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LIFE CYCLE ASSESSMENT AS A DESIGN AID TOOL FOR URBAN PROJECTS

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Abstract

Sustainability is now targeted in nearly all urban projects, but life cycle assessment (LCA) is generally seen as too complex, so that more qualitative approaches are preferred. Indeed, the importance of environmental problems regarding e.g. climate change, human health, biodiversity and resource depletion justifies a more precise decision making process.

A life cycle simulation tool has been developed to model urban projects including various buildings, streets, green and other public spaces, and networks (drinking water, waste water, district heating...). This tool, developed in an object oriented approach, associates dynamic building energy simulation and LCA, complemented with modules for open spaces and networks. A set of environmental indicators is evaluated, e.g. resource depletion, energy and water consumption, global warming, waste generation, toxicity. Several alternatives can be compared, constituting an urban design aid.

Continuous improvement of the tool has been performed since the 90's, expanding the boundaries from buildings to districts assessment. A dynamic model was recently introduced to take into account temporal variation of the electricity consumption in buildings and interaction with the electricity system. Results show the importance of this dynamic evaluation in the case of plus-energy buildings.

This multidisciplinary approach allows comprehensive assessment of districts, constituting a decision support in early phases of urban projects. The assessment of a project in the Greater Paris Area is presented to illustrate this integrated approach.

Keywords:

Life Cycle Assessment; Urban projects; Eco-design tool; dynamic simulation

1 INTRODUCTION

Beside stricter energy regulations, environmental consciousness is increasing in the building sector. Thermal simulation tools are now widely used to assist building designers in creating comfortable and energy-efficient buildings. In such low energy buildings, the environmental impacts of the use stages are reduced and other stages become important, particularly the fabrication of the building products. Life cycle assessment (LCA) tools have therefore been developed, according to the ISO 14040 standard. This allows low energy and plus energy buildings to be evaluated on a more comprehensive basis, accounting for the fabrication of materials and equipment like solar energy systems as well as the energy consumed and possibly exported to the grid.

Building LCA tools have been expanded to the district scale allowing a more integrated approach to be developed.

In France in 2011 almost 60 % of the total electricity production was consumed in buildings [1]. 33 % of dwellings and 25 % of office buildings are heated by electricity [2] and more than 45 % of dwellings also use electricity to produce domestic hot water [2]. This consumption is highly time-dependent, with daily, weekly and seasonal variations. For instance, electric heating induces a seasonal peak demand in winter with a high dependency on temperature, which is

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increasing every year [1]. Local production of electricity, such as photovoltaic panels on buildings roofs, also has a time-dependent production. However, standard LCA practice is based on an average annual electricity mix, neglecting this variation.

The first objective of this communication is to present the district assessment methodology through an illustrative case study. The second objective is to show how the use of a dynamic electricity mix could improve the accuracy of LCA of building and district through a focus on space heating system and the effect of photovoltaic system installation on the environmental performance of the project.

After an introduction on the overall methodology for LCA of buildings and districts, the model developed to calculate the hourly electricity mixes is exposed. The LCA methodology is then illustrated on a case study: a district development project in the Greater Paris Area. Finally we discuss limitations of the dynamic mix model and future possible developments.

2 MATERIALS AND METHODS

2.1 Buildings' LCA

Since the 1980's, several tools have been developed around the world. Thanks to research projects like REGENER [3], a common methodology basis was sketched out for buildings' LCA tools. Eight European tools were then compared in the frame of the thematic network PRESCO [4].

Impact indicator	Unit
Cumulative Energy Demand (CED)	GJ
Water consumption (W)	m^3
Abiotic Depletion Potential (ADP)	kg Sb-eq
Non-radioactive waste creation (NRW)	t eq
Radioactive Waste Creation (RW)	dm^3
Global Warming Potential (GWP)	t CO_2-eq
Acidification Potential (AP)	kg SO_2-eq
Eutrophication Potential (EP)	kg PO_4^{3-}-eq
Damage caused to ecosystems (BD)	PDF.m².yr
Damage to human health (HD)	DALY
Photochemical Oxidant Formation (smog) (POP)	kg C_2H_4-eq
Odour (O)	Mm^3

Table 1: Environmental indicators in EQUER

Linked to the dynamic building energy simulation (BES) tool COMFIE [5], the novaEQUER tool has been developed to model the life-cycle of buildings, from construction to dismantling, through utilisation and renovation stages [6,7]. It considers twelve indicators, mostly from the CML2002 and Ecoindicator 99 methods to get a comprehensive set of environmental impacts (see Table 1). It also includes an extension to urban district evaluation [8].

2.2 Electricity system simulation model

Since 2012, the French electricity transmission system operator (RTE) provides hourly production values for 10 groups of electricity production technologies (listed in Table 2).

This data has been used to reconstruct hourly electricity mixes averaging climatic and economical hazards of real years. Both electricity demand and production have been modelled. The model developed uses the same meteorological data as used for the thermal simulation of buildings. It allows evaluating buildings and district projects and their interaction with the grid in a consistent way.

Electricity production is split between dispatchable and non-dispatchable production, as indicated in Table 2. The methodological process is briefly summarised in the paragraphs below.

Electricity demand

The electricity demand is the sum of the national electricity demand, electricity needed for pumped storage capacities and external electricity demand (exports).

The national electricity demand is based on hourly, daily and monthly coefficients and a linear relation with national average ambient temperature, as shown in eq (1) below.

$$C_{nat}(h_d, d_w, m, s, T_{ext}) = P_{base} \times W_1 \times W_2 \times W_3 + ThE \times \overline{\Delta T(T_{ext})} \quad (1)$$

W1, W2 and W3 are modulation coefficients of the electricity demand depending on the hour of the day (W1), the day of the week (W2) and the month of the year (W3). The ThE coefficient represent the thermal sensitivity of the electricity consumption. Its average value for France is 2367 MW.°C^{-1} for winter (when temperature is below 15 °C) and 500 MW.°C^{-1} for summer (when temperature is above 18 °C). P_{base} is a base power load. Its value is set at 46.5 GW after identification on French 2013 data.

Electricity exports are modelled using a two layer neural network calibrated on year 2013 and using as input the nuclear plant availability, the photovoltaic and wind production and the national electricity consumption.

Pumped storage facilities mainly consume electricity at the daily minimum of national electricity demand and on week-ends. Based on these main features, a model has been identified

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on 2013 data (eq (2)). Moreover, the modelled pumped storage capacity can only consume electricity if the electricity demand is below the weekly average.

$$\mathrm{STEP_{pump}}(h_1, j_3) = A \times \left[1 - \tanh\left(-l\left(Res(h_1, j_3) - Min_{j_3}[Res(h_1, j_3)]\right)\right)\right] \quad (2)$$

A is the availability of the power plant, $Min_{j_3}[Res(h_1, j_3)]$ is the daily minimum of the residual national electricity demand. "l" is a parameter calibrated on 2012 data. Its value is 1.1E-4 MW^{-1}.

Nondispatchable production

Nondispatchable production consists of various technologies that are not able to adjust their production when a change in demand occurs.

They can be driven by local economy or municipalities needs (gas and fuel CHP, biogas, biomass waste incineration facilities) or by meteorological parameters (run-of-river hydro, wind and PV).

Gas and fuel CHP, biogas, biomass and waste incineration hourly load factors were constructed using historical data from years 2012 and 2013. Run-of-river hydro hourly load factor was built based on daily minimum of total hydraulic production from year 2007 to 2013.

The Photovoltaic load factor was estimated from radiation data and the wind power load factor was estimated from wind speed given in the meteorological data from the French building thermal regulation (RT2012). Load factors were weighted according to the installed capacity in each climatic zone included in RT2012.

Dispatchable production

Dispatchable production was estimated using a bounded and constrained optimisation model minimising cost of electricity generation on a monthly horizon.

It takes into account ramp constraints and minimal and maximal load for each group of technologies. The parameters were identified in 2013.

Name	Share in annual average mix 2014 (%)	Description
Nondispatchable		
Run-of-river / small dams	8.2	Reservoir filling duration < 200 h
Combined Heat and power (CHP) Gas / Fuel	2.4	Decentralised production, not dispatchable
Wind	3.1	1-3 MW wind turbines
REN – Thermal	1.2	Municipal waste (58 %), Biomass (19 %), Biogas (19 %)
Photovoltaic (PV)	1.1	Open ground (37 %), on-roof multi-Si systems (43 %) and small on-roof mono-Si systems (20 %)
Dispatchable		
Nuclear	77.1	Pressurised Water Reactor
Large dams	3.2	Reservoir filling duration > 200 h
Coal & Gas	2.5	Centralised power plant from coal (70 %) and gas (30 %)
Pumped storage hydro	1.2	Electricity consumption of pumped storage excluded of the inventory
Peak / Imports / Others	<0.1	Fuel power plants, fuel and gas turbines Imports: Belgium (50 %), Germany (26 %), Spain (21 %), Switzerland (2 %) and Italy (1 %)

Table 2: List of Electricity production technologies in France

Model validation

The model was validated in 2014. The mean absolute percentage error (MAPE) for the total electricity demand is 3.8 %. The MAPE for nuclear production that represents around 77 % of the total electricity production in 2014 is less than 2 %. Correlation coefficients between modelled and measured data range from 0.7 (pumped storage) to 0.99 (nuclear). Only peak load technologies are not well represented but they account for less than 0.1 % of the total production in 2014.

The model was considered to be robust enough to give a representation of hourly variation of the electricity mix for a typical meteorological year.

2.3 Case study description

The studied project includes collective residential buildings (33 124 m²), offices (44758 m²) and shops (3829 m²) on a total land area of around 40 000 m² with an estimated 1060 inhabitants, 3715 office employees and 176 shop employees. 24 % of the total area will be composed of green

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spaces. An overview of the site plan is given in fig.1.

Three buildings' envelope alternatives were assessed from this plan: a reference project following current French energy regulation (RT2012), a passive alternative (PAS) and a plus energy alternative (BEPOS). The BEPOS alternative is based on the PAS alternative, and integrates an on-roof photovoltaic system of 872 kWc. The main features of the two buildings' envelope alternatives are displayed in Table 3.

	RT2012	PAS-BEPOS
External wall	Internal insulation Concrete (16cm) Rockwool (20cm)	External insulation Concrete (16cm) Rockwool (25 cm)
Ceiling insulation	Rockwool (26cm)	Rockwool (26cm)
Floor	Concrete (20cm) Rockwool (16cm)	Concrete (20cm) Rockwool (20cm)
Intermediary floor	Concrete (20cm)	Concrete (20cm)
Glazing	Double glazing	Double glazing
Ventilation	Without heat recovery	With heat recovery (efficiency of 50 %)

Table 3: Main features of the envelope alternatives

The set point temperature for heating is 19°C when occupants are inside the buildings and 16°C otherwise. Dwellings do not have chilling systems. The set point for cooling in offices and shops is set at 26°C during opening hours (and 30°C otherwise). The average occupancy rate is 0.03 occ.m^{-2} for dwellings, 0.08 occ.m^{-2} for offices, and 0.14 occ.m^{-2} for shops.

Shading devices and opening of windows (at night in dwellings, in both alternatives) were taken into account to evaluate the cooling rate and ensure occupants' comfort.

2.4 LCA hypotheses

The LCA of the whole project was performed for the two alternatives considering a 100 year life-span, accounting for transport of districts users and domestic waste generation.

An average of a 100 km transport distance by truck was considered from the factories to the buildings' sites, 20 km from the buildings sites to incineration facilities and 2 km to landfill. The considered lifespans are 10 years for buildings' finishes, 30 years for windows and doors, 25 years for the photovoltaic system, and 100 years for the other elements and the buildings as a whole.

Environmental impact related to electricity consumption and production are evaluated at each hour of the typical meteorological year, following the methodology exposed in [9].

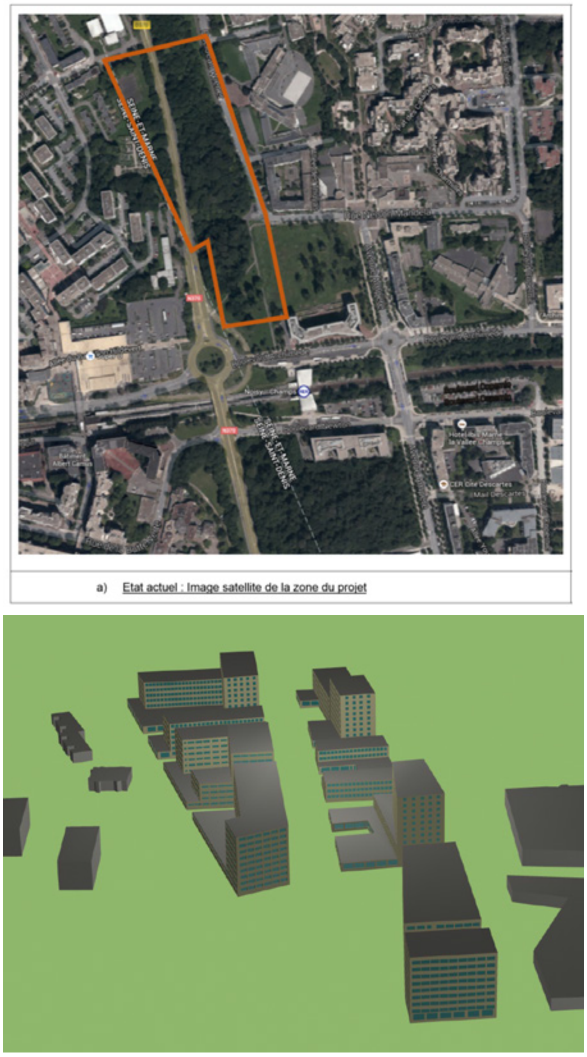

Figure 1: Overview of the district project

3 RESULTS

3.1 BES results

BES results are presented in Table 4. The heating load is relatively low in both alternatives due to high internal gains in offices.

Average results hide important disparities between the different buildings and thermal zones. For instance, considering the RT2012 alternative, heating load varies from 31 (north oriented dwellings) to 3 kWh.m^{-2}.yr^{-1} (south oriented offices) and cooling load from 1 to 7 kWh.m^{-2}.yr^{-1}.

In kWh/m²/yr	RT2012	PAS-BEPOS
Heating load	11	2
Cooling load	3	4
Hot water	7.2	7.2

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Specific electricity	19.7	19.7
Fans consumption (Ventilation)	1.8	3.4

Table 4: BES results

3.2 LCA results

Contribution analysis

Results comparing the RT2012, the PAS and the BEPOS alternatives for cumulative energy demand, global warming potential and radioactive waste generation are presented in Fig.2. The considered heating system was electric heating, a system still popular in France.

Transport and domestic waste are important contributors. For the RT2012 alternative, they represent more than 40 % of GWP for instance.

Electricity consumption (specific electricity, space cooling, space heating, water heating, and ventilation) is also a major contributor, representing 36 % of GWP and more than 80 % of CED and Rad.Waste.

The BEPOS alternative is seen as the most favourable one: its GWP impact is similar to the PAS alternative but CED and Rad.Waste indicators are respectively 14 % and 16 % lower, due to avoided electricity production from the grid thanks to the PV system.

Transport, waste and public spaces

Occupants' daily travel, domestic waste and public spaces are other neighbourhood contributors. Together they have a large contribution to the total impacts: more than 50 % of GWP, 19 % of CED and 20 % of radioactive waste generation. At the district scale, actions can be taken that affect transport (bike lanes, multimodal facilities, number of parking spots) or domestic wastes practices (collective composting, recyclable bottle collection...). They have to be included in the evaluation when studying a district level project.

Dynamic vs static electricity mix

The use of the static electricity mix generates errors regarding the impact of electricity consumption. For this project, avoided GWP due to the photovoltaic system electricity production is overestimated by 13 % when using an annual average mix instead of an hourly mix (Fig. 3). On the contrary, electrical heating impact is underestimated by more than 20 % for the RT2012 and the PAS alternative (see Fig.3).

Electric space heating contributes to 8 % of GWP, 16 % of CED and 15 % of Rad.Waste considering the RT2012 alternative (see Fig.2). It is still an important area of improvement that should not be underestimated.

Moreover, the use of an hourly mix allows evaluating peak shifting strategies. The global warming potential per kWh for electrical heating varies from 50 to 200 gCO2eq. Control strategies, particularly efficient in well-insulated buildings [10], could be implemented. They can be more precisely evaluated with the suggested model than using an annual average electricity mix.

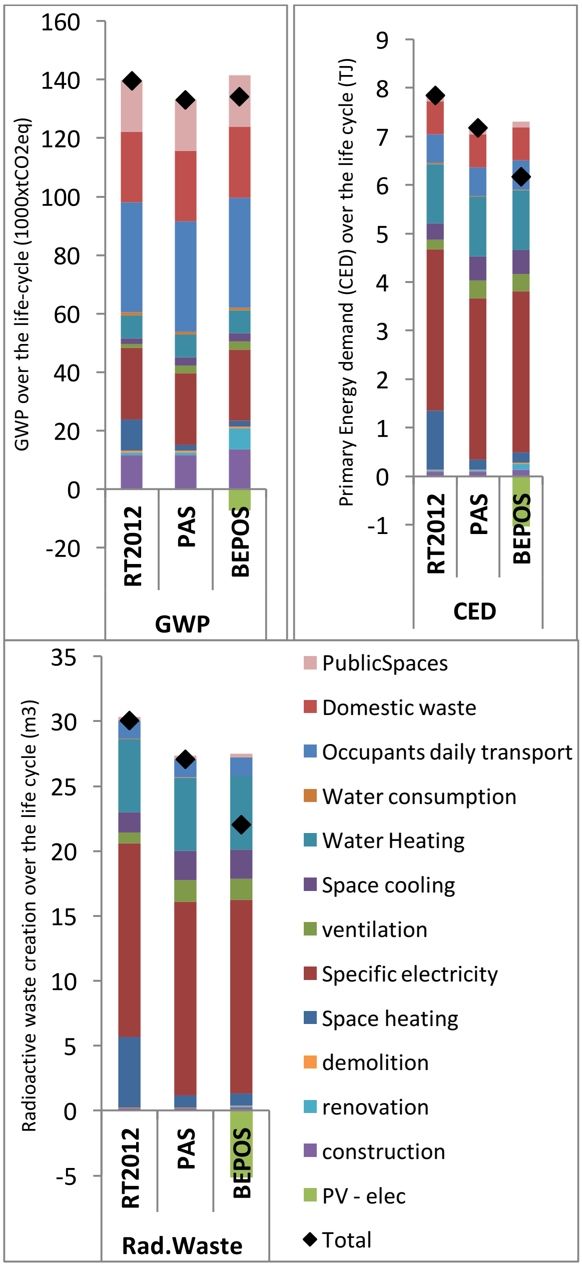

Figure 2: LCA results for the three alternatives

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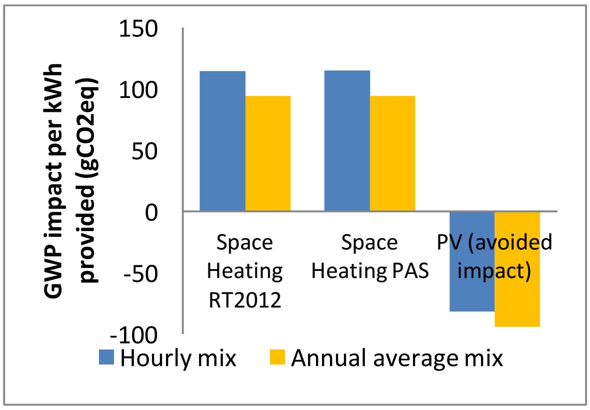

Figure 3: GWP impact of electric space heating and avoided impact of photovoltaic production using an hourly or an annual average mix.

4 DISCUSSION AND CONCLUSION

LCA tools are now available and operational to assess the environmental performance of an urban project at the district level [11].

Domestic waste treatment, occupant daily transport and public spaces have to be integrated as they can be influenced by district design and are important contributors (e.g. more than 50 % of GWP).

New developments of the novaEQUER tool regarding the hourly variation of the electricity mix allows evaluating more precisely smart and plus-energy buildings.

Current research perspectives are investigation of prospective and consequential aspects. Environmental evaluation of alternatives of a future project is meant to provide help for project designers in their decision making process. Therefore a consequential approach [12,13] using system expansion allocation and marginal suppliers for electricity and materials could be studied. Buildings and infrastructure are long lasting, e.g. 100 years or more. The electricity mix will probably change during such a life span, as shown in the prospective studies conducted by the French transmission system operator [1].

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