Building and Environment 51 (2012) 276–284

Contents lists available at SciVerse ScienceDirect

Building and Environment

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

Energy and environmental assessment of two high energy performance residential buildings

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ARTICLE INFO

Article history:
Received 6 July 2011
Received in revised form
23 November 2011
Accepted 24 November 2011

Keywords:
Life cycle assessment
Positive energy building
Zero-energy building
Heating system
Simulation

ABSTRACT

The «positive energy building[3] concept combines energy saving and electricity production using renewable resources, aiming a positive primary energy balance on a yearly basis. Compared to other concepts of high energy performance buildings, it is very ambitious on an energy point of view, but more materials and components are used, this is why the environmental relevance of this concept has to be questioned.

In order to contribute to answer this question, a life cycle assessment (LCA), including the fabrication of components, construction, operation, maintenance, dismantling and waste treatment, has been used to evaluate the environmental impacts of two high energy performance buildings: a renovated multi-family social housing building and two passive attached houses. Both buildings are located in North of France. For the purpose of this study, renewable energy production has been assumed to achieve nearly positive energy balances.

For these buildings, four different heating solutions have been studied: an electric heat pump, a wood pellet condensing boiler, a wood pellet micro-cogeneration unit, and district heating.

Modeling and simulation have been performed using the building thermal simulation tool COMFIE, to evaluate the heating load and thermal comfort level, and the LCA tool EQUER to evaluate twelve impact indicators.

The results show the level of performance as well as the influence of the choice of the heating system on the environmental impacts considered in this assessment.

1. Introduction

Energy performance of buildings is today recognized as a major issue to address the worrying questions of human-induced global warming and depletion of fossil energy resources. To this purpose, several high energy performance building (HEPB) concepts have been proposed, from *low-energy building* through *passive building* and *zero-energy building* to *positive energy building* and even *autonomous building*. Nowadays a lot of national regulations introduce such concepts as targets for the buildings to be constructed [1]. In particular, the recast of the European Energy Performance of Buildings Directive (EPBD) [2] targets *nearly-zero-energy* performance for all new buildings by the end of 2020.

Beyond energy issues, high energy performance buildings are supposed to contribute to the reduction of the environmental burden of the building sector. Moreover it seems relevant to consider that the more energy-performing a building is, the less negative environmental impacts it induces. This is surely true during the operation phase of the building, but compared to standard buildings, a HEPB generally requires more material (thicker insulation, triple glazing windows, etc.) and more components (solar panels, etc.) and thus induces more environmental impacts during the other phases of the building life (construction, refurbishment, demolition). Several previous studies have been performed, showing more or less clearly this phenomenon [3–10]. Especially, Feist [7] shows that overall cumulative energy demand (primary energy) can be higher for a self-sufficient solar house than for a passive house due to the production and replacement of the additional technical systems.

The aim of this paper is to evaluate the environmental relevance of HEPBs on a life cycle approach, considering more recent life cycle data and impact assessment methods. Definitions are first reminded, then the method is presented and results are provided for two case studies in France.

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doi:10.1016/j.buildenv.2011.11.018

2. Definitions

“Low-energy” is a generic expression meaning that the performance level in terms of energy is better than the performance level of a standard building, whereas “passive” refers to the Passivhaus standard, developed in Germany by the Passivhaus Institute [11], which aims very low heating load and total energy demand. This standard defines three precise requirements that certified passive buildings have to fulfill [12]: heating energy demand[1] lower than 15 kWh m^{-2} yr^{-1}, total primary energy demand[2] lower than 120 kWh m^{-2} yr^{-1} and air infiltration at 50 Pa lower than 0.6 vol h^{-1}.

The “positive energy building” concept (PEB), closely related to “zero(-net) energy building” (ZEB) concept [13], combines energy saving and energy recovery from local renewable resources, such as solar radiation, wind, biomass or heat from the environment. Energy can be saved by the combination of a high insulation level, heat recovery from extracted air, a high level of air-tightness, and the use of efficient equipment. Thus, the “Passive-house” approach can be used to design a PEB. Energy recovery from local renewable resources can provide part or the whole building energy demand including heating load and hot water production, and can supply power for local consumption or to feed the electricity grid.

An “autonomous” building is a type of ZEB with no connection to any energy distribution grid. Its energy needs are supplied by local resources at any moment, which practically requires the implementation of energy storage devices (see e.g. the experimental house build in Germany by the Fraunhofer Institute in 1992 [14]). In practice, this kind of building is indispensable in remote locations but is not considered today as a practical solution in locations where grid connection is possible. That is why autonomous building is not addressed in this paper.

As PEB is a rather new concept, its definition is not yet definitely settled and several approaches remain possible [1,13,15,16]. Defining PEB –as well as defining ZEB– requires to precise the metric of energy accounting (e.g. final or primary energy), the period of the balance (e.g. one year, the lifetime of the building), the kind of consumption (typically building heating and cooling, ventilation, lighting, electric appliances, water heating) and the energy forms to account for (electricity, heat, others), the system considered (building, outdoor spaces, transport), the way renewable energy is supplied to the building (either on-site or off-site), the type of balance (consumption/generation or import/export). The variety of possible ZEB/PEB definitions and methods is studied in the IEA SHC Task 40/ECBCS Annex 52 [13]. In most cases, the difference between ZEB and PEB only lays in the energy balance accounted during one year of operation: balanced for ZEB or net producer for PEB. Nevertheless, the balance could also be computed for the whole lifespan of the building, accounting for energy embodied in the materials and involved in the construction, retrofit and demolition phases of the building, following a life cycle approach [17].

Since the beginning of the 21st century, a lot of low-energy buildings have been constructed, mainly residential and tertiary buildings, in Europe, North-America and Asia [18–21]. This emergence of highly efficient buildings has been encouraged by research programs –such as CEPHEUS European project [22]– or exemplary projects –such as “Wohnen und Arbeiten” building and the “PlusEnergy” houses in Freiburg-im-Breisgau, Germany [23,24]– which helped proving the effectiveness of the achieved performance and identifying the best practice.

Regarding ZEBs/PEBs, most achievements are very recent and more and more upcoming buildings are announced to be zero- or positive energy buildings. Nevertheless, feedback about the true achieved energy performance of such buildings is still not substantial [20,25] and further studies are expected.

The definition of PEB which has been chosen for this study corresponds to the “Net Zero source Energy Building” defined by Torcellini et al. [16]: “A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building’s total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.”

3. Method

Life cycle assessment (LCA) has been used to evaluate the environmental impacts of two different HEPBs. This method is now well established and can be applied to any kind of system, and especially to a component of a building [26,27], to a building [10,28–32] or even to a settlement [33]. For a building, LCA integrates fabrication of the components, construction, operation, maintenance, dismantling and waste treatment. For each phase of the life cycle, the various energy and material flows are assessed and then various impact indicators can be evaluated.

The two buildings under study differ in size and performance level, and several possible heating solutions have been compared in order to evaluate their influence on the environmental assessment, leading to six different cases.

In a first step, the annual heating load and the thermal comfort level of each building have been evaluated using COMFIE, a dynamic thermal simulation tool for multi-zone buildings developed by CEP at MINES ParisTech [34]. For validation purposes, results computed by COMFIE have been compared to measurements on a PASSYS test cell and to benchmark values derived from international reference models in the frame of task 12 of the IEA Solar heating and cooling programme [35].

In a second phase, twelve environmental impact indicators (Table 1) have been calculated for the eight configurations using EQUER, a software dedicated to the LCA of buildings [32]. EQUER is based on the life cycle inventories of the Swiss Ecoinvent database (Version 2.0) [36]. Computation results have been compared to benchmarks in the frame of European projects (REGENER, PRESCO [37]) showing good correspondence with the average values. Case

Table 1
List of the impact indicators computed by EQUER [33].

Impact indicator	Unit	Legend
Cumulative Energy Demand	GJ	PRIMARY ENERGY
Water consumption	m^3	WATER
Abiotic Depletion Potential	kg Sb-eq	ABIOTIC RESOURCES
Non-radioactive waste creation	t eq	WASTE
Radioactive waste creation	dm^3	RADIOACTIVE WASTE
Global Warming Potential at 100 years (GWP_{100})	t CO_2-eq	GWP_{100}
Acidification Potential	kg SO_2-eq	ACIDIFICATION
Eutrophication Potential	kg PO_4^{3-}-eq	EUTROPHICATION
Damage caused by the ecotoxic emissions to ecosystems	PDF m^2 yr	ECOTOXICITY
Damage to human health	DALY	HUMAN HEALTH
Photochemical Oxidant Formation Potential (Smog)	kg C_2H_4-eq	SMOG
Odour	10^6 m^3	ODOUR

[1] Useful energy per net floor area within the thermal envelope (treated floor area).

[2] Non-renewable primary energy per net floor area within thermal envelope, including heating, domestic hot water, auxiliary and household electricity.

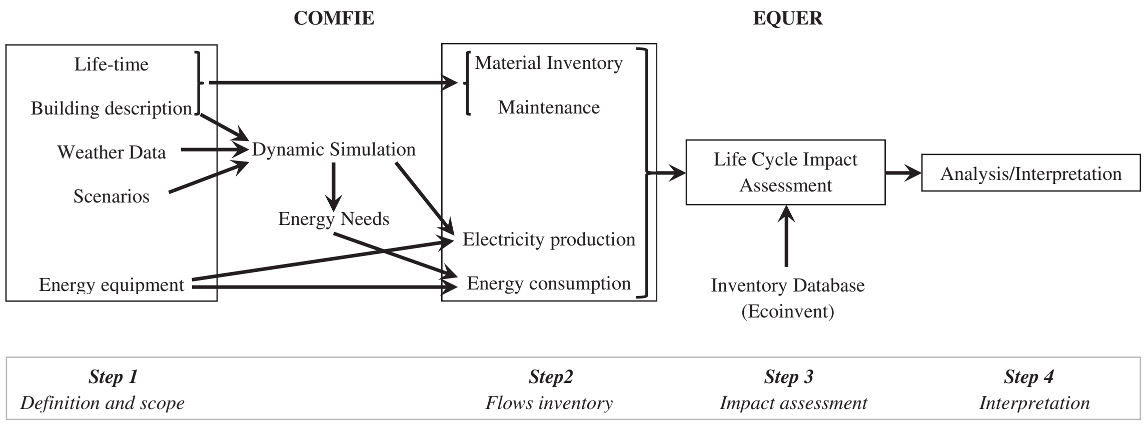

Fig. 1. Summary of the LCA process followed in this study.

studies have also been performed in the European ENSLIC Building project [5] and research coordination action LoRe-LCA.

The implemented LCA process follows the four steps of the international standard (ISO 14040) [38]. This process is summarized in Fig. 1.

3.1. Description of the buildings under study

Two actual buildings, located in France, have been studied: two attached passive houses (in Formerie) and a renovated collective social housing building (in Montreuil).

The two attached houses built in 2007 in Picardy region (Fig. 2) are the first certified "Passive-House" buildings in France. Each house is two-storied, with an inhabitable area of 132 m^2, a garage, a terrace, a balcony and a garden. The internal structure is the same for both of them: a hall, an office, a living room and a kitchen downstairs, and a small lounge, a bathroom and three bedrooms upstairs. Only the location of the garage differs (North or West). These dwellings are designed for families of four people.

Timber-frame external walls are insulated by cellulose (22 cm) and polystyrene (15 cm), the slab by polystyrene (20 cm) and the attic by cellulose (40 cm) (U-value: 0.125 W m^{-2} K^{-1}). Triple-glazed windows and insulated external doors provide high insulation and air-tightness[3]. External Venetian blinds provide solar protection during spring and summer. Thermal bridges are supposed to be limited to 0.1 W m^{-1} K^{-1} around the slab and the attic.

Both houses are equipped with a 30 m-long earth-to-air heat exchanger (ETAHE) for summer cooling, with a heat recovery ventilation, with 5 m^2 of solar thermal panels for water heating, and with a compact electric heat pump for space heating and domestic hot water backup (annual coefficient of performance (COP): 3).

The multi-family social housing building (Fig. 3) has been built in 1969 and then renovated in 2001 in the frame of the REGEN-LINK European project [39]. It is an L-shaped, five-storied building including 52 dwellings with an inhabitable area of 4500 m^2. The first floor is occupied by associations and collective spaces. Heating is supplied by district heating. All walls are made of reinforced concrete (20 cm). After renovation, the external walls and roof terrace are respectively externally insulated by glass wool (U-value: 0.484 W m^{-2} K^{-1}) and polyurethane (U-value: 0.360 W m^{-2} K^{-1}). Single-glazed windows have been replaced by low emissivity

Fig. 2. Two attached passive houses in Formerie (Arch.: En Act architecture, contractor: les Airelles).

double glazing, except for the first floor. Thermal bridges are supposed to be limited to 0.1 W m^{-1} K^{-1}, except for the first floor and around the balconies where they have not been treated (a value of 0.7 W m^{-1} K^{-1} is considered).

Only the south-west wing of the building has been studied here, representing 2500 m^2 inhabitable area, 36 dwellings and assuming 144 inhabitants.

3.2. Modeling and simulation

These two buildings were not designed or renovated to achieve a zero-energy goal. In reality, they include no renewable electricity

Fig. 3. Multi-family social housing building in Montreuil (after renovation).

[3] The houses fulfill the corresponding Passivhaus criterion: the air exchange rate is inferior to 0.6 vol h^{-1} with a pressure difference between inside and outside at 50 Pa.

Table 2
Theoretical improvement and heating systems of the buildings (underlined: actual systems).

	Formerie	Montreuil
	Attached houses	Collective social housing
Energy saving	Earth-to-air heat exchanger, Heat recovery ventilation (average efficiency: 70%)	Earth-to-air heat exchanger, Heat recovery ventilation (average efficiency: 70%)
Energy generation	76.8 m^2 PV modules	180 m^2 solar thermal modules 400 m^2 PV modules
Domestic hot water	5 m^2 Solar hot water (solar fraction: 50%)	District heating (3% heat loss in distribution)
Possible heating system	Heat pump (COP: 3) Condensing boiler (average annual efficiency: 0.75) Micro-CHP (+HWS 700 l)	District heating (3% heat loss in distribution) Inverter heat pump (COP: 3.45) Micro-CHP (+HWS 15,000 l)

production device; nevertheless their respective energy performance is rather high. For the need of this study, some realistic additional devices have been implemented in the models in order to get higher energy performance. In particular, photovoltaic modules have been assumed to cover most part of the available best-oriented roof area (Table 2). Moreover, several possible heating systems have been considered: air-to-air heat pumps (HP), wood pellet micro-CHP coupled with hot water storage (HWS), wood condensing boiler (CB) and district heating (DH). Each heating device has been sized to fit the building heating load. HWS are vertical cylinders (length to diameter ratio: 2), insulated by polyurethane (5 cm, R-value: 2 K m^2 W^{-1}). The heat pump and the condensing boiler are basically modeled by their average annual efficiency, whereas detailed models used for micro-CHP units, photovoltaic modules, solar thermal collectors and earth-to-air heat exchangers were available from previous works (respectively [40–43]). These are dynamic models, coupled to the building model and included in the simulation tool as additional modules.

The weather data used for the simulations correspond to the local climatic zone of Paris greater area (oceanic climate, 2700 heating degree-days @ 18 °C). Thermal zones are gathering rooms with similar temperature profiles, e.g. North or South oriented spaces, unheated spaces, rooms with a similar occupancy pattern. Ventilation flows, occupancy, shading and internal gains are modeled in each zone by defining hourly scenarios. Ventilation scenarios consider hygienic ventilation rates in winter and high ventilation rates in summer for night cooling. Internal gain scenarios consider a sparing use of efficient electrical appliances (Table 3); a lower value has been assumed for the attached houses due to more efficient appliances. Occupancy and shading scenarios are as realistic as possible. All these scenarios are described in details in [44]. Hot water consumption is assumed to be 40 l/person/day.

Regarding LCA, the materials, water and energy flows have been taken into account during the life cycle of the buildings. Assumed lifetimes of the buildings elements are given in Table 4. Assuming that the lifetime of the renovated building is extended by refurbishment, lifetime for both buildings is assumed to be equal to 80 years. A 10% waste of material has been assumed during the construction phase.

Table 3
Some modeling assumptions for both buildings.

	Formerie	Montreuil
	Attached houses	Collective social housing
Thermal zones	5 zone for each house: *Kitchen + Living room (South)* *Hall + Office (North)* *Two bedrooms + Lounge (South)* *One bedroom + Bathroom (North)* *Garage (unheated)*	3 zones: *North (4 floors)* *South (4 floors)* *First floor (unheated)*
Internal gain	1500 kWh yr^{-1} per house	2000 kWh yr^{-1} per dwelling
Hot water consumption	2628 kWh yr^{-1} per house	2628 kWh yr^{-1} per dwelling

4. Results

4.1. Energy assessment

In a first step, the energy needs have been studied independently from the equipment. They appear to be very low for both buildings (Table 5, Fig. 4). Regarding the building of Montreuil, the heating load is nearly fulfilling the passive house criteria, whereas the houses in Formerie are clearly passive.

The local renewable heat and electricity generation is summarized in Table 6. The global building energy assessment is shown in Fig. 4.

The annual final energy consumption depends on the heating device. The net primary energy indicator is the algebraic sum of the various energy flows expressed in primary energy (PE), using the primary energy conversion ratios given in Table 7. These ratios have been derived from Ecoinvent V2.0 database [36] taking into account the local energy generation mix related to each type of energy consumption. Two electricity mixes have been distinguished: a “heating” mix corresponding to the heat pump consumption and a “base” mix for all other electricity consumptions. Whereas the “base” mix is an annual average mix, the “heating” mix corresponds to the marginal production that is specifically devoted to electricity supply during the winter peak periods. This explains the higher

Table 4
Assumptions for lifetimes.

Device	Lifetime
Door and windows	30 years
Coatings	10 years
PV panels	30 years
Solar water heater	20 years
Hot water storage tank	25 years
Micro-CHP unit	100,000 working hours
Heat pump	20 years
Earth-to-air heat exchanger	30 years
Whole building	*80 years*

Table 5
Computed energy needs.

Final use	Formerie		Montreuil	
	kWh yr^{-1}	kWh m^{-2} yr^{-1}	kWh yr^{-1}	kWh m^{-2} yr^{-1}
Heating Load	2032	7.7	39,650	15.9
Domestic Hot Water Production	5255	19.9	94,600	37.8
Lighting and Domestic Appliances	2354	8.9	66,522	26.6
Ventilation	1807	6.8	17,369	7.0

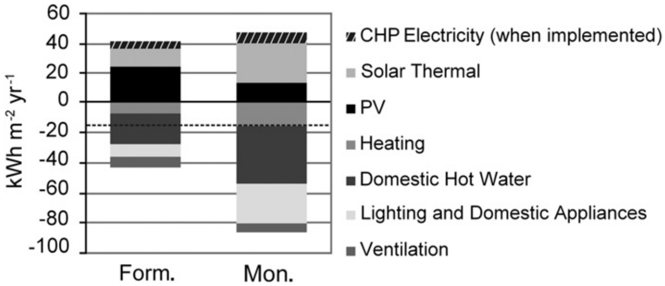

Fig. 4. Computed energy needs and renewable production per inhabitable area. The dotted line represents the maximal heating load of the Passive house standard (15 kWh m^{-2} yr^{-1}).

Table 6
Computed electricity and heat generation.

Generation (kWh yr^{-1})	Formerie	Montreuil
Solar PV Electricity	6418	33,638
Solar Heat	3227	64,116
CHP Electricity (when implemented)	1168	19,863

contributions of the fossil fuels, resulting in a higher primary energy conversion ratio. District heating is provided in Montreuil by a coal and fuel boiler, inducing rather high primary energy conversion ratio.

Generated electricity is fully exported to the grid and considered as reduction of consumption. The net primary energy assessment has been computed for the six cases (Table 8), taking into account a 9% electricity loss in the grid and a 3% loss in district heating which results in slightly higher PE ratios. Only two alternatives of the Formerie attached houses (HP and CB) reach a positive net primary energy assessment. The ratio of net primary energy by inhabitable area (Fig. 5) shows that the newly-built, passive, attached houses of Formerie are much more energy efficient than

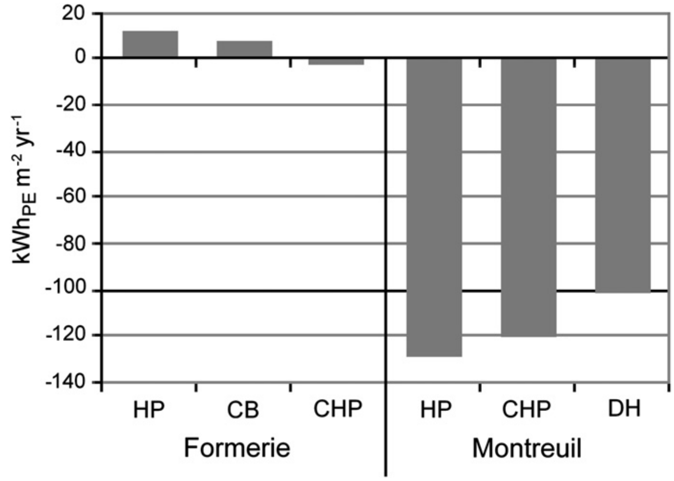

Fig. 5. Net primary energy assessment per living area and per year.

the renovated social housing apartment building, where the most consuming items are hot water production and electric appliances, which cannot be totally compensated by solar collection. Moreover, the micro-CHP solution remains primary-energy-consuming, mainly due to the limited performance of the implemented wood pellet micro-CHP unit.

Thermal comfort has been evaluated, basing on the computed hourly indoor temperatures. In winter, heating avoids cold discomfort. In summer, overheating has been evaluated using the discomfort degree-days indicator. For a given limit temperature T_{lim}, the annual, hourly based, discomfort degree-days indicator, is defined as follows: $\text{DDD}_{T_{\text{lim}}} = 1/24 \cdot \sum_{h=1}^{8760} (T_{\text{in}}(h) - T_{\text{lim}})^{+}$ where T_{in} is the indoor temperature and '+' designates the positive part of the considered expression. This indicator shows that indoor comfortable conditions are ensured most of the time (Table 9). Overheating periods are very limited essentially thanks to night ventilation but also to pre-cooling by earth-to-air heat exchanger.

Table 7
Production mixes and primary energy conversion ratios.

	Nuclear	Hydro	Natural Gas	Coal	Fuel	Primary Energy Conversion Ratios
Electricity production						
Primary energy ratios	*3.52*	*1.06*	*3.11*	*3.46*	*3.45*	*kWh$_{PE}$/kWh*
Electricity Base (France)	77%	12%	5%	5%	1%	3.2
Electricity Heating (France)	48%	5%	10%	27%	10%	3.33
District heating						
Primary energy ratios	-	-	*1.17*	*1.05*	*1.35*	*kWh$_{PE}$/kWh*
District Heating (Montreuil)	-	-	1%	85%	14%	1.09

4.2. Environmental assessment

In order to identify the contribution of the envelope and equipment in the overall environmental balance, on Figs. 6–9, the impacts related to the equipment (fabrication and end of life) have

Table 9
Hot discomfort for both buildings with and without night ventilation.

Hot discomfort (DDD @ 27 °C)	Formerie	Montreuil
With night ventilation and ETAHE	15	25
Without night ventilation, with ETAHE	40	93

Table 8
Computed energy consumption, electricity supply and net primary energy balance (HP: Heat Pump, CB: Condensing Boiler, CHP: Micro-Cogeneration, DH: District Heating).

Building	Heating Device	Consumption (*kWh/yr*)				Supply (*kWh/yr*)	Net Primary Energy Balance. (*kWh$_{PE}$/yr*)
		Wood Pellets	District Heating	Electricity *heating*	Electricity *base*	Electricity *base*	
Formerie	HP	0	0	677	4837	6418	+3082
	CB	5413	0	0	4161	6418	+1874
	CHP	9228	0	0	4870	7586	-785
Montreuil	HP	0	0	11,493	114,375	33,638	-325,967
	CHP	145,772	0	0	93,347	53,501	-303,382
	DH	0	70,134	0	83,891	33,638	-255,615
Overall PE ratios		*1.12*	*1.125*	*3.66*	*3.52*	*3.52*	

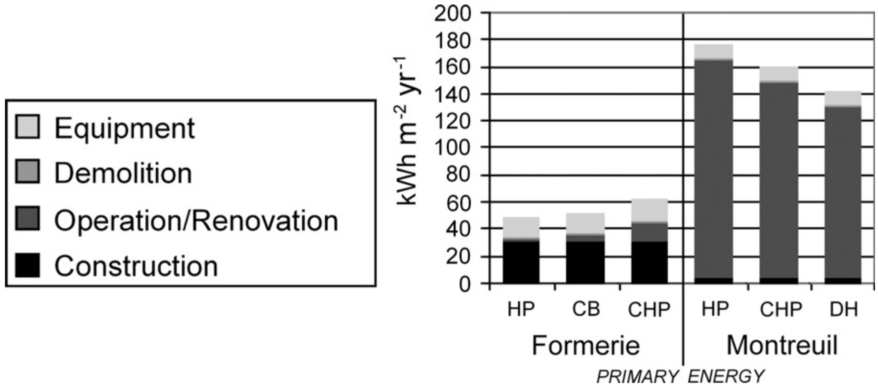

Fig. 6. Indicator mainly influenced by energy processes.

been separated. The computed indicators have been expressed per inhabitable area and per year in order to allow inter-comparison. To facilitate interpretation, the results are presented in four separate figures; environmental indicators have been grouped according to the main parameter which influences them; e.g. the waste indicator is more influenced by the construction materials, whereas GWP_{100} and resources indicators are more related to energy processes.

The PRIMARY ENERGY indicator depends on the efficiency of the energy chain (Fig. 6). Due to embedded energy of materials and equipment and to water consumption, this indicator is above zero even for "zero-energy buildings". The contribution of the operation phase is very small in the Formerie houses; hence the embedded energy constitutes the main contribution. This is completely different in the case of the Montreuil building where the embedded energy represents at most 11% of the whole primary energy.

The WASTE indicator depends mainly on the materials implemented in the building; the chosen heating device has no significant influence (Fig. 7). Here, the demolition phase appears to be dominating (at least 43% −respectively 52%− of the total contribution for Montreuil −respectively Formerie− building).

Four indicators mainly depend on electricity consumption, mostly due to the electricity generation processes (Fig. 8). This is obvious for RADIOACTIVE WASTE, ABIOTIC RESOURCES and GWP_{100}, but WATER is also influenced, to a lesser extent though, by the cooling of thermal power plants. Two of these indicators

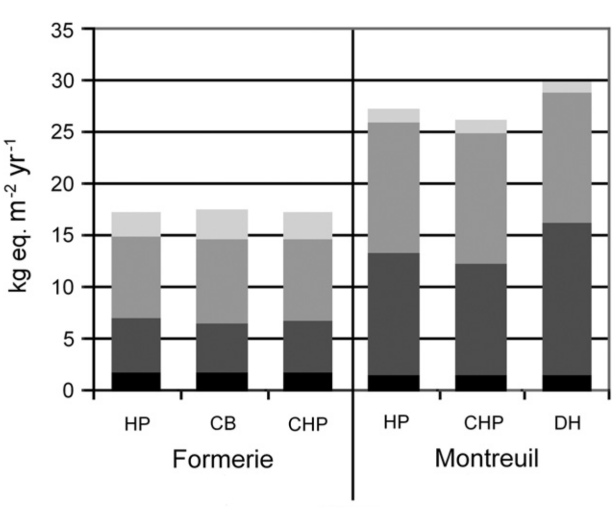

Fig. 7. Indicator mainly influenced by the materials implemented in the building.

(GWP_{100} and ABIOTIC RESOURCES) are also higher for district heating.

Six indicators are influenced by wood combustion, occurring when micro-CHP or condensing boiler is implemented (Fig. 9). Nevertheless, other contributions also strongly influence some of these indicators, such as equipment or materials fabrication processes.

5. Discussion

The buildings studied here show high energy and environmental performances, e.g. GWP_{100} is far below the average value in France (32 kg CO_2 eq. m^{-2} yr in 2007 [45]) whatever the heating solution (Fig. 8). Nevertheless, even for the positive energy cases, during the operation phase most of the environmental impacts remain positive. This is mainly due to the impacts of wood combustion or electricity production and to domestic water consumption.

Another important contribution to six impacts (ECOTOXICITY, ODOUR, PRIMARY ENERGY, ABIOTIC RESOURCES, ACIDIFICATION,) is induced by the equipment (solar panels, heating system, hot water tank etc.) which has to be periodically renewed. The impacts of this equipment surely can be lowered, either by improving the production processes of the systems or by recycling them at end of life. This especially concerns PV panels whose contribution to the overall energy performance is major.

Regarding indicators strongly influenced by the construction phase, the contribution of this phase is higher for the Formerie houses than for the Montreuil building, because e.g. more insulation materials have been used to get this higher performance. Reversely, the construction phase has little influence on the apartment building in Montreuil because higher energy performance (almost passive house level) has been achieved with e.g. less insulation. This can be explained by the higher compactness and occupant density of the building (5.8 inhabitants per 100 m^2 vs. 3 in Formerie).

Compared to heat pump and micro-CHP, coal and fuel-based district heating almost doubles ABIOTIC RESOURCES, GWP_{100} and ACIDIFICATION indicators but reduces slightly ODOUR and PRIMARY ENERGY. But another energy mix for district heating would probably result in other effects. Ultimate reserves are considered in the ABIOTIC RESOURCES indicator, which reduces the weight of uranium in the balance. Most of these resources cannot be exploited because the uranium concentration in the ore is so low that more energy would be needed for extraction than the production potential. Considering probable reserves instead would probably be more relevant to compare different energy sources.

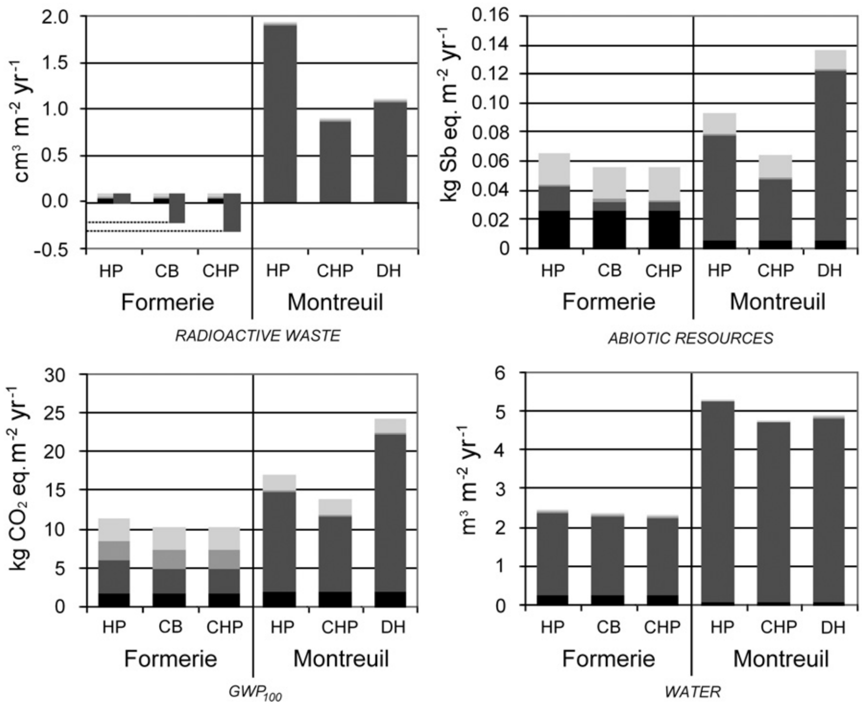

Fig. 8. Indicators influenced by the electricity generation processes and by district heating.

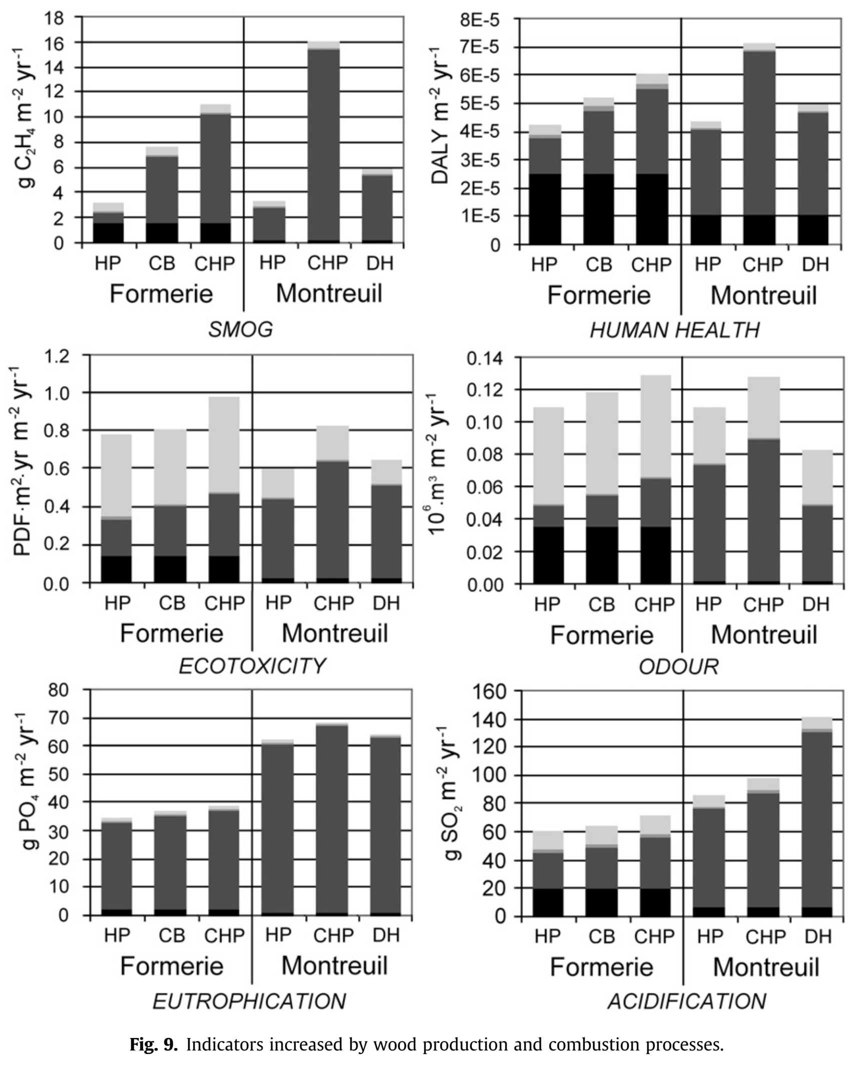

Fig. 9. Indicators increased by wood production and combustion processes.

6. Conclusions

LCA has been applied to study two low-energy buildings, allowing also various heating devices to be compared.

The primary energy assessment of the buildings during their operation phase is influenced by both the thermal envelope and the equipment. In this case study, new eco-designed buildings, such as the passive houses in Formerie, have higher performance than renovated buildings. Actually, in renovation, it is more difficult to reach a very high envelope efficiency than in new buildings and adding solar panels is not always optimal, e.g. due to a bad solar exposure or to a limited available roof area. Nevertheless, in both cases, renewable resources can contribute to a major share of the overall energy supply (Fig. 4) which strongly conditions the overall primary energy balance. Moreover Fig. 5 shows that the choice and sizing of the heating system can significantly affect the overall primary energy balance, depending on the share of heating load in the overall energy needs.

Interpretation work is needed to analyze the LCA results given by twelve impact indicators. Several parameters, such as energy efficiency, electricity consumption, wood consumption and the amount of implemented materials can have a strong influence on some indicators and very few on some others. This multi-criteria approach does not allow identifying one solution as the very best one: choices depend on the priorities given to the various environmental concerns.

For instance, in the French context addressed by this study –where about 75% of the electricity is generated by nuclear plants– the electric heat pump appears to be the best heating solution for 5 to 7 indicators and as the worst one for 3 to 4 indicators, depending on the building under consideration. Thus, according to the priorities of the decisionmaker involved in a construction or renovation programme, the heat pump solution may be adopted or rejected. Similarly, condensing boiler and CHP solutions reduce the impacts on abiotic resources and global warming, but due to wood consumption, they also affect impacts linked to air and water chemical pollution. Of course, the improvement of the efficiency of the micro-CHP unit should also lower these impacts. But actually, none of the four heating solutions studied above seems optimal on every indicator. Reduction of energy demand is therefore useful in any case.

Regardless the chosen heating system, the building with most positive primary energy balance (Formerie houses) has the best performance for 8 indicators, due to the smaller contribution of its operation phase. For instance, this building contributes to reduce the radioactive waste production, especially if heat is not provided by electricity. Considering a longer lifetime for the buildings might even emphasize this advantage, since the radioactive waste production indicator is negative during the operation phase. On the contrary, this building is not the best one with regard to indicators such as ODOUR, ECOTOXICITY and HUMAN HEALTH, essentially because the contribution of the construction and demolition phases to those indicators is dominating. Hence, studying the implementation of low impact materials seems a relevant perspective.

A building with high energy performance tends to present a higher environmental performance than a standard or simply low-energy building. But the choice of the construction materials and the equipment can strongly impact the environment either on a positive or negative way.

The work done here could be extended to other types of HEPBs and to other heating systems in order to complement these conclusions and to better understand the influence of some parameters such as the lifespan of the building. Occupant's behavior is also an essential aspect of the environmental performance, and the efforts made by designers should be complemented by awareness-raising of users.

Acknowledgments

This work was supported by grants from the Île-de-France region, the French National Research Agency (ANR) and the European Community (research coordination action LoRe-LCA).

Acronyms

CB	Condensing Boiler
CEP	Center for Energy and Processes
CEPHEUS	Cost Efficient Passive Houses as European Standards
CHP	Combined Heat and Power
COP	Coefficient of Performance
DALY	Disability Adjusted Life Years
DH	District Heating
ECBCS	Energy Conservation in Buildings and Community Systems
ENSLIC Building	Energy Saving through Promotion of Life Cycle Assessment in Buildings
EPBD	Energy Performance of Buildings Directive
ETAHE	Earth-to-Air Heat Exchanger
GWP	Global Warming Potential
HEPB	High Energy Performance Building
HP	Heat Pump
HWS	Hot Water Storage
IEA	International Energy Agency
LCA	Life Cycle Assessment
LoRe-LCA	Low Resource consumption buildings and constructions by use of LCA in design and decision making
PDF	Potentially Disappeared Fraction of species
PE	Primary Energy
PEB	Positive Energy Building
PRESCO	Practical Recommendations for Sustainable Construction
PV	Photovoltaic
SHC	Solar Heating and Cooling
U-value	Overall heat transfer coefficient
ZEB	Zero(-net) Energy Building

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