban context in which the building is located were developed. These indicators were all validated by the regional authorities in charge of urban planning policies, in the framework of a regional handbook for sustainable neighbourhoods [35,36]. All the threshold values presented below are those developed and validated in this handbook [35,36]:

- Train services: this criterion takes into account the distance from the neighbourhood to the train station and the type of station (regional or local). The distance to a regional train station must be less than 1500 m or the distance to a local train station must be less than 1000 m.
- Bus services: this criterion takes into account the number of buses per day in the area surrounding the neighbourhood (the assessment takes place in an area of 700 m around the boundaries of the neighbourhood). Target values are adapted according to the location of the neighbourhood: minimum 34 buses per day in urban cores and city centres and minimum 20 in villages and rural cores.
- Diversity of functions: the neighbourhood must be located in a mixed-use environment to favour active commuting and reduce travelled distance. The target values are at least 15 different functions (alimentary shops, bakeries, post offices, etc.) in an area of 700 m around the boundaries of the neighbourhood in urban cores and city centres and at least 5 in villages and rural cores. Moreover, at least, three different categories of functions must

Table 4
Summary of the input data needed in the simplified assessment and in the detailed assessment.

	Simplified assessment	Detailed assessment
Urban form	Type of neighbourhood (8 possibilities, from city centre to rural settlement)	Type of neighbourhood (8 possibilities, from city centre to rural settlement)
Location and household composition	Name of the district/municipality (1348 choices) Number of adults/children in the household	Name of the district/municipality (1348 choices) Number of adults/children in the household
Transportation	Number of km travelled each year by car/bus/train/bike/on foot	For each transportation trip: – origin and intermediary and final destinations – mode(s) of transportation – characteristics of the mode(s) of transportation (e.g. for private car: type of fuel, consumption of the car, number of people in the car, etc.) – travelled distances – number of trips per week and per year
Type of dwelling	Type of house/apartment Surface area Year of construction	Type of house apartment Orientation of the main facade Surface area Year of construction
Constructive details	(Provided by the tool, based on the year of construction)	Type of insulation in the slab/walls/roofs Type of windows Type of ventilation system Heating set-point
Heating system	Type of boiler Type of fuel	Type of boiler Type of fuel
Hot water/electricity	(Mean value provided by the tool)	Type of boiler Type of fuel Type of electricity network
Renewable energy	PV and thermal panels: surface area, slope, and orientation	PV and thermal panels: surface area, slope, and orientation Biomass Micro-cogeneration Heat pump
Costs	(Provided by the tool)	Annual cost for transportation, by mode Annual cost (from invoices) for heating and electricity

be represented (amongst supermarkets, shops, leisure, services, and public services).

- Proximity of school facilities: there is a least one school in the surroundings of the neighbourhood.

These indicators can be assessed one by one but also combined into an integrated indicator of sustainability (from a very low accessibility to a very high accessibility). This combined indicator allows for comparison of the potential for different residential locations, taking into account the activities going on in the considered locations.

4. SOLEN online interactive tool

4.1. Presentation of the SOLEN tool

The SOLEN online interactive tool was developed, based on an initial online tool (that was dedicated to only suburban buildings and neighbourhoods [16]). This tool, available free at www.solen-energie.be, makes accessible to a large non-specialized audience, the numerous results of a three-year study dedicated to energy uses in buildings and neighbourhoods. The website comprises three different assessment tools, each with different objectives. The simplified assessment is very easy and quick to use and is dedicated to a user/household without any specific knowledge of energy consumption and buildings. The detailed assessment allows for a precise assessment of energy uses in a building, but the questionnaire takes longer to complete and requires specific information (such as the centimetres of insulation in the wall, the types of windows, etc.). Table 4 summarizes the input data needed for these two types of assessments, focusing on household energy consumption.

Last but not least, the neighbourhood assessment is dedicated to local authorities, architects, and private developers and allows for assessment of an entire (existing or planned) neighbourhood, taking into account both building and transportation energy uses. The methodologies and indicators presented in this paper are related to the assessment of individual buildings. They have been adapted during the research to allow for the development of the "neighbourhood assessment tool", but these adaptations are not presented here, because of the length limit for this paper. For more information on the neighbourhood assessment tool, the interested reader can refer to [43].

To ensure a wide diffusion of the SOLEN online portal, the questionnaires used in the evaluation tools are simple, intuitive, and easy to complete, as illustrated in Fig. 2. The results are also expressed in a very simple form, as seen in Fig. 3, for energy uses in the considered dwelling, and in Fig. 4, for the annual energy balance (dwelling + transportation + renewable energy) of a household.

Several strategies to improve the energy efficiency of the tested building are then provided to the user (such as insulation of the roof, change of the glazing, insulation of the building's envelope, behavioural changes, etc.). They are personalized according to the characteristics of each dwelling. Quantification (in kW h/year, in%, and in €) of the potential energy savings linked to each strategy is also provided based on the results stored in the database and the unique code used to store the results (Table 1).

4.2. Validation and accuracy of the results

All the software used in the development of the database and the SOLEN tool were validated. TRNSys thermal simulation software is a whole building energy simulation program that was deemed as a BESTEST reference standard [37] and the methods develop by the research team have been extensively presented and validated in previous papers [10,16–18,29,33–36]. Individual results obtained through the methodologies presented in this paper have been compared with data from regional year books and surveys to ensure their accuracy [19]. The total energy consumption of the Walloon building stock was calculated via the methodology presented in this

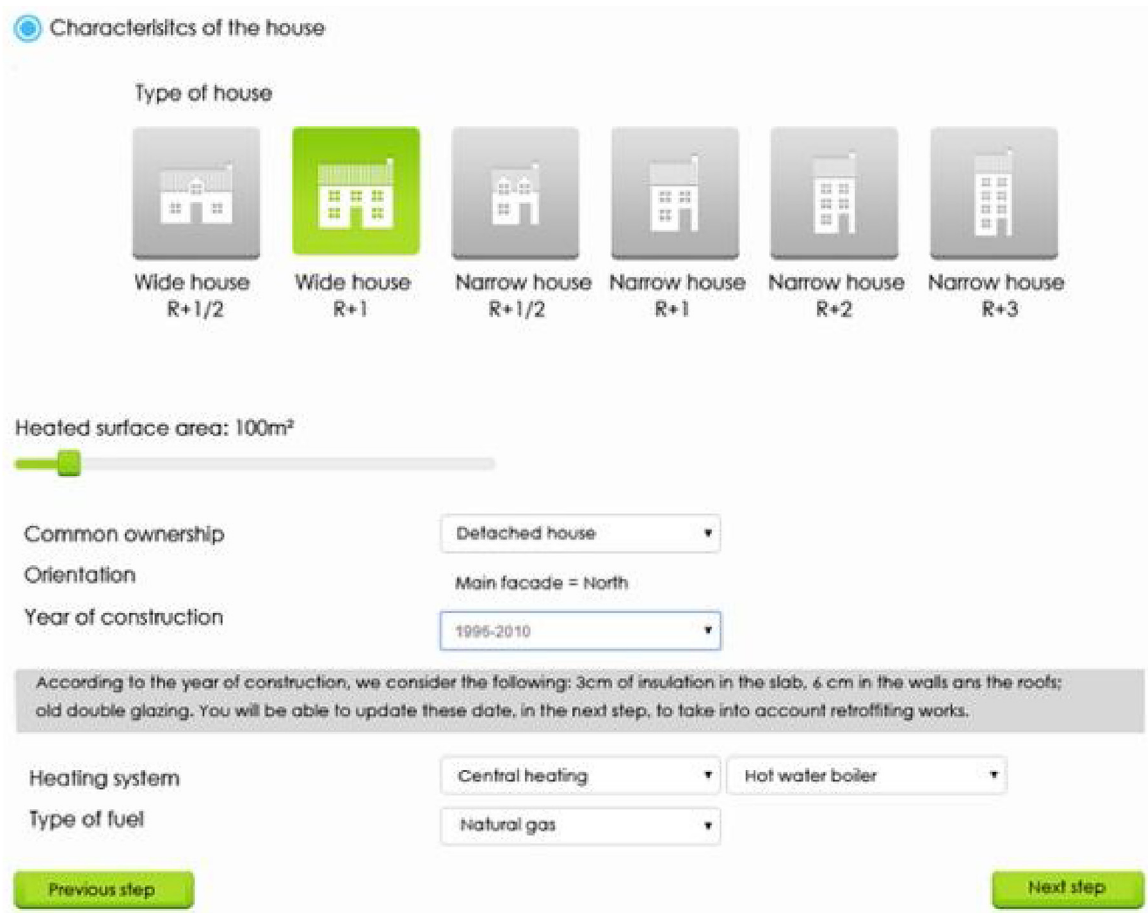

Fig. 2. Example of user's input interface provided in the SOLEN online portal (here, to define the main characteristics of the dwelling).

Fig. 3. Example of results provided in the SOLEN online portal (energy consumption in the dwelling, per type of consumption). The energy consumption of the household is also compared with a reference case corresponding to current thermal regulations.

paper and the result was compared with a regional yearbook (data collected by ICEDD [19]).The difference between the calculated and the real value was only 8.2%, which was considered acceptable.

Several retrofitting scenarios of the building stock were finally tested and quantified during the research. They provide information regarding the development of specific policies adapted to the particular characteristics of main types of buildings and of the environment in which they are located. These results also show the importance of the retrofitting of the private building stock and the relevance of taking into account, in an integrated approach, building energy uses and transportation energy uses including urban characteristics.

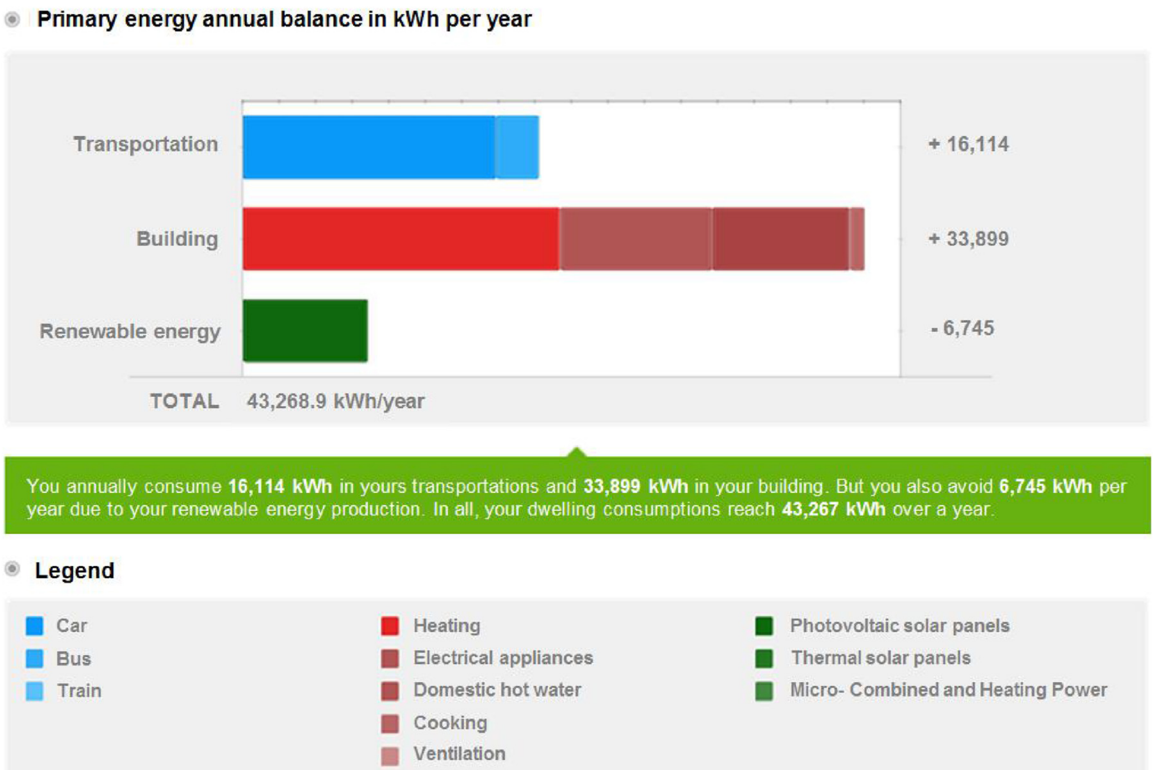

Fig. 4. Example of results provided in the online tool: comparison, in primary energy, of the annual energy consumption of a household for transportation (per mode of transport); energy consumption in the dwelling (for heating, appliances, domestic hot water, cooking, and ventilation); and the production of renewable energy of this household (here, PV panels, thermal panels, and micro-combined and heating power are considered).

4.3. "Usability" testing

The final version of the SOLEN tool has been online since of the end of 2014 at www.solen-energie.be (only in French). Real users (80 individuals) tested the final version of the online tool. Two initial test sessions were organized with the help of the regional authority in charge of energy. They gathered 58 professional users deeply involved in the fields of sustainable architecture and energy efficiency in their daily work. These users came from the regional departments of energy and urban planning (24), local administrations (19), architecture or engineering agencies (11), and private developer groups (4) currently developing or interested in energy efficiency in retrofitting projects. Then, two more test sessions were organized with students in architectural engineering (15) and researchers in energy efficiency (7). After a presentation of the research by the research team and a test session of the entire SOLEN tool including the three types of evaluation and the specification sheets, participants were asked to answer a questionnaire individually and after having tested the tool alone by applying it to their own projects. Feedback from these initial users was quite positive, with 93.1% of the respondents classifying the SOLEN tool "from useful to very useful", in the framework of their professional or personal practice. The assessment tool that received the most votes was the detailed evaluation one (62.1%).

The most positive aspects highlighted by the testers were (1) the possibility to easily, quickly, and accurately assess energy consumption in buildings (the fact that the tool is based upon scientific research was highly appreciated by the respondents), in particular in order to define the most efficient retrofitting to do (changing the glazing? Insulating the roof? With how many centimetres?) and (2) the possibility to compare building energy uses and transportation energy uses (as numerous testers did not realize the environmental impacts and the cost of their mobility behaviours). A large majority of respondents (93.1%) considered the tool very easy to use; the web interface friendly; and the results numerous, well presented, and directly relevant to them.

As far as concrete actions are concerned, 84.6% of the respondents declared that the use of the tool is "from susceptible to very susceptible" to led them to concretely invest in retrofitting to reduce the energy consumption of their dwelling; whereas 72% of the respondents declared that the use of the tool is "from susceptible to highly susceptible" to encourage behavioural changes in their household to those that are more energy efficient. Behavioural changes related to buildings (reducing the temperature, etc.) were more appreciated than behavioural changes related to mobility and transportation (modal changes, etc.). Changing mobility behaviours is more difficult, namely because of housing location (far from city centres, with no alternatives to cars).

In addition to the development of the SOLEN online tool, numerous actions have been—and will be—undertaken by the research team to promote this initiative and to extensively raise awareness on the importance of improving energy efficiency in buildings, starting from the individual scale. These actions are dedicated to a wide range of actors: students in architecture and urban planning, researchers, local and regional stakeholders, private developers, architects, and, of course, citizens.

5. Conclusion

This paper presented a methodology that enables one to precisely assess energy needs and energy consumption for space heating, cooling, ventilation, lighting, appliances, and cooking within individual dwellings based on a "bottom-up" approach. This methodology was based on a typological classification of buildings, thermal simulations, and local yearbooks, to cover a wide range of buildings and parameters. The impacts of the climate and of the location in which a dwelling is located have been taken into account via the application of correction factors based on the built density of the neighbourhood. This methodology was applied to the Walloon residential building stock to build a huge database that included more than 250,000 individual results. This established database was mobilized to build the SOLEN online interactive portal that aims to raise public awareness of energy efficiency in buildings. Thus, citizens are able to assess the sources of energy consumption for buildings easily. They may also compare these different energy consumption sources in order to determine relevant and personalized recommendations with which to reduce their energy consumption. This interactive online portal represents the main result of an important three-year scientific research project dedicated to energy efficiency in Walloon that is accessible to a large non-specialized audience, which is crucial in the scope of sustainable development. The tool, available since 2014, was tested by real users and the feedback was quite positive. The SOLEN tool has been awarded the “2014 National energy globe award – Belgium” to applaud its efforts towards more sustainability in the built environment, starting at the individual scale [38].

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Appendix A. Heating system yield coefficient used to get the energy consumption for space heating [26,27]

Combustion heating system	Natural gas	Gazole	Propane Butane LPG	Coal	Wood
Hot water condensing boiler	0.78	0.82	0.80	0.84	0.81
Hot water non condensing boiler	0.70	0.74	0.72	0.75	0.73
Domestic micro combined heat and power	0.75	0.77	–	–	0.77
Collective micro combined heat and power	0.61	0.63	–	–	0.62
Stove	0.65	0.65	0.65	0.61	0.59

Electrical heating system	
Resistance heating	0.87
Storage heating with external sensor	0.92
Storage heating without external sensor	0.85
Radiator/convector with electronic regulation	0.96
Radiator/convector without electronic regulation	0.90
Air heat pump	2.18
Hot water heat pump with surface heating	1.78
Hot water heat pump with radiator/convector	1.07

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