Life cycle assessment of a positive energy house in France

Stéphane Thiers, Bruno Peuportier

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S. Thiers[1]; B. Peuportier[1]

1: Centre for Energy and Processes, MINES ParisTech, 60 bd St-Michel, 75272 PARIS CEDEX 06

ABSTRACT

The « positive energy house » concept combines energy saving, e.g. applying the passive house approach, and electricity production using a renewable resource, leading to a positive primary energy balance on a yearly basis. Compared to a standard house, more materials and components are used (thicker insulation, triple glazing windows, renewable energy systems…), this is why the environmental relevance of this concept is often questioned.

In order to contribute to answer this question, a life cycle assessment (LCA) has been used to evaluate the environmental impacts of such buildings, including the fabrication of components, construction, operation, maintenance, dismantling and waste treatment. This paper presents results in the case of a positive energy building, showing also the influence of the choice of the heating system on various environmental impacts considered in this assessment (e.g. global warming potential, radioactive waste production, photochemical oxidant formation potential, cumulative energy demand, abiotic depletion potential).

The case study concerns two attached passive houses built in Picardy, France, in which renewable energy systems are studied theoretically: the real houses include solar water heating but no renewable electricity production. The envelope has a high insulation, high air-tightness and very low thermal bridges. The technical equipment includes a heat recovery ventilation and an earth-to-air heat exchanger. In this study, PV solar panels mounted on the roof have been added so as to obtain a positive primary energy assessment. For these houses, three different heating solutions have been studied: an electric heat-pump, a wood pellet condensing boiler and a wood pellet micro-cogeneration unit.

The three alternatives have been modeled using the building thermal simulation tool COMFIE, in order to evaluate their heating load, possibly cooling load and thermal comfort level. Environmental impact indicators have been evaluated for these alternatives applying the LCA tool EQUER, linked to the building simulation tool COMFIE and using life cycle inventories from the Swiss Ecoinvent data base.

INTRODUCTION

The « positive energy house » concept (PEH) is a concept of high-performance residential building, which combines energy saving and the recovery of energy from local renewable resources such as solar radiation, wind, biomass or heat from the environment. Energy can be saved by a high insulation level, the recovery of heat from extracted air, a high level of air tightness, and the use of efficient equipment – for instance applying the "Passive House" approach of the Passivhaus Institut of Darmstadt, Germany [1]. The recovery of energy from local renewable resources can provide a part or the whole building's heating load and of the hot water production, and can supply electricity to the grid or for local consumption.

Due to the relative newness of the PEH concept, its definition has not been clearly settled yet and several approaches remain possible [2]. In this paper, we assume that its objective is to achieve a positive *primary* energy balance for the building on a yearly basis (*local balance approach* in [2]). This means that, during a one-year period, a PEH recovers more renewable energy than the amount of primary energy it requires for its own operation.

Compared to standard house, a PEH generally requires more materials (thicker insulation, triple glazing windows, etc.) and more components (solar panels, etc.). Consequently its construction generally requires more energy (embodied energy) and induces increased impacts on the environment. Thus the environmental relevance of the PEH concept, which is often questioned, has to be studied.

METHOD

In order to contribute to answer this question, a life cycle assessment (LCA) has been used to evaluate the environmental impacts of a PEH. This method is now well established and can be applied to any kind of systems, and especially to the equipments of a building [3], to a building [4] or even to a settlement [5]. For a building, a LCA consists in analysing the fabrication of the components, construction, operation, maintenance, dismantling and waste treatment. For each phase, the various energy and material flows are assessed and then various impact indicators can be computed.

In this study, three different heating devices have been studied in order to evaluate their influence on the environmental assessment: a heat pump (HP), a wood pellet micro-CHP unit (CHP) and a wood pellet condensing boiler (CB).

In a first step, the annual heating load and the thermal comfort level in each thermal zone of the building have been computed using COMFIE, a dynamic, multizone, building thermal simulation tool developed by the CEP at MINES ParisTech [6].

In a second phase, the environmental impact indicators have been calculated for the three heating solutions using the software EQUER, dedicated to the LCA of buildings [4]. EQUER is based on the life cycle inventories of the Swiss Ecoinvent data base and can compute twelve different impacts [7] (Table 1). Case studies are being performed in the ENSLIC Building project.

Impact indicator	Unit	Legend
Cumulative Energy Demand	GJ	ENERGY
Water consumption	m^3	WATER
Abiotic Depletion Potential	kg Sb-eq	RESOURCE
Non-radioactive waste creation	t eq	WASTE
Radioactive waste creation	dm^3	RADWASTE
Global Warming Potential at 100 years (GWP_{100})	t CO_2-eq	GWP_{100}
Acidification Potential	kg SO_2-eq	ACIDIF.
Eutrophication Potential	kg PO_4^{3-}-eq	EUTROPH.
Damage caused by the ecotoxic emissions to ecosystems	PDF.m^2.yr	ECOTOX
Damage to human health	DALY	HUMHEALTH
Photochemical Oxidant Formation Potential (Smog)	kg C_2H_4-eq	O_3-SMOG
Odour	Mm^3	ODOUR

Table 1: List of the impact indicators computed by EQUER [5]

DESCRIPTION OF THE BUILDING UNDER STUDY

The building under study is a group of two attached houses built in 2007 in Picardy region, France (Figure1). These houses are the first "Passive-House" buildings in France [1, 8].

Figure 1: General view of the two houses (Arch.: En Act architecture, contractor: les Airelles)

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 sitting room, a bathroom and three bedrooms upstairs. Only the situation of the garage differs. These dwellings are designed for a family of four people.

Wood-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). Triple-glazed windows and insulated external doors provide good insulation and good air-tightness[1]. External venetian blinds provide solar protection during spring and summer. Thermal bridges are very low, 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 for summer cooling, with a heat recovery ventilation (average efficiency: 70%), with 5 m^2 of solar panels for solar water heating (solar fraction: 50%), and with a compact electric heat pump for the air heating and the water heating backup (annual coefficient of performance: 3).

SIMULATIONS

The real houses include no electricity production, but in the present case we assume that 76,8 m^2 of photovoltaic solar panels made of polycrystalline silicon are mounted on the roof (slope: 25°, azimuth angle: 35°E) so as to obtain a positive primary energy balance.

Three different heating solutions have been studied and compared:

- the above-mentioned electric compact heat-pump (HP),
- a wood pellet condensing boiler (CB) (average High Heating Value efficiency: 75%),
- a wood pellet Stirling engine micro-cogeneration unit (CHP), corresponding to the "Sunmachine® Pellet" pre-series version (electric power: 3 kW, thermal power: 5.5 kW).

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[1] The houses fulfill the corresponding Passivhaus criterion : the air exchange rate is inferior to 0,6 $vol.h^{-1}$at 50 Pa.

The dynamical model used to compute the wood pellet consumption of the micro-CHP unit during a year has been developed by the authors and calibrated from experimental data [9].

The meteorological data used for the simulation correspond to the local climatic zone (oceanic climate). Ventilation, occupancy and internal heat gains are modeled by scenarios.

RESULTS

The total energy needs of the houses are very low due to the implemented energy saving solutions (Table 2). The heating needs are far inferior to the domestic hot water (DHW) production needs which represent nearly half of the total building energy needs.

Energy	Use	kWh/yr	kWh/m²/yr	
Heat	Heating	2032	7.7	17.7%
	Domestic Hot Water Production	5255	19.9	45.9%
Electricity	Cooking, Lighting, other Appliances	2354	8.9	20.6%
	Ventilation	1807	6.8	15.8%
Total		*11448*	*43.4*	*100%*

Table 2: Computed energy needs of the two houses

The annual energy recovery from local renewable resources raises 6418 kWh for the PV electricity, 3227 kWh for the solar heat. The annual final energy consumption depends on the heating device (Table 3).

Heating device	Consumption *kWh/yr*			Supply *kWh/yr*	*kWh_{PE}/yr*
	Wood pellets	Electricity *heating*	Electricity *base*	Electricity *base*	Net Primary Energy Prod.
HP	0	677	4837	6418	+2805
CB	5413	0	4161	6418	+1160
CHP	9228	0	4870	7586	-1644
PE ratios *kWh_{PE}/kWh*	1.12	3.33	3.2	3.2	

Table 3: Computed energy consumption and supply of the two houses, and net primary energy production

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 3 and considering supply as saved consumption. For both heat pump and wood pellet boiler solutions the building is a positive energy building, whereas the micro-CHP solution remains primary-energy-consuming, mainly due to the limited performance of the micro-CHP unit. Nonetheless, these three assessments correspond to very high level of performance (respectively +10.6, +4.4 and -6.2 $kWh_{PE}/m^2/yr$).

A simplified analysis, based on the indoor temperatures, shows that the thermal comfort in the houses is satisfactory most of the time during the year, and especially in the summer, whatever the heating solution.

The LCA of the houses considers the material, domestic water and energy flows during their life cycle (lifetime: 80 yr). The results for the above-mentioned 12 impact indicators and for the three heating solutions lead to the identification of 4 types of impact indicators (Figure 2).

The primary energy indicator depends on the efficiency of the energy chain; the WASTE indicator depends mainly on the materials implemented in the building and not on the chosen heating device; four indicators are increased by the electricity consumption (RADWASTE, WATER, RESOURCE, GWP_{100}), mainly due to the production processes of electricity; six indicators are increased by wood combustion (ACIDIF, EUTROPH, O_3-SMOG, HUMHEALTH, ECOTOX, ODOUR).

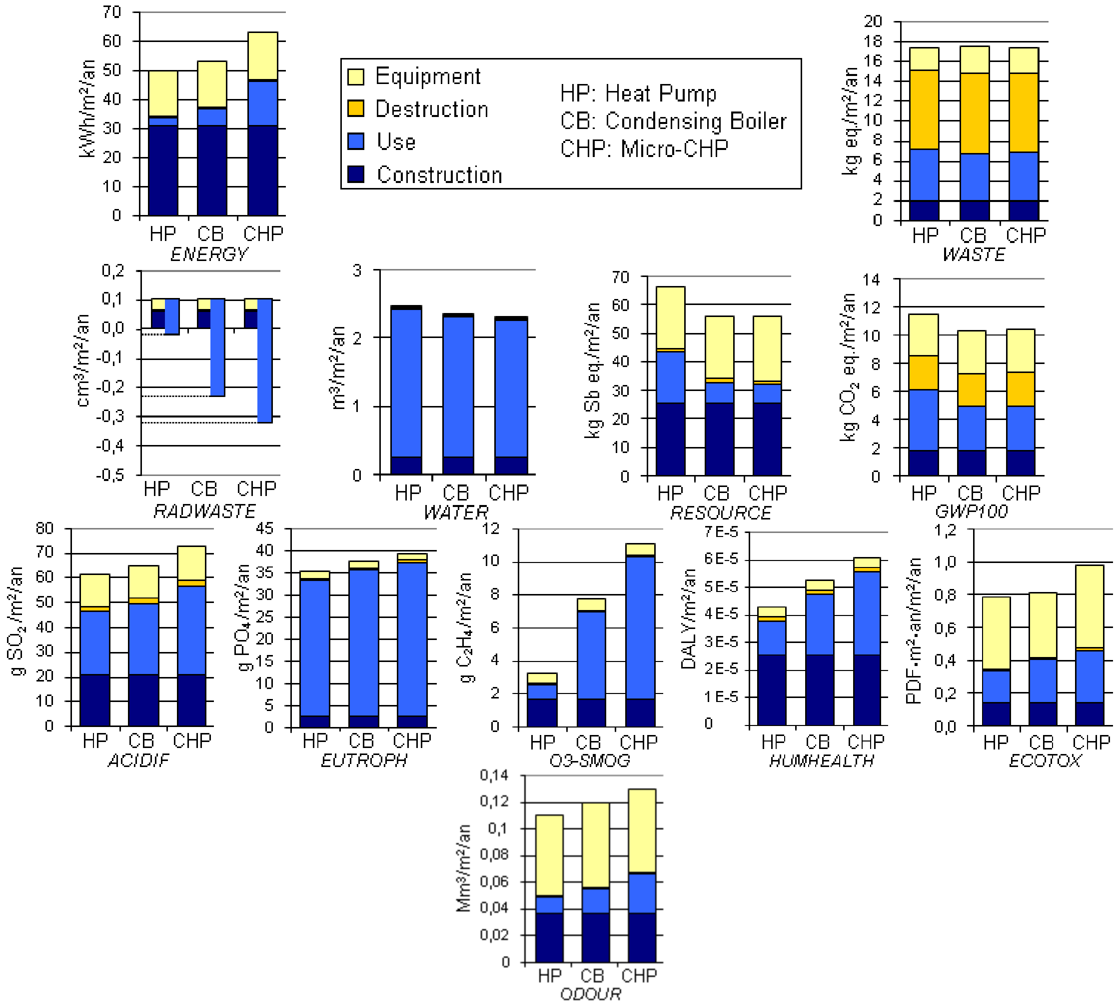

Figure 2: LCA detailed results for the two houses, for each indicator and for each phase

Discussion and Conclusion

The LCA has been applied to a positive energy building. The PEH studied here presents high energy and environmental performance, like a GWP limited to about 11 kg CO_2 eq./m^2/yr whatever the heating solution (the average value in France is about 37 kg CO_2 eq./m^2/yr [10]).

Nevertheless, in spite of a positive energy assessment, the majority of the environmental impacts remains positive during the operation phase. This is mainly due to the impacts of wood combustion or electricity production and to the domestic water consumption. Another important contribution to some impacts is induced by the equipments (solar panels, heating device, hot water tank etc.) which must be regularly renewed. The impacts of these equipments surely can be reduced, either by the improvement of their production process or by their recycling at end of life. This especially concerns PV panels which contribution to the performance of the PEH is major.

This study shows the influence of the heating device on the environmental impact of the PEH. In the French context – where about 75% of the electricity is generated by nuclear plants – none of the three solutions studied above seems optimal, but the PEH can contribute to reduce the radioactive waste production, especially if heat is not provided by a heat pump. The CB and CHP solutions reduce also the impacts on abiotic resources and greenhouse effect, but due to wood consumption, they affect the impacts linked to air and water chemical pollution. The improvement of the efficiency of the micro-CHP unit should also reduce these negative impacts.

ACKNOWLEDGEMENTS

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

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