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Towards guidance values for the environmental performance of buildings: application to the statistical analysis of 40 low-energy single family houses' LCA in France

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Abstract

Purpose In this study, life cycle assessment (LCA) is applied to a sample of 40 low-energy individual houses for the French context in order to identify guidance values for different environmental priorities (energy and water consumption, greenhouse gases emissions, waste generation etc.).

Methods Calculation rules for the LCA derived from EeBGuide guidance and HQE Performance specific rules for the French context. Data are based on Environmental Product Declaration (EPD for the impacts related to products and technical equipment while generic data are used for energy and water processes. The LCA is defined for the entire life cycle of a building from cradle-to-grave according to NF EN 15978 standard. It includes the products and equipment implemented in the building, the different uses of energy for heating, domestic hot water, lighting, ventilation and auxiliaries, and the different uses of water consumption.

Results and discussion Results for the 40 houses showed that the average life cycle non-renewable primary energy consumption is about 37 kWh/(m^2*year) while the life cycle greenhouse gases emissions are of 8.4 kg CO_2-eq/(m^2*year). The embodied impacts represent between 40% and 72% for the following indicators: acidification, global warming, non-renewable primary energy, and radioactive waste. The net fresh water use is mostly determined by the direct use of the water in use, and the non-hazardous waste indicator is only linked to the materials and equipment. When integrating the variability of the different houses design, energy performance, climate requirements, it was found that those values can vary of an order of two between the 10 and 90% percentiles' values. It was found that the results are also sensitive to the enlargement of the system boundaries (e.g. inclusion of the other uses of energy such as building appliances) and the modification of the reference study period.

Conclusions and recommendations This study provided a first set of LCA guidance values describing a range of environmental impacts for new low-energy individual houses in France. Results were also reported for different design parameters, system boundaries and reference study period. The outcomes of this study can now serve as a basis to guide and support new LCA-based labelling systems developed by public authorities and labelling schemes (e.g. the HQE Association).

Keywords Buildings · Embodied energy · Embodied carbon · EPD · Impact assessment · LCA · Operational energy and water uses · Statistical analysis

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1 Introduction

Since the 1970s, following the oil crisis, several efforts have been made on the improvement of the energy performance of buildings by first looking at the heating demand (e.g. increase of the insulation thickness, reduction of heat losses etc.). Different requirements were defined leading in the years

2000s to more stringent energy performance requirements, e.g. through the Energy Performance of Buildings Directive (OJEU 2010) in Europe and in France through the thermal regulation RT 2012, e.g. a new building should now consume less than 50 kWh/m2/year for the heating, cooling, lighting and ventilation aspects (JORF 2013). While improving the energy performance of buildings, previous studies have shown that the proportions between the energy consumed during the use phase and the energy needed to produce the products integrated in buildings (also called 'embodied energy') has changed (Blengini and Di Carlo 2008). The relative importance of the embodied energy becomes more important as far as buildings are more insulated and include more and more energy systems. In that context, there is a need to use a life cycle perspective in order to have a complete view of the energy improvement potentials. However, assessing only the performance of buildings from an energy point of view is a very limited scope. Indeed, buildings generate millions of tons of waste; they are responsible of several environmental impacts such as the climate change (to ~25% in Europe), and the release of air, water and soil emissions leading to toxic and ecotoxic impacts. In that context, the use of the life cycle assessment (LCA) is a relevant methodology to assess from a multi criteria approach a building. This methodology is defined in ISO 14040-44 series of standards (ISO, 2006). It has been applied in the building sector by researchers and practitioners for many years to identify the hotspots of the environmental impacts of building components or buildings as a whole (Adalberth 1997a; Adalberth 1997b; Peuportier 2001; Scheuer et al. 2003; Kohler et al. 2005; Asif et al. 2007; Bribian et al. 2009; Brunklaus et al. 2010; Malmqvist et al. 2011).

In this study, a sample of 40 LCAs based on the same calculation rules,conducted on low-energy buildings is analysed in order to identify guidance values for different environmental aspects (energy, water, greenhouse gases emissions, waste etc.). It comes after previous LCA studies also conducted on large buildings' sample size. For instance, the IMPRO project (JRC 2008) studied different building types for several climate requirements in Europe. They proposed averages values of impacts for a same building type according to the country and the climate in order to progress towards reference values for the European context. More recently, Passer et al. (2012) analysed the environmental performance of 5 low-energy buildings in Austria. The authors found that the embodied impacts related to the technical equipment are not negligible in low-energy buildings while providing the average impacts of 5 different building constructive systems.

To help harmonizing the LCA studies in Europe, the CEN TC 350 'Sustainability of Construction Works' published two standards for product and building LCA namely the EN 15804 (2012) and EN 15978 (2011). These standards proposed harmonised rules for the calculation of the environmental performance of products and buildings. In the same time, sector-specific databases are being developed in the form of Environmental Product Declaration (EPD), operational guidance are being developed, and finally user-friendly LCA tools and certification schemes for buildings (e.g. BREEAM, DGNB, HQE, LEED, VERDE) are provided to the building stakeholders in every national context (EeBGuide 2013).

By doing so, the interest and the use of LCA is quickly growing among the building stakeholders. The challenge is now to be able to first identify hotspots and environmental improvement actions. Then, it is also needed to provide reference impact values to compare, from a LCA point of view, a building project (new or refurbishment) with the current average, good or best practice.

Different approaches can be used to derive reference values. Previous studies established LCA reference values based on a top-down approach (König and De Cristofaro 2011; Wittstock et al. 2011). They focused on the definition of building's models assumed to be representative of a building stock. In this paper, we present the results of a bottom up approach based on a statistical analysis of 40 LCAs of new low-energy individual houses.

2 Materials and methods

The LCAs and statistical analysis of these 40 individual houses were conducted according to available guidance for building LCA including the new European standard EN 15978 'Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method', the EeBGuide InfoHub guidance for building LCA (EeBGuide 2013; Lasvaux et al. 2014) and specific guidance documents developed within the HQE Performance pilot test conducted in France from 2010 to 2013 (HQE 2012).

2.1 Scope and boundaries of the assessment

The baseline system boundaries include all upstream and downstream processes needed to provide and maintain the functions of the buildings. According to the conventional life cycle stages of a building defined in EN 15978 (2011), we take into account:

- Module A (product and construction stage);
- Module B (use);
- Module C (end of life).

The production and construction phase includes the upstream processes, e.g. raw material extraction and the related transports, the manufacture of the building products and technical equipment at the production plant, and their transport to the building site and the on-site implementation. The use phase includes the maintenance and the replacement of building products and equipment, and the energy and water consumptions. The end-of-life phase includes the transport of building products to their final disposal and the impact of the disposal.

According to EeBGuide (2013) and SBA (2010) guidance, the building environmental impacts are also divided in three contributors: the building products and equipment impacts from cradle to grave (modules A1-A3, A4-A5, B2, B4, C2-C4 in EN 15978), the regulated operational energy use (module B6 in EN 15978), and the operational water use impacts (module B7 in EN 15978).

The baseline system boundary was chosen according to the on-going pilot project at the time of the study (2012) from the French Ministry for Environment and Housing and the HQE Association. As new LCA-based labels first and regulations afterwards (from the Ministry and from the HQE Association) are planned to be developed for new buildings by 2020, these two public bodies were interested to know the average life-cycle related impacts of new buildings. The focus was put on three different impact sources of a building: the embodied life cycle-related impacts of technical systems and building products, the operational regulated uses according to the French RT 2012 regulation, and the operational water use. During the project, other impact sources were assessed, e.g. the construction site or the other uses of the energy consumption, e.g. building related uses (e.g. appliances), non-building related uses (e.g. lifts). These assessments will be detailed in Section 4 of this paper (in sensitivity analyses).

Figure 1 presents the system boundaries with the life cycle stages, the EN 15978 modules and the three contributors.

2.2 Calculation rules for the LCA

The calculation rules derived from operational guidance for building LCA available in the European EeBGuide InfoHub (EeBGuide 2013). Specific rules were then defined in the framework of the French HQE Performance pilot test (HQE 2012).

As shown by previous studies e.g., Peuportier et al. (2013), the three contributors 'building products and technical equipment', 'operational energy consumption', and 'operational water consumption' are physically linked, i.e. the quantity of the products integrated in the buildings (e.g. the thickness of the insulation products) influences the energy consumption while the efficiency of energy systems also determined the operational water consumption. This is one of the particularities of the LCAs of buildings. In this study, even if the calculations of each contributor were done separately, they used the same assumptions for consistency purposes, i.e. the energy consumption results corresponds to the bill of quantities that were used to calculate the building products and equipment impacts.

2.2.1 Calculation rules for building products and technical equipment

Table 1 presents the classification of the building products and technical equipment used in this study. Three categories are defined: the building structure and external works (gathering 3 sub-classes), the finishing and interior elements (gathering 4 sub-classes), and the technical equipment (gathering 7 sub-classes). The detailed classification of products and equipment within each sub-class is available in the Electronic Supplementary Material (ESM) 'Online Resource 1: Detailed hypotheses for the LCA calculations'. Then, for each building element, a LCI data is associated using harmonized calculation rules described below.

The calculation rules for building products are based on the INIES EPD program developed in France since 2004 (AFNOR 2004). The cradle-to-gate data describe the environmental impacts of a product or a technical equipment sold in the French market. The data represent either a group of manufacturers' EPD or a single manfacturer's EPD. The other life cycle stages (see Fig. 2) are calculated using scenarios as defined in the Product Category Rules (PCR) (which is the NF P01-010 standard in France recently replaced by the NF EN 15804+A1:2012 and NF EN 15804/CN standards). For the transport and on-site implementation, an average transport distance is accounted for as well as the type of transport (e.g. lorry, boat, rail) and a loss rate is take into account for the implementation of the product in the building.

The reference service lives (RSL) and the corresponding replacement rates for each building product and technical equipment are based on manufacturer's declaration according to the PCR (AFNOR 2004).

For the end-of-life (EOL), a default approach is proposed in the NF P01-010 standard considering a landfilling of the building products and equipment unless the manufacturer can justify that his product is currently not landfilled (i.e., if it is partially or totally recycled or incinerated with heat recovery). In that case, the EOL is context-specific. The recycling and incineration modelling follow the stock flow approach defined in NF P01-010 (2004) and EN 15804 (2012). The impacts related to the incineration or recycling process are allocated to the second product, without substitution credits.

The detailed calculation rules for the production, transport, on-site implementation, use and end of life scenarios can be found in NF P01-010 (2004). Similar modelling rules are followed for EPDs of technical equipment (PEP Ecopasseport 2013).

2.2.2 Calculation rules for the operational energy consumption

The HQE Performance rules precisely defined the calculation rules of the regulated operational energy uses corresponding to module B6 of EN 15978 (2011). According to Fig. 1, the following uses are taken into account: heating, cooling, domestic hot water (DHW), ventilation, lighting, and auxiliaries. First, the building's energy consumption is calculated according to the French thermal regulation (JORF 2013). The final energy values (outcomes of the energy calculations) are then associated to a LCA data describing the

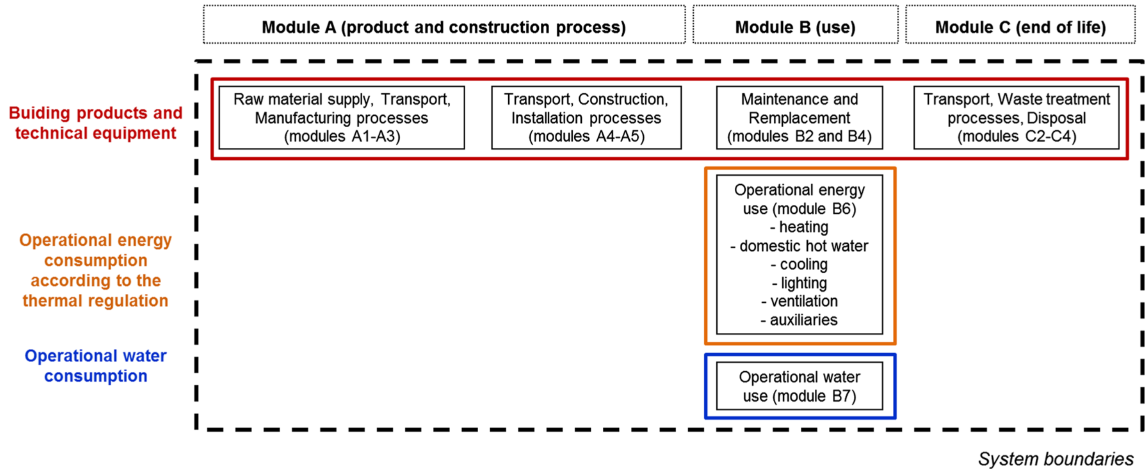

Fig. 1 System boundaries for the LCA of each building with the representation of the life cycle stages and modules according to EN 15978 and the contributors according to SBA and EeBGuide guidance

impacts of the provision of 1 MJ of natural gas, electricity (average mix), fuel, or biomass energy. The background infrastructures of these energy processes were taken into account in the LCA. The foreground infrastructures localized on the building site (i.e. the equipment such as the boiler, the PV panel, the heat pump) were separated from the energy carrier and included in the embodied life cycle related impacts of building technical equipment. The production of on-site energy from PV panels, solar hot water panels, air-to-air and geothermal heat pumps was considered as a renewable source and thus no upstream impacts was allocated to these energy carriers (i.e. 1 MJ of final energy =1 MJ of renewable primary energy for the LCA). For the on-site electricity produced by PV panels, 100% of the impact related to the production, transport, implementation, and end of life of the panels was allocated to the building assuming all the produced renewable energy is self-consumed. This rule is on line with NF EN 15978 standard (2011). In case of an overproduction of on-site electricity according to the building total electricity consumption, no avoided burdens were taken into account. This amount of electricity was not integrated in the results of this experiment.

2.2.3 Calculation rules for the operational water consumption

The calculation rules of the operation water consumption of module B7 of EN 15978 follow the HQE Performance rules (HQE 2012; Schiopu et al. 2012). The calculation of water consumption is achieved by using conventional data of water consumption for the following uses:

- Domestic hot water;
- Non drinkable (unsanitary) water.

If the equipment or facilities are installed in the building with, e.g. water saving devices, a specific scenario of reduction was used to adjust the conventional consumption. The sources of water can be the potable water system, the water collected on-site (surface water, groundwater, etc.), and the

Table 1 Characteristics of the 40 individual houses (constructive system; net floor area, climate zone, and primary energy performance coefficient according to the French thermal regulation RT2012)

Building structure and external works	Finishing and interior elements	Technical equipment
1. External works	4. Roof elements	8. HVAC
2. Foundations -infrastructure	5. Interior walls	9. Sanitary facilities
3. Structural elements (walls, slabs)	6. Windows and joinery work	10. Electricity and communication network
	7. Interior finishes	11. Safety equipments
		12. Lighting
		13. Lifts
		14. On-site electricity generating units

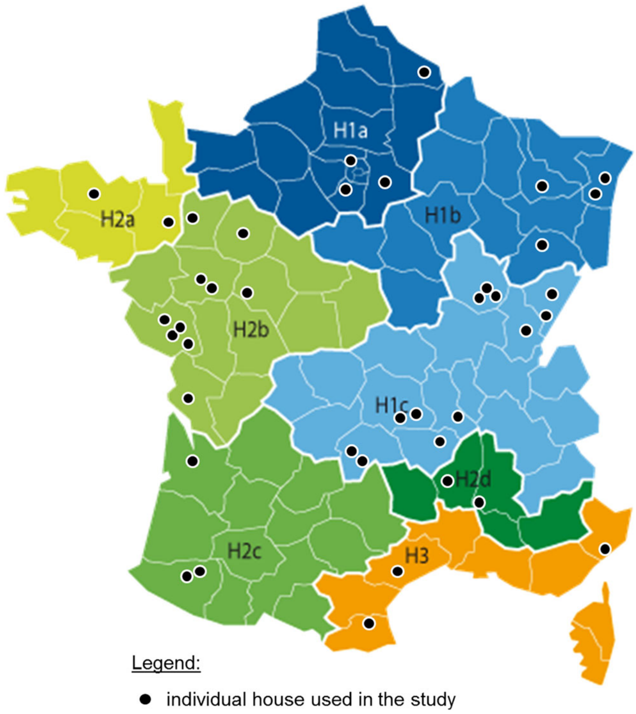

Fig. 2 Map of France with the different climate zones (H1a, H1b, H1c, H2a, H2b, H2c, H2d, and H3) and the location of the single family houses

recovered water (rainwater, recycled water, etc.). Such equipment or facilities are in this case considered to be part of the building. The following water consumption uses were considered as compulsory in these LCAs:

– Toilets and sinks;
– Watering of green spaces;
– Sinks, showers, baths.

Optional uses were those related to the appliances (e.g. washing machine and dishwater). If recovery rainwater or grey water equipment exists, they were taken into account in the calculation. The avoided consumption of drinking tap water could not exceed regulatory purposes of rainwater and grey water.

2.2.4 Functional equivalent and reference study period

The functional equivalent is a representation of the required and quantified functional and technical requirements for a building or an assembled system (part of works), which is used as a basis for comparison. In this study, all the 40 individual houses comply with the French thermal regulation leading to identical thermal comfort requirements, i.e. with a temperature range between 19 and 27 °C. The environmental impacts of these houses are calculated for a reference study period (RSP) of 50 years (baseline scenario).

2.3 Life cycle inventory

This step is described to be consistent with ISO 14040-44 but also to improve the reporting of assumptions of building LCA studies (Optis and Wild 2010).

However, the building stakeholders that conducted the LCA of the single family houses only used a building LCA tool (see section 2.5) with aggregated environmental indicators derived from these LCIs without the LCI information. This section is only intended for improving the interpretation of the results presented in this article.

For each house, different LCI data describing the resources consumption and resulting air, water and soil emissions of building product, technical equipment, energy carriers, tap water, and waste water treatment were used. These LCI data were associated with the building related data such as the quantity of building products and equipment derived from the bill of quantities, the final energy consumption for the regulated end-uses (heating, domestic hot water, ventilation, lighting, and auxiliaries) and the volume of the water consumption for the use phase.

2.3.1 LCI for the building products and technical equipment data

Each building product and technical equipment was described using a detailed documentation recorded in each building project's report. We used LCA data for building products and technical equipment as much as possible representative of the French market. Table 2 presents the types of LCI data used. By doing so, building products were modelled using EPDs. They are provided by building manufacturers and stored in the national EPD database of building products (INIES 2013). These EPDs are cradle-to-grave data modelled

Table 2 Classification of construction products and technical equipment according to the HQE Performance operational rules

Building products and technical equipment	LCI data	Source
Building products	Cradle-to-grave LCI specific to a manufacturer or a group of manufacturers	INIES EPD database (www.inies.fr)
Technical equipment	Cradle-to-grave LCI specific to a manufacturer or a group of manufacturers	PEP EPD database (www.pep-ecopassport.org)
Other building products and technical equipment	Cradle-to-grave LCI based on ecoinvent cradle-to-gate data if EPDs were missing.	ecoinvent v2

using production data of the manufacturers and scenarios for the transport, on-site implementation, maintenance, replacement, and end of life phases (cf. calculation rules in 2.2.1).

EPDs of technical equipment were taken into account, if available, using data available in the French EPD program PEP Ecopasseport (2013). The impacts related to the use phase were removed in order to avoid a double counting between the EPD of equipment and the energy consumption reported in the module B6.

Some generic LCA data were used as proxy when EPDs were missing for a building product or for technical equipment. These data were taken from the ecoinvent database version 2.01 (Frischknecht et al. 2007a). In that case, the electricity mix of the production phase was adapted for the French context. Calculations for the transport, construction, use and end of life phases were conducted based on the PCR for building products (NF P01–010 standard) and based on the statistical ratio of impacts of cradle-to-grave EPDs (Lasvaux 2010).

The assumptions for the reference service lives (RSL) are based on manufacturer's declaration and can be retrieved in the EPD database (INIES 2013). All structural elements are not replaced during the study period of the buildings.

2.3.2 LCI for the operational energy consumption data

According to the LCA calculation rules, the final energy data for heating, DHW, lighting, ventilation, and auxiliaries were combined with LCI data describing the final energy consumption of the corresponding energy carriers (electricity from the grid, natural gas, pellets, on-site renewable energy production). The Electronic Supplementary Material (ESM) 'Online Resource 1: Detailed hypotheses for the LCA calculations' presents the energy carrier of each building of the sample for the heating, domestic hot water, cooling, lighting and auxiliaries. Table 3 presents the assumptions related to the LCI data for the energy carried found in the 40 single family houses. This study was conducted during an update of the LCA database of the building LCA software used for this study (ELODIE). Originally, LCA data for energy carriers were taken from the DEAM database and were replaced by ecoinvent data. It is important to highlight that whatever the data used (DEAM or ecoinvent), the technical equipment (e.g., the boiler) was always excluded from the energy carrier LCA data. Their impacts were recalculated and accounted for separately in the building products and technical equipment contributor.

2.3.3 LCI for the operational water consumption data

According to the LCA calculation rules (see Section 2.2.3), the water consumption data for domestic hot water, unsanitary water, toilets and sinks, watering of green spaces, showers, and baths were combined with LCI data describing the upstream process (tap water) and downstream processes (waste water treatment). A leakage factor of 5% was considered for the upstream impacts (delivery of tap water through an urban drinking water network).

Two LCI data were considered for the waste water treatment: one collective waste treatment based on the ecoinvent study from Doka (2007)) and a specific study for non-collective waste treatment based on a French study (Schiopu et Chevalier, 2012). The Electronic Supplementary Material provides the LCI information for each building i.e. the number of users, the direct water consumption and the water treatment process used while Table 4 presents the sources for the LCI data used to derive the impacts of upstream and downstream processes.

2.4 Life cycle impact assessment

In this paper, the analysis was limited to indicators describing environmental priorities that are on-line with public policies. Following the French 'Grenelle de l'Environnement' in 2010, four main aspects were defined in the legislation (JORF 2010): greenhouse gases emissions, energy consumption, water consumption, and waste generation. In addition, two more aspects corresponding to the effects of the acidifying substances and ionizing substances were also taken into account in this study.

Table 5 presents the names and units of the indicators used to assess these aspects. The life cycle impact assessment (LCIA) methods are based on the methods defined in the NF P01-010 and EN 15978 (standards for European and French EPDs) based upon Guinée et al. (2002) for the two mid-point indicators GWP and AP (CML 2001). In addition, reminder flows according to the ILCD Handbook (EC 2010) or parameters describing resources use and waste generation according to EN 15978 (2011) were also

Table 3 LCI data linked to quantities of building products and technical equipment

Energy carrier	LCI data	Source
Electricity	Electricity, consumption mix FR	ecoinvent v2
Natural gas	Heat, natural gas, at boiler condensing modulating <100 kW	ecoinvent v2
Wood energy (pellets)	Heat, wood pellets, at furnace 15 kWh	ecoinvent v2
Wood energy (mixed logs)	Heat, mixed logs, at wood heater 6 kWh	ecoinvent v2

Table 4 LCI data linked to final energy values for heating, domestic hot water, ventilation, lighting and auxiliaries

Processes	LCI data	Source
Tap water	tap water, at user	ecoinvent v2
Waste water treatment (collective)	treatment, sewage, from residence, to wastewater treatment, class 2	ecoinvent v2
Waste water treatment (non collective)	treatment, sewage, from residence, to wastewater treatment, non collective	CSTB

calculated: the non-renewable primary energy consumption (PE-nr), the net fresh water consumption (WC), the non-hazardous and inert wastes. The NHIW indicator is the sum of the inert and non-hazardous wastes generated without weighting (NHIW) and the radioactive waste (RW). For ecoinvent data, energy and waste flows were calculated using heating values provided by the Cumulative Energy Demand method and waste conversion factors provided in the EDIP method (Frischknecht et al. 2007b).

2.5 LCA software used

All the calculations were conducted by the building LCA software ELODIE (ELODIE 2013; Schiopu et al. 2012). Only data with environmental indicators attached (e.g., LCIA indicators or indicators describing the use of energy or the waste generation) are integrated in the software in order to ease the modelling by building practitioners who are non-LCA experts. Such choice is consistent with the existing guidelines for building LCAs (LoRe-LCA 2013; EeBGuide 2013; Lasvaux et al. 2014). All the data used in this study correspond to the data stored in the database of the ELODIE software in 2012.

2.6 Sample of new individual houses

In this study, 40 new individual houses were selected using a call for tenders for building stakeholders to conduct LCA studies of Energy efficient buildings (EeB). The sample covers both under construction or recently constructed buildings until 2012. Most of them consumed less than 50 kWh/(m^2*an) of primary energy according to the RT2012 thermal regulation, and BBC Effinergie energy label end-uses: heating, hot water production, ventilation, lighting, cooling, and auxiliaries (Effinergie 2011; 2010; JORF 2013). These individual houses represent more than 7000 m^2 in total. The study takes into account different construction systems commonly used in France for the construction of new houses. The sample was built according to the market shares for the reinforced concrete, the concrete block, the wooden houses, the brick, and the steel frame constructive systems. For instance, the wooden houses represent from 12 to 30% of the market shares in France according to different studies Effinergie (2012); CODIFAB (2013). In addition, buildings were selected according to different climate requirements according to the French thermal regulation. Table 6 presents the characteristics of the buildings including the constructive system, the energy and ventilation systems, the climate zone, and the primary energy coefficient (Cep) according to the BBC label and the thermal regulation RT2012. Figure 2 also represents the 8 climate zones and the locations of the different individual houses used in our sample. In the French thermal regulation, a maximum conventional primary energy coefficient (Cep_{max}) is defined at 50 kWh per m^2 per year of primary energy. This target value is then be modulated according to the climate zone i.e., +20% for H1a and H1c, +30% for H1b, +10% for H2a, 0% for H2b, −10% for H2c and H2d and −20% for H3. Each house needs to comply with the Cep max though some can have a much lower Cep coefficient. For instance, if an individual house uses on-site electricity

Table 5 LCI data linked to water consumption values (both upstream and downstream processes)

	Abbreviation	Unit	Method
Indicators describing environmental impacts			
Acidification potential of land and water	AP	kg SO2 equiv.	(CML, 2001)
Global Warming Potential (100 years)	GWP	kg CO2 equiv.	(CML, 2001)
Parameters describing resource use			
Non renewable primary energy consumption	PE-nr	MJ equiv.	(NF P01-010; EN 15978)
Net fresh water consumption	WC	L	(NF P01-010; EN 15978)
Parameters describing waste categories			
Non hazardous and inert waste	NHIW	kg equiv.	(NF P01-010; EN 15978)
Radioactive waste	RW	kg equiv.	(NF P01-010; EN 15978)

Table 6 Environmental indicators considered in this study

Houses	Net floor area (in m^2)	French thermal regulation RT2012		Constructive systems	Energy systems		Controlled Mechanical Ventilation (CML)	On-site renewable electricity production equipments
		Climate zone	Cep coefficient* ($kWhep/m^2/an$)		Heating	Domestic hot water (DHW)		
1	559.21	H1a	38.4	Wood/concret	Wood boiler	Solar hot water panels (+ wood booster)	Simple flow	
2	93.4	H1a	62.18	Brick	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Simple flow	
3	123	H1a	54	Aerated concrete	Heat pump + recovered energy	Solar hot water panels (+ electric booster)	Simple flow	
4	298	H1a	65	Steel	Natural gas condensing boiler (combined heating and DHW)		?	PV panels
5	93	H1b	−7.8	Aerated concrete	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Simple flow	PV panels
6	201	H1b	29.59	Brick	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Double flow	PV panels
7	103.95	H1b	70	Brick	Heat pump (combined heating and DHW)		?	
8	134	H1b	65	Brick (alveolate)	Heat pump (combined heating and DHW)		Simple flow	
9	113.19	H1c	64.82	Brick (alveolate)	Heat pump	Solar hot water panels	Double flow	
10	195.9	H1c	57.6	Brick (alveolate)	Natural gas condensing boiler (combined heating and DHW)	Simple flow		
11	150	H1c	5	Concrete block	Wood pellets boiler (+ electric booster)	Solar hot water panels (+ electric booster)	Simple flow	PV panels
12	115.95	H1c	57.33	Aerated concrete	Natural gas condensing boiler Solar hot water panels		Simple flow	
13	110.24	H1c	54.2	Brick	Natural gas condensing boiler (combined heatin integrated to the boiler)		Simple flow	
14	116	H1c	54.5	Brick	Natural gas condensing boiler	Electric DHW	Simple flow	PV panels
15	91	H1c	64.3	Brick	Wood pellets boiler	Electric DHW	?	
16	121.13	H1c	70	Brick	Wood pellets boiler	Electric DHW	Simple flow	
17	152.79	H1c	43.2	Brick	Wood pellets boiler (+ electric booster)	Electric DHW	Simple flow	
18	151	H1c	56.1	Wood	Electrical heat pump (combined heating and DHW)		Simple flow	
19	109.9	H1c	54.99	Wood	Natural gas condensing boiler (combined heating and DHW)		Simple flow	
20	905.8	H1c	41.43	Wood	Natural gas condensing boiler (combined heating and DHW)		Simple flow	
21	208	H2a	−33.9	Brick (alveolate)	Heat pump (+ wood pellets boiler)	Solar hot water panels (+ electric booster)	Double flow	PV panels
22	205.7	H2a	50.42	Concrete block	Natural gas condensing boiler (combined heating and DHW)		Simple flow	
23	128.96	H2b	49.8	Concrete block	Heat pump		Simple flow	

Table 6 (continued)

Houses	Net floor area (in m^2)	French thermal regulation RT2012		Constructive systems	Energy systems		Controlled Mechanical Ventilation (CML)	On-site renewable electricity production equipments
		Climate zone	Cep coefficient* ($kWhep/m^2/an$)		Heating	Domestic hot water (DHW)		
						Solar hot water panels (+ electric booster)		
24	120	H2b	49.2	Concrete block	Heat pump	Solar hot water panels (+ electric booster)	Simple flow	
25	138	H2b	50	Concrete block	Natural gas condensing boiler (combined heating and DHW)		?	
26	108	H2b	47.9	Concrete block	Natural gas condensing boiler Solar hot water panels (+ gas booster)		Simple flow	
27	162.31	H2b	49	Brick	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Simple flow	
28	138.2	H2b	43.95	Brick	Heat pump	Solar hot water panels (+ electric booster)	Double flow	
29	101.72	H2b	49.47	Brick	Heat pump + recovered energy	Solar hot water panels (+ electric booster)	Simple flow	
30	147.72	H2b	50	Brick	Wood pellets boiler (+ electric booster)	Solar hot water panels (+ electric booster)	Double flow	
31	120.17	H2b	50	Other	Wood pellets boiler (+ electric booster)	Solar hot water panels (+ electric booster)	Double flow	PV panels
32	130	H2b	40.1	Steel	Heat pump (combined heating and DHW)		Double flow	
33	147.39	H2c	−10.65	Aerated concrete	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Simple flow	PV panels
34	234	H2c	22.34	Aerated concrete	Heat pump (combined heating and DHW)		Double flow	
35	256	H2c	45	Wood	Wood boiler (+ electric booster)	Solar hot water panels (+ electric booster)	?	
36	192	H2d	35.5	Concrete block	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Double flow	
37	98.18	H2d	43.9	Brick	Heat pump + recovered energy	Solar hot water panels (+ electric booster)	?	
38	150.65	H3	40	Concrete block	Electric combined system for heating and DHW		Simple flow	
39	147.35	H3	31.85	Aerated concrete	Natural gas condensing boiler	Solar hot water panels (+ gas booster)	Simple flow	
40	177	H3	45	Wood	Wood pellets boiler	Solar hot water panels (+ electric booster)	Simple flow	PV panels

production through PV panels, the PV energy can be withdrawn from the total of energy consumption needed for heating, hot water production, ventilation, lighting, cooling, and auxiliaries. That is the reason why some Cep values may be negative in Table 6. In that case, the building produces more energy than it needs.

3 Results

The statistical results of the 40 LCAs are first presented in relative proportions (share of impacts between the three contributors). We then present the statistical distribution of the 6 indicators for the three contributors of the baseline system boundaries. Detailed results are also reported for the embodied impacts variability and for the influence of construction systems, climate zone, and energy for heating on the LCA results.

3.1 Share between life cycle-related building products and technical equipment impacts and the operational energy (related uses) and water consumption impacts

Figure 3 and Table 7 present the share of impacts and the median impacts driven by the three contributors defined in Section 2.1 for the six indicators introduced in Section 2.5. Different trends are noticed for each indicator. Results are first presented for the energy related indicators (PE-nr, radioactive waste, GWP, AP), then for the net fresh water use and for the non-hazardous and inert waste indicators.

The impacts related to the operational energy consumption (module B6) are mainly driven by indicators related to fossil and nuclear energy consumption such as the PE-nr, the radioactive waste, the GWP, and the AP indicators.

PE-nr results showed that 40% of the non-renewable energy consumption is due to the building products and technical equipment from cradle-to-grave while 57% are due to the heating, DHW, cooling, ventilation, and lighting end-uses. The energy consumption (in background processes) related to the operational water consumption (module B7) is negligible for this indicator. Similar trends are found for the radioactive waste indicator due to the high proportion of electrical heating systems found in new low-energy houses. Unlike PE-nr and radioactive waste indicators, most of the GWP impacts are driven by the products and equipment contributor (~65%). The operational energy consumption account for 25% of the GWP impacts while the water consumption has a negligible share for this indicator (< 5%). The AP indicator presents similar shares with slightly more impacts for the products and equipment (72%), and for the water consumption during the use phase (7%).

The water consumption (module B7) mostly determines the net fresh water indicator (WC). Around 90% of the water use is due to the direct uses of the water in the building. A very limited part is linked to the indirect use related to the products and equipment (6%) and to the operational energy use (3%).

Finally, the non-hazardous waste indicator is exclusively controlled by the volume of waste produced by the products and technical equipment (97%).

3.2 Variability of impacts between life cycle-related building products and technical equipment impacts and the operational energy (related uses) and water consumption impacts

Following the global analysis of the median shares of the three contributors, Fig. 4 presents the absolute results including the variability of impacts found for each contributor and for the total system boundaries (products and equipment + operational energy use + operational water use). The variability of the impacts is displayed by means of boxplots. The lower and the upper horizontal line of the boxplots represent the first Q1 (25%) and third Q3 (75%) quartile while the line in-between is the median value (50%). The range of the boxplot represents half of

Fig. 3 Median share of impacts between the "building products and technical equipment", "operational energy consumption (related uses)" and operational water consumption" contributors of the 40 low-energy individual houses

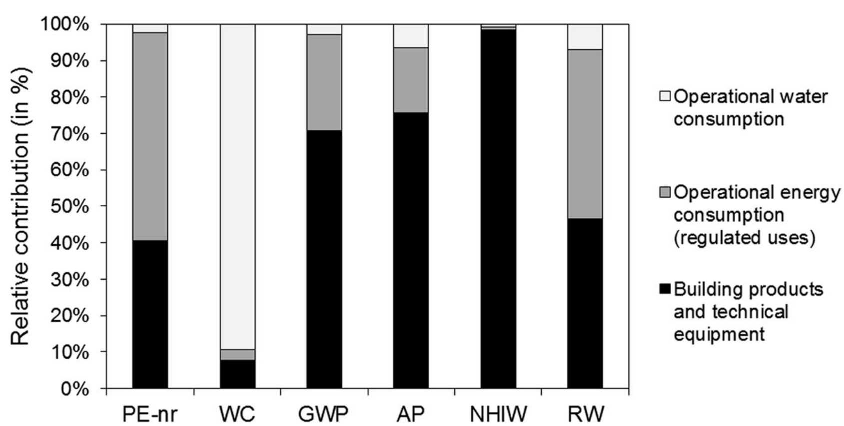

Table 7 Median results for the different environmental indicatorss

in unit of indicator per m^2_{NFA} per year	PE-nr *kWh*	WC *L*	GWP *CO_2-eq*	AP *SO2-eq*	NHIW *kg*	RW *kg*
Building products and technical equipment (median value)	37.0	107	8.4	0.043	35.4	8.6E-04
Operational energy consumption (median value)	52.1	41	3.1	0.010	0.3	1.1E-03
Operational water consumption (median value)	2.1	1245	0.3	0.004	0.3	1.6E-04
Baseline system boundaries (median value)	91.2	1394	11.8	0.057	36.0	2.3E-03

the statistical distribution. The whiskers correspond to the 10% and 90% percentiles (P1 and P9).

Statistical variability is first analysed for the indicators linked to fossil and nuclear energy consumption (PE-nr, radioactive waste, GWP, AP), then for the net fresh water use and non-hazardous and inert waste indicators.

Generally speaking, the impacts related to the operational energy consumption (module B6) present different variability

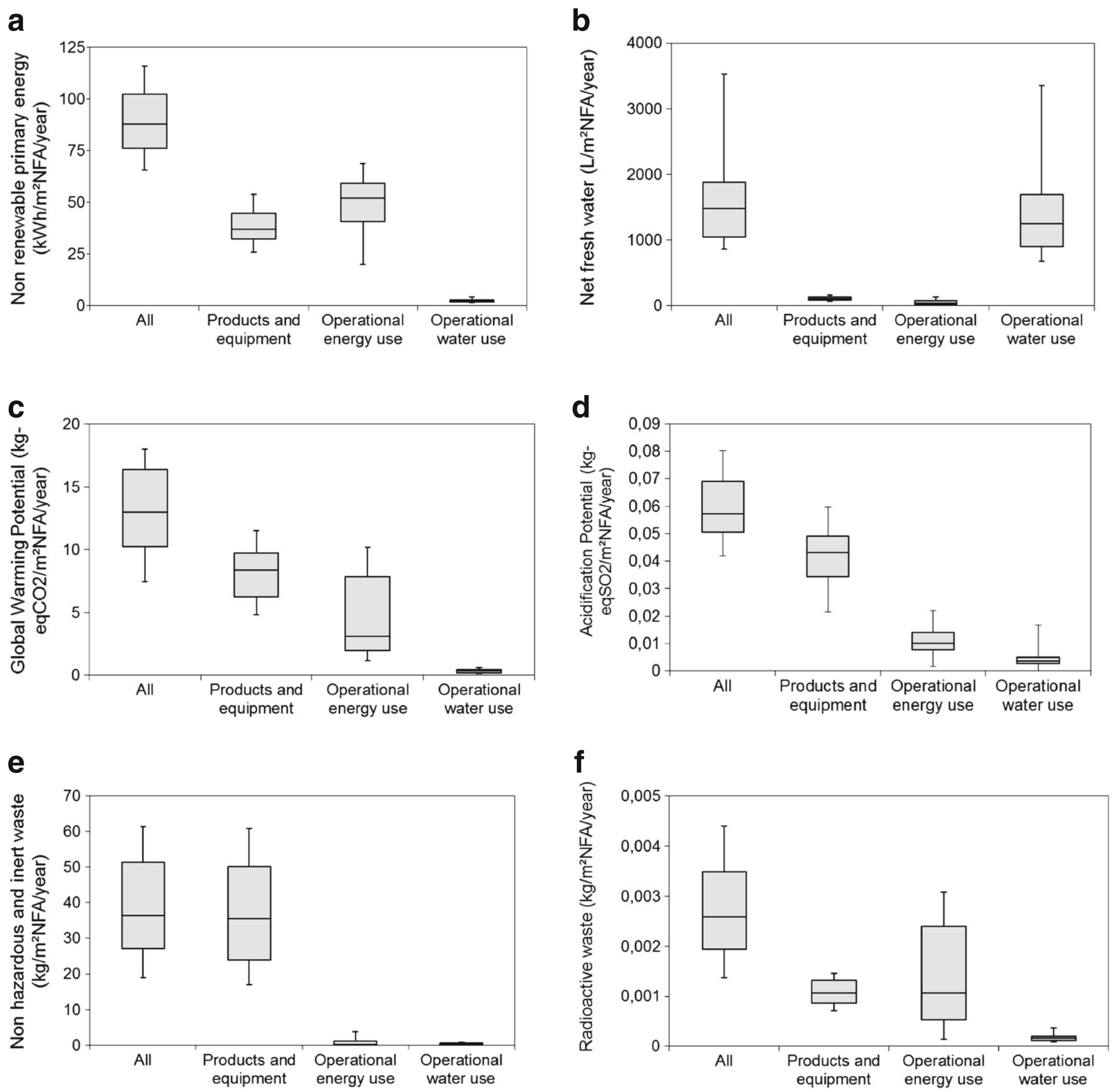

Fig. 4 Variability of impacts for each contributor and for the total (products and equipment + operational energy use + operational water use) of the life cycle of individual houses for the non-renewable energy (**a**), net fresh water use (**b**), global warming potential (**c**), acidification potential (**d**), non-hazardous waste (**e**), and radioactive waste (**f**) indicators

trends depending on indicators. The same is found for the products and equipment contributor.

Global PE-nr results vary, for the percentiles P1 and P9, between 66 and 116 kWh/(m^2*year) for the baseline system boundaries. The variability is higher for the operational energy consumption than for the product and equipment with a P1-P9 range between 20 and 69 kWh/(m^2*year). Looking at the product and equipment contributor, the dispersion of results is much lower (between 26 and 54 kWh/(m^2*year) for the P1-P9 range). Similar trends are found for the radioactive waste indicator. The variability of the products and equipment results is low (around 0.001 kg/(m^2*year) of radioactive waste produced) while it is much higher for the operational energy consumption (between 0.001 and 0.003 kg/(m^2*year) of radioactive waste produced).

Global GWP results vary between 7.5 and 18 kg CO_2-eq/(m^2*year) for the baseline system boundaries. Looking at the operational energy consumption, the variability is even higher with an order of magnitude of 9 between the first percentile (1.2 kg CO_2-eq) and the ninth percentile (10.2 kg CO_2-eq). The greenhouse gases emissions related to products and equipment are found higher but with less variability (between 4.8 to 11.5 kg CO_2-eq). The global AP results vary from 0.043 to 0.079 kg SO_2-eq/(m^2*year). As for the GWP results, the products and equipment contributor has more impact than the operational energy use. However, the variability linked to the

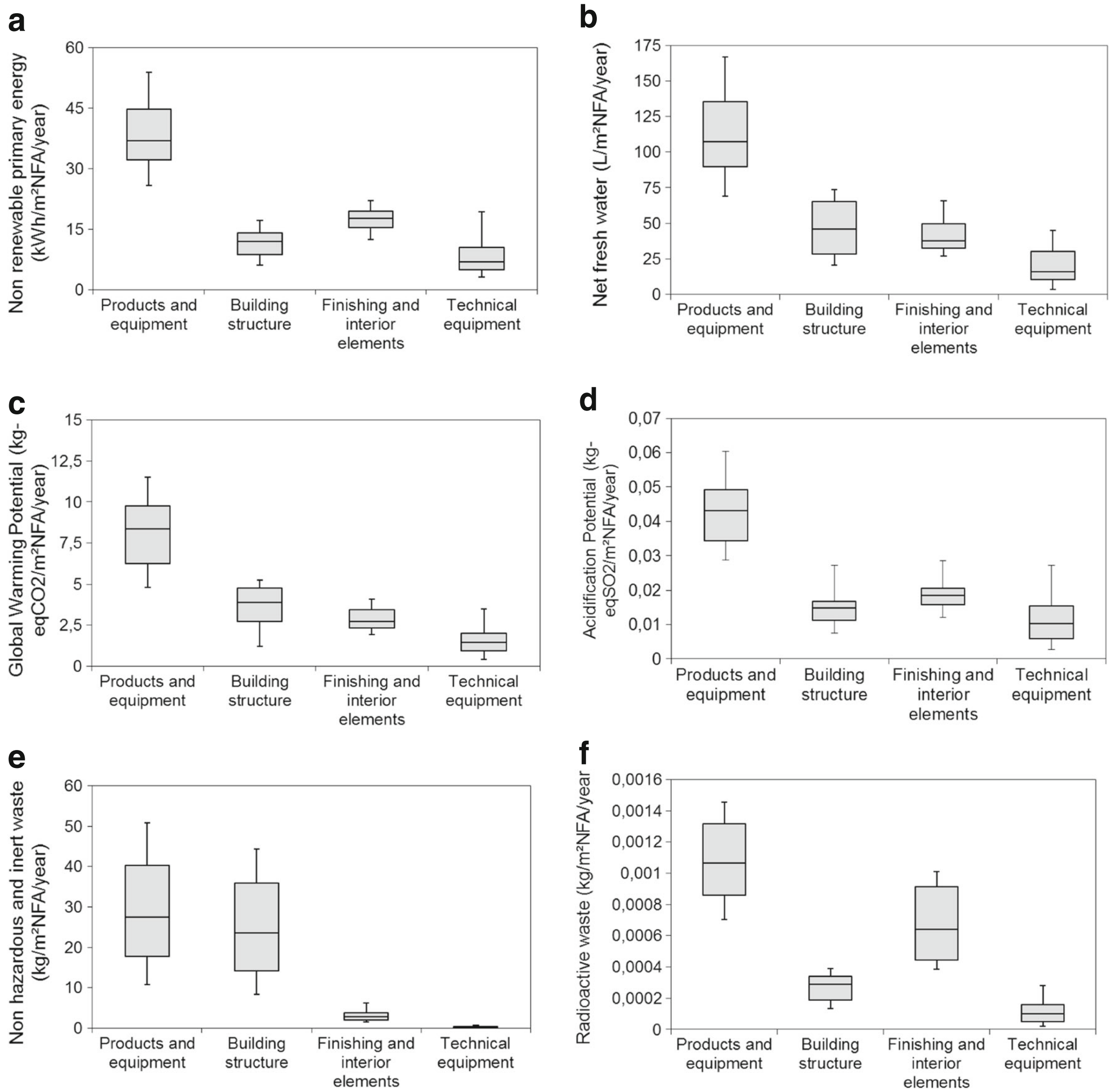

Fig. 5 Detailed results for the products and equipment contributor with the building fabric, the finishing and interior elements and the technical equipment for the non-renewable energy (**a**), net fresh water use (**b**), global warming potential (**c**), acidification potential (**d**), non-hazardous waste (**e**), and radioactive waste (**f**) indicators

operational energy consumption is now less important (between 0.006 to 0.020 kg SO_2-eq/(m^2*year)).

The statistical distribution for the net fresh water use indicator confirms the negligible importance of the products, equipment, and operational energy use contributors. In opposite, the operational water use has a substantial variability with percentiles P1 and P9 values comprised between 0.674 and 3.348 m^3/(m^2*year).

Finally, the non-hazardous waste indicator is exclusively controlled by the volume of waste produced by products and technical equipment. In addition, the volume of non-hazardous and inert waste is found highly variable in Fig. 5 (P1-P9 range about 20 to 60 kg/(m^2*year). Most of the quantities correspond to wastes generated at the end of life (EOL) of buildings due to inert construction materials (e.g. brick, concrete).

3.3 Detailed results for the products and equipment contributor

Figure 5 presents the breakdown of the embodied impacts related to products and equipment. They are presented according to the three classes of the building products classification (see Table 2). Other breakdown could be used but the goal of these detailed results is to identify the share of impacts between the building structure, the interior elements and finishing and the technical equipment.

In median values, the interior elements have higher impacts for the PE-nr and the AP while the building structure has more impacts on the GWP and net fresh water use indicators. For the radioactive waste, the main impact comes from the interior elements, the structure, and equipment having less contribution. For the non-hazardous and inert wastes, as expected, the building structure is fully responsible of the generated waste (in quantity), the share of the technical equipment being insignificant. Substantial variability is found for the waste produced by the building structure due to the different constructive systems considered in the sample of buildings.

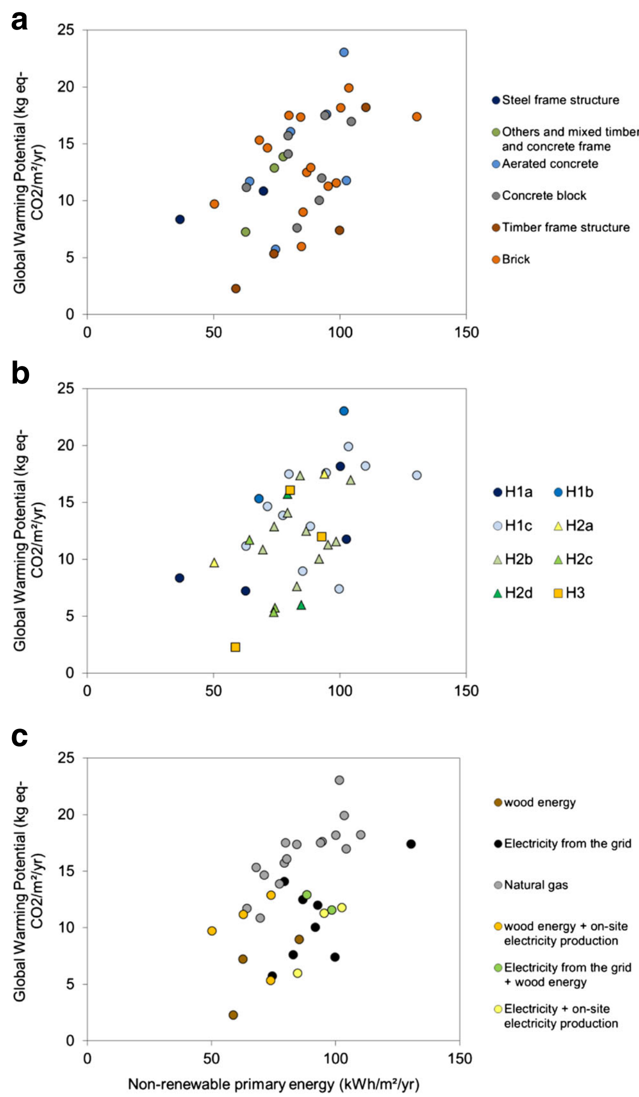

Fig. 6 Scatterplots of the LCA results of the individual houses for the PE-nr and GWP indicators and for the baseline system boundaries depending on the constructive systems (**a**), the climate zone according to the French thermal regulation (**b**), and the energy carrier for heating (**c**)

3.4 Scatterplots of building LCA results depending on three design parameters

In this section, the influence of three design parameters is analysed: the constructive systems, the climate zone, and the energy for heating. As each single family house has different characteristics (cf. Table 1) and present a substantial variability (cf. Figure 4 and Fig. 5), it is useful to know whether LCA results are influenced by one of these three parameters. The analysis is limited to the GWP and PE-nr indicators. Figure 6 presents the three scatterplots.

Generally speaking, no significant influence is noticed in Fig. 6a, i.e. we do not observe clusters of buildings with the same constructive systems. The same results are found for the climate zone according to the French thermal regulation (Fig. 6b). Buildings can have a different environmental performance even if they belong to the same climate zone, e.g. for H1a the GWP impacts vary from 6 to 18 kg CO_2-eq/(m^2*year). The scatterplots for the energy carrier for heating are presented in Fig. 6c. It shows a cluster of similar energy carrier for heating (i.e. natural gas) is found at the upper part of the cloud. Yet, for the other energy carrier, no obvious clusters can be drawn, i.e. the buildings heated with the same energy carrier are not necessarily grouped.

These results showed that, taken one by one, each parameter does not seem to significantly influence the environmental performances of the houses. However, when combined altogether, we can notice that some buildings perform better.

For instance, a timber frame house built in H3 climate zone (Mediterranean area) with a wood boiler presents the lowest non-renewable primary energy use and greenhouse gases emissions. This is due to the low level of heating demand in H3 climate zone as well as the low carbon footprint of wood energy carrier and wood structural material. In opposite, one autoclaved aerated concrete house built in H1b climate zone (not the coldest) and equipped with a natural gas solution presents the highest level of greenhouse gases emissions with more than 20 kg CO_2-eq/(m^2*year). In between these best and worst cases, the influence of these parameters is less evident.

4 Discussion

4.1 Discussions of findings

Generally speaking, the results presented in Section 3 provide LCA information for practitioners and decision makers regarding the key factors that drive the environmental performance of low-energy houses in the French context. The dispersion of the impact values (Figs. 4, 5, and 6) also showed the different environmental performances of the studied buildings. These results confirm the relative importance of the embodied impacts related to building products and building integrated technical systems in low-energy buildings when compared to conventional buildings as shown in previous studies, e.g. Scheuer et al. (2003), Sartori and Hestnes (2007), Passer et al. (2012)). It is even a key issue for the GWP indicator in the French context due to the low carbon content of electricity and the relatively high shares of electrical energy systems in the sample of houses (e.g. heat pumps, PV panels). However, dispersions were also found in the results of the operational energy use contributor due to the other energy systems installed in the houses (e.g. natural gas boiler, wood boilers etc.). As the unitary environmental impacts of the energy pathways are very different, it is consistent to find a dispersion of the results for the corresponding indicators (PE-nr, GWP, AP, and radioactive waste).

This study also confirmed that the volume of non-hazardous and inert waste is linked to the current high amount of mineral materials such as concrete used in the building. In opposite, the net fresh water indicator is only determined by the operational water use. This is an interesting piece of information as industry frequently considers it as a major impact for the building materials, products and equipment (Dubois 2009).

In parallel, the sensitivity to design parameters should be further analysed to better understand the variability found in the results as we showed that neither the constructive system nor the climate zone fully influence the results.

4.2 Sensitivity analyses

4.2.1 System boundaries: inclusion of the construction site and the other uses of energy (not regulated)

In this section, the influence of system boundaries' extension is investigated in order to know if the results well represent the overall building's environmental impacts. As an illustration, Fig. 7 presents the relative contributions for the primary energy, non-renewable, net fresh water use, GWP, AP, non-hazardous and inert waste and radioactive waste indicators between the baseline system boundaries (products and equipment, operational regulated energy use, operational water use) and the alternative boundaries (baseline boundaries + the other uses of energy, building related and building non-related, and the construction site activities). They are calculated based on assumptions of Tables 8 and 9. For the other uses of energy, a ratio of 20 kWh of final electricity per m^2 per year was used following the results of Enertech (2010). In this sensitivity analysis, all the electricity from the grid is

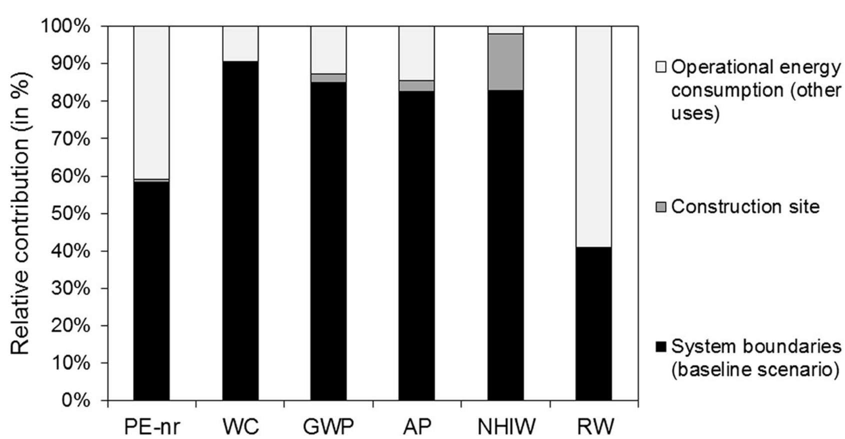

Fig. 7 Relative contributions of the PE-nr, WC, GWP, AP, NHIW, and RW indicators between the system boundaries (baseline) and the additional contributors (other uses of energy, building related, building non-related, and construction site)

Table 8 Assumption for the system boundaries' sensitivity analysis for the other uses of operational energy use (not regulated)

	Operational energy use (other uses)
Final energy consumption (kWh/m^2/yr)	20
Energy type	Electricity
LCI data	Electricity, consumption mix FR
Source	ecoinvent v2

assumed to cover all the other uses of energy (conservative assumption). For the construction site impacts, the ratio is based on the study from Lebert et al. (2013).

It is interesting to note that for some indicators, the extensions of the system boundaries lead to a substantial decrease in percentage of the baseline scenario results (in relative value). The main concerns are for the non-renewable primary energy (PE-nr) and radioactive waste (RW) indicators for which the baseline system boundaries contributions drop to 60 and 40%. The decrease is less significant for the GWP, AP and WC indicators. This can be explained by the final energy value used in this sensitivity analysis (20 kWh of electricity from the grid per m^2 per year). On the other side, including the construction site in the boundaries of the study does not change the results except for the NHIW indicator (the share of the construction site being 15% in Fig. 7). Thus, while assessing and improving the environmental performance of buildings, Fig. 7 shows that it is important to also include the other uses of energy consumption even if those are currently not included in the thermal RT 2012 regulation.

4.2.2 Reference study period (from 50 to 100 years)

One of the key parameters of this study is the reference study period (RSP) which was set at 50 years in the baseline scenario. However, it is interesting to analyse whether the replacement rates of the different building products and technical equipment drastically change or not the mean values of impacts. As an illustration, Table 10 presents the influence of the RSP on the results of (i) the building products and technical equipment contributor and (ii) the baseline system boundaries.

Table 10 showed that the impacts related to the building structure are logically lightened for all the indicators due to the extension of the RSP as the structural components are assumed not to be changed across the life cycle of the houses. On the other side, the impacts related to the building finishing and interior elements are not really lightened due to the increase of the replacement rates. All in all, the overall impacts are reduced from −2 to −18% depending on the indicators. The same conclusions are found for the technical equipment for which the RSL is very often equal to 25 years (e.g. for the boilers, the PV panels, the thermal solar panels etc.).

At the scale of the product and equipment contributor, the results are reduced from −16 to −44% depending on the indicator. Looking at the baseline system boundaries, the results are decreased but they now depend on the share of the products and equipment contribution in the total impacts. For instance, the NHIW indicator is much more reduced than the WC indicator as the products and equipment contributor is a key driver of the waste indicator and nearly negligible for the water consumption indicator.

4.3 From statistical results to LCA reference values for buildings?

The statistical variability found in the sample of buildings could now led to the definition of environmental performances classes such as A, B, C, D, and/or threshold for each contributor (e.g. corresponding to the maximum value, to the third quartile, the ninth percentile etc.). To that purpose, a choice of a system boundaries and RSP would be needed as the LCA results vary depending on these initial assumptions.

Such reference values would enable a practitioner to compare and optimize his project according to the current

Table 9 Assumption for the system boundaries' sensitivity analysis for the construction site

	Energy consumption	Water consumption	Transport of materials	Transport of persons	Waste treatment
Quantity	1.3 L/m^2	0.1m^3/m^2	20 T.km/m^2	30 p.km/m^2	0,5 T/m^2
LCI data	Diesel, burned in building machine	Tap water, at user	Lorry, 20-28 T	Passenger car	Inert waste treatment
Source	ecoinvent v2	ecoinvent v2	ecoinvent v2	ecoinvent v2	ecoinvent v2

Table 10 Influence of the results to a change of the RSP from 50 to 100 years (upper part of the table: results presented for the building products and technical equipment and breakdown for the building structure, finishing and interior elements and technical equipment; lower part of the table: results presented for the baseline system boundaries)

	PE-nr *kWh/m^2_{NFA}/year*	WC *L/m^2_{NFA}/year*	GWP *kgkg eq-CO_2/m^2_{NFA}/year*	AP *$kgSO_2$-eq/m^2_{NFA}/year*	NHIW *kg/m^2_{NFA}/year*	RW *kg/m^2_{NFA}/year*
Results for the building products and technical equipment (median value)						
RSP = 50 years	37.0	107	8.4	0.043	35.4	1.1E-03
RSP = 100 years	31.1	83	6.3	0.035	20.9	8.6E-04
Relative deviation (in %)	*−16%*	*−23%*	*−25%*	*−18%*	*−41%*	*−19%*
Results for the building structure (median value)						
RSP = 50 years	12.0	46	3.9	0.015	26.3	2.9E-04
RSP = 100 years	6.9	25	2.1	0.008	13.3	1.6E-04
Relative deviation (in %)	*−42%*	*−46%*	*−47%*	*−45%*	*−49%*	*−44%*
Results for the finishing and interior elements (median value)						
RSP = 50 years	17.6	37	2.7	0.019	5.9	6.4E-04
RSP = 100 years	16.2	33	2.6	0.017	4.9	5.8E-04
Relative deviation (in %)	*−8%*	*−12%*	*−2%*	*−11%*	*−18%*	*−9%*
Results for the technical equipment (median value)						
RSP = 50 years	7.0	16	1.4	0.010	2.2	9.9E-05
RSP = 100 years	6.3	15	1.3	0.009	2.1	9.7E-05
Relative deviation (in %)	*−9%*	*−6%*	*−11%*	*−11%*	*−2%*	*−2%*
Results for the baseline system boundaries (median value)						
RSP: 50 years	91.2	1394	11.8	0.057	36.0	2.3E-03
RSP: 100 years	85.3	1369	9.7	0.049	21.5	2.1E-03
Relative deviation (in %)	*−6%*	*−2%*	*−18%*	*−14%*	*−40%*	*−9%*

low, average, and best practice. In that context, this study showed that in order to optimize the environmental performances of buildings, there is not a single solution due to the multicriteria approach. A work indicator per indicator is needed to identify improvement actions.

In the same time, further studies should be conducted to consolidate the sample size, to improve the quality of the data used (bill of quantities, EPDs etc.), and to better identify the parameters that influence the LCA results' variability. For instance, the LCA reference values are sensitive depending on the architectural, design and local constraints' parameters (e.g. climate requirements). To that purpose, a complete understanding of the influence and the interaction of all these parameters would be needed.

5 Conclusion and short-term perspectives

This study provides a first set of LCA guidance values determined for new low-energy single family houses in France based on a bottom-up approach (i.e. by statistical analysis of a sample of representative LCA studies). This paper is part of an overall project that also includes the analysis of 75 LCA of other building typologies such as multi-family buildings and offices (Lebert et al. 2013). For low-energy single family houses, the results showed that the embodied impacts are more critical for the greenhouse gases emissions indicator with 70% of contribution than for the primary energy (non-renewable) indicator with 40% of contribution. In parallel, the variability of impact values found in this study also showed that each building performs differently from an environmental point of view and that it is possible to optimise the building design for each indicator. The results of this paper and its related operational projet (HQE Performance) are thus a basis to support the development of reference and/or target values in new LCA-based labelling system for new buildings.

As a short term perspective' illustration of this paper, in late 2016, a new LCA-based label entitled "Energie Positive & Réduction Carbone (E+|C-)" was launched in France to support the development of plus energy low carbon buildings. This label is broken down in two parts: one part deals with plus energy building requirements and assumes each building must comply first with the RT 2012 requirements. It includes four different performance levels for the energy balance of all the operational energy uses (regulated and not regulated) using a "BEPOS" indicator. The second part deals with the assessment of the greenhouse gas (GHG) emissions of the building calculated using a LCA according to NF EN 15978. This part has been developed since 2014 mainly between public authorities, different building stakeholders, and the CSTB (among other players).The label has been adjusted (e.g., choice of LCA data e.g., for energy process from the national "Base Carbone" from the French Environment and Energy Management Agency (ADEME) instead of ecoinvent) and at some point simplified compared to the LCA data, methodology, and calculation rules presented in this paper even though the main aspects remain present in the label. The LCA part of the label (i.e. "Réduction Carbone") proposes two performance levels with target values for the greenhouse gas (GHG) emissions associated with two system boundaries: (i) the assessment of both life cycle related-embodied GHG emissions of materials and technical equipment and the operational GHG emissions of energy use and (ii) the single assessment of life cycle-related embodied GHG emissions of materials and technical equipment. This new label, supported by public policies and labelling systems such as HQE, is one of the first label available so far which combines at once both energy performance requirements (towards plus energy buildings) and environmental performance requirements (towards low carbon buildings) and environmental performance requirements (toward low carbon buildings) (MEEM, 2016a; MEEM, 2016b). It remains an intermediate step towards a new "energy and environmental" regulation for new buildings planned for 2020 in France. More generally, this paper and the related project and operational label (E+|C-) are also a contribution to the on-going discussions for the development of an EU approach for the environmental performances of buildings (European Union 2015).

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