Considering temporal variation in the life cycle assessment of buildings, application to electricity consumption and production

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Abstract: *Existing tool for environmental impact assessment of buildings and districts according to the LCA procedure are based upon a static method, considering yearly average processes and impacts. A dynamic method has been developed in order to model the temporal variation of electricity production and allocate environmental impacts to different uses. It allows to evaluate low-energy and plus energy buildings on a more precise basis.*

Based upon data from the French electricity grid manager, the model evaluates the production mix in terms of temperatures in French climates and several periodic functions corresponding to variation frequencies identified by a Fourier analysis. In a second step, specific production mixes are derived for different uses: heating, cooling, domestic hot water, domestic appliances and office appliances.

The model has been tested on a single family passive house, allowing solar hot water and photovoltaic systems to be assessed using a dynamic method.

Dynamic Life-cycle Assessment, Buildings, Electricity production, consequential life cycle assessment

Introduction

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 hot water [2]. This consumption is highly time-dependent, from summer to winter, from day to night and from week to week-ends. Production of electricity follows this variability. For instance, electric heating induces a seasonal peak demand in winter with a high dependency to temperature, which is 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 purpose of the work presented here is to improve the precision of LCA, by integrating a dynamic electricity mix, disaggregated on different uses. The model developed to calculate the electricity mixes is first exposed. Then we explain how it was integrated in Building LCA tool. Afterwards we show implications of this modification in terms of environmental impacts assessment of buildings. Finally we discuss limitations of the model and future possible developments.

Building LCA

From the 80's, several tools have been developed around the world to evaluate environmental impacts of buildings according to the LCA method. Thanks to research projects like REGENER [3], and a common methodology basis has been sketched out for building LCA tools. Eight European tools have then been compared as part of the thematic network PRESCO [4].

One of these tools is EQUER [5], [6]. It was developed to model the life-cycle of buildings, from construction to dismantling, through utilization and renovation phase. It also includes an extension to urban district evaluation. Due to the importance of energy issues in buildings environmental balance, it is linked to a dynamic termal simulation tool, COMFIE [7].

After an analysis of sustainability objectives performed in the E-Co-Housing Project [8], it considers eleven indicators, mostly from the CML2000 and Ecoindicator 99 methods to get a comprehensive set of environmental impacts (see table 1).

Table 1:
Environmental indicators in EQUER

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 100)	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

Modelling the production of electricity

The French electricity grid manager (RTE) provides hourly production values for nuclear, hydro-electricity, gas & coal, and fuel thermal plants. At time of study, data was available from 2007 to 2009. Our model has been based upon 2008 data because this year fits the most with a typical climate (lowest temperature discrepancy compared to the average 1971-2000, according to MeteoFrance).

The electricity production changes according to the seasonal, weekly and daily variation of the consumption. Fourier analysis allows the different frequencies composing a signal to be identified. This method has therefore been applied. The main frequencies correspond to 12 h, 24 h, 168 h (i.e. one week), 4392 h (half a year, 2008 being bissextile), and 8784 h (one year). The electricity production is then expressed as a sum of periodic functions corresponding to the identified frequencies (daily, weekly, seasonal and yearly variations). Due to the importance of the electric heating in France, the production also depends on climatic conditions, and mainly external temperatures. As production data is available on a national scale, a reference temperature has been evaluated as an average between several locations (MeteoFrance data), weighted according to the corresponding population. The production P is then expressed as a function of this average temperature T_{av} and of time t:

$$P(t, T_{av}) = \sum_i (X_i(T_{av}) * \cos(w_i * t + Y_i)) + Z(T_{av}) \quad (1)$$

Where w_i are the identified frequencies.

Parameters $X_i(T_{av})$, Y_i and $Z(T_{av})$ are identified by a least square method (quasi-Newton algorithm) in order to minimize the discrepancy between calculated and measured production values. Yi are assumed constant.

The average discrepancy between calculated and measured production is 4%. The discrepancy is higher (11%) when comparing the year 2009 values (see the discussion session).

A part of the consumed electricity (around 6% of production) is imported. RTE data include hourly imported quantities from different countries: Germany, Switzerland, Spain, Italy, UK and Belgium. This has been integrated to the model, so that a complete electricity production mix is derived.

Construction of use specific electricity mixes

The total impacts of electricity production can be evaluated at each hour using the model presented above. But electricity is used for several purposes: lighting, domestic appliances, cooling, heating, tertiary uses, domestic hot water production etc. These different uses can be regarded as co-products, and different allocation methods can be applied. If electricity is consumed during a winter night both for heating and hot water, considering the same production mix would lead to account for high CO_2 emissions also for electric hot water production, though these high emissions are due to the seasonal peak induced mainly by heating. It seems therefore more relevant to differentiate the production mix according to the different uses.

A yearly constant base load mix is first identified according to the yearly minimum values of nuclear and hydro power production.This mix is used to evaluate the environmental impacts related to hot water production, the solar hot water contribution being marginal at the moment in France. Subtracting the yearly minimal production from the weekly minimal production allows a mix to be identified for heating and cooling. This mix is evaluated for each week. A correction based upon a linear approximation is applied at each hour to account for climatic variation within a week [9]. The weekly minimum production is then subtracted to the hourly production values in order to study other domestic and professional uses (i.e. other than heating, cooling and hot water). Week-end production is assumed, by approximation, to correspond to domestic uses. This allows the domestic and professional contributions to be identified. This process is applied to each production type (nuclear, hydro-power, thermal plants) so that hourly electricity production mixes are evaluated for each use type. The same grid efficiency (9% losses) is considered for all production types.

Integration in Building LCA

The output of the model described above consists of 5 different hourly mixes for the 5 uses considered adapted to a typical climatic year.

In a first approach, usages have been associated to their major variation scheme:

- Seasonal consumption : Heating and cooling
- Base load : Domestic hot water, stand-by consumption, cold appliances
- Daily consumption : Other Domestic appliances
- Weekly consumption : Professional appliances
- Average hourly mix (not disaggregated by use), eg. for a local electricity production

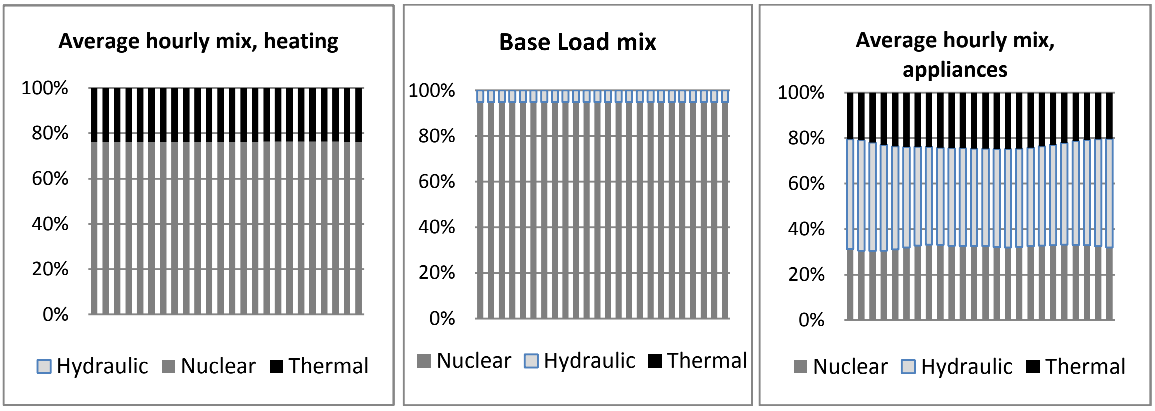

Figure 1: Results of the model presented as average hourly mixes

In order to be integrated in the building LCA tool EQUER, the model has been recalibrated on a typical year (mean temperature over twenty years), so that it is compatible with the simulation tool COMFIE, in terms of temperature used to evaluate the heating and cooling loads, provided as hourly values. The energy consumed for appliances generally contributes to heat the building, and this heat gain is defined in an hourly scenario in COMFIE.

Dynamic LCA seems particularly adapted to assess Plus energy buildings because local production is generally variable (e.G. in terms of solar radiation or wind).

Local electricity production is firstly consumed in the building. The allocation to each use is proportional to its share in total electricity consumption at each hour. Residual production is then evaluated as exported to the grid and corresponds to an avoided grid production evaluated using the general hourly mix at the same hour. The corresponding avoided impacts are subtracted from the total impacts of the building. Impacts linked with the production of equipments (Production and transport of photovoltaic modules for instance) are entirely allocated to the building.

Case study

This model has been tested on a case study. A family house has been chosen, situated on the Incas platform, near Chambery [10]. It was built to respect the passive house standard. The heated floor area is 90m².

Figure 2: One of the INCAs House, in Chambéry [10]

Using the thermal dynamic simulation tool COMFIE, the calculated heating load (19°C temperature set point) is 18 kWh/m^2/year.

Two renewable energy systems, added to a "base" house, have been evaluated using the annual average and hourly electricity mix models:

- 4m² of solar thermal panels, facing south, 71.7° slope
- 39.3 m² of polycrystalline photovoltaic Si panels, facing south and with 26.5° slope

Electric air heating is used for space heating. Hot water is produced by an electric hot water tank. The annual consumption for other uses (lighting, ventilation, domestic appliances) is set to 2700kWh; corresponding to an average consumption per household in Europe [11]. Final energy consumption for each use satisfied by electricity is reported in the following table.

Table 2:
Annual final consumption and production of electricity

	Space heating (kWh)	Water heating (kWh)	Specific electricity (kWh)	PV Electricity production (kWh)
Base	1790	2544	2700	0
Base+Solar thermal (SolTh)	1790	551	2700	0
Base+PV (PV)	1790	2544	2700	5021
Base+ SolarThermal+PV (SolThPV)	1790	551	2700	5021

Regarding life cycle assessment, fabrication of materials is evaluated considering a 5% surplus added in order to account for on-site processes, broken elements and purchased quantities. An average 100 km transport distance by truck is considered from the factories to the building site, 20 km from the building site to incineration facilities and 2 km to landfill.

Life spans considered are 10 years for building finishes, 30 years for windows and doors and 80 years for the other elements and the whole building. The photovoltaic system has been evaluated with a 25 years lifespan and the thermal solar panels with a 20 years lifespan. At end-of-life, all demolition waste is assumed to be landfilled. 4 inhabitants are considered, consuming each 100 l of cold water and 40 l of hot water (at 50°C) per day.

As the objective is to study impacts related to the electricity consumed in the building, domestic waste management and daily mobility of inhabitants are not included. We have used Ecoinvent 2010 database [12] for the life-cycle inventory data.

Results

Life-cycle impacts have been calculated for the base case and the three alternatives. After normalization procedure, results for photochemical Oxidant Formation and damaged caused to ecosystem have been removed as all studied systems had a very small contribution in both of these impacts.

The following graphs show for each alternative the relative discrepancy between a calculation using a yearly average mix and a use-specific hourly mix:

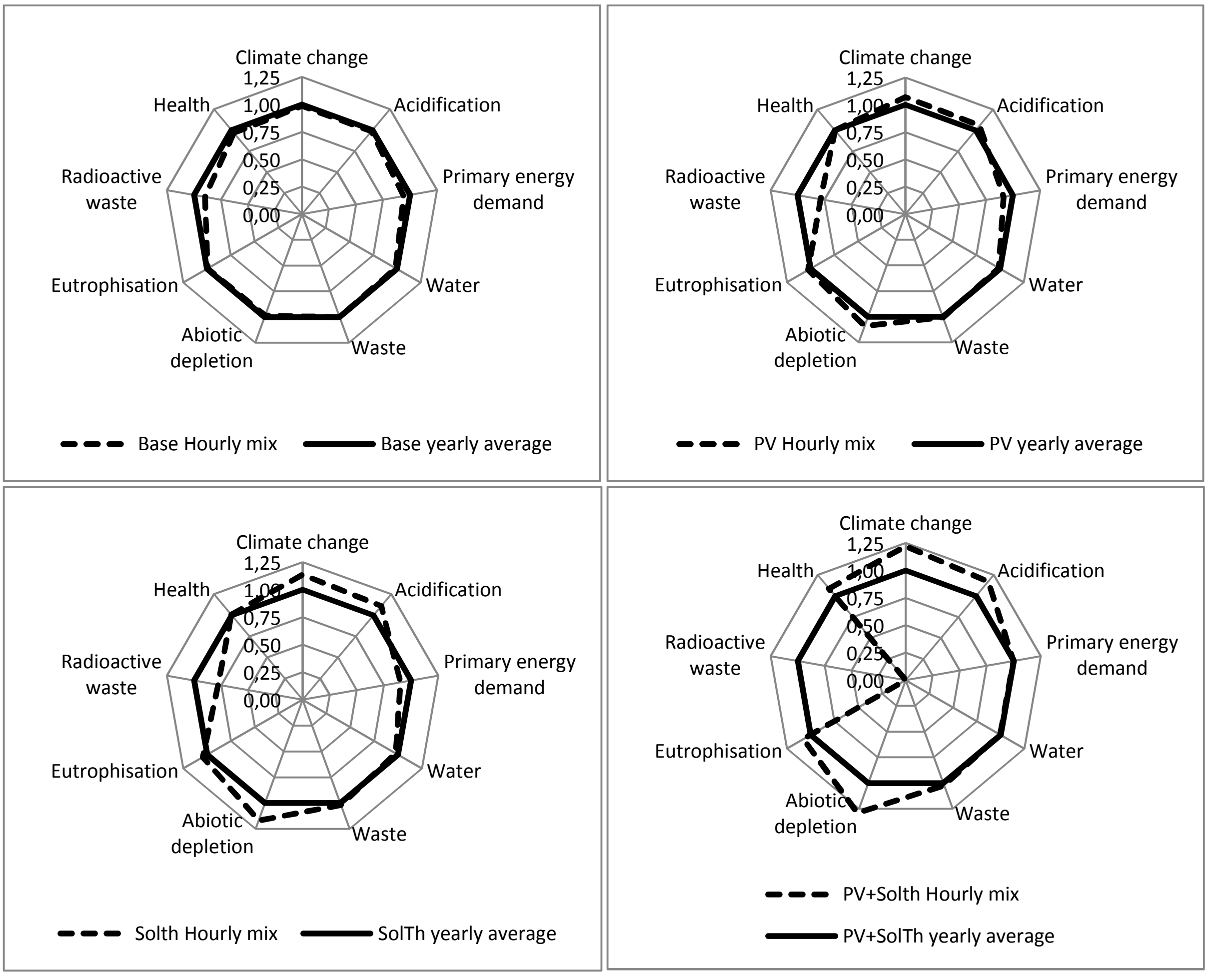

Figure 3: Relative discrepancy between a yearly averaged mix and a use-specific hourly mix

Using the hourly mix method tends to increase environmental impacts related to thermal electricity generation technologies (Climate and Resources for instance) of more than 7% (and up to 30%) and decreases environmental impacts related to nuclear production (Primary Energy demand and Radioactive waste). Only base case result show small differencies between the two methods. Results thus indicate that the amount of thermal technologies used to generate this electricity is higher than what is suggested using an annual mix. Differencies are the highest for the alternative integrating thermal solar panels, which is explained by the base load mix (nuclear and hydraulic power), associated with water heating.

Discussion

The results show how important it is to consider time-variation in energy consumption and production, especially when assessing low and plus-energy buildings.

The model has been calibrated on the year 2008 and tested on 2008 and 2009. At the time of development, it was the only years for which detailed data were available. The model is currently being updated since new detailed datais now available for the years 2012 and 2013. Economic parameters are not included. As an example, in 2009 in France, the economic crisis has had a large influence on electricity consumed by industry. The decrease of electricity consumption from industry has made nuclear capacity available for other uses. This is one explanation of the discrepancy between results of the model and measured electricity production in 2009. A larger period of study may reduce discrepancy due to economic variations.

The model has shown difficulties to treat extreme weather events and intermediate season when dependency to temperature is lower. Furthermore it only takes into account temperature but it would be useful to integrate a solar radiation parameter. The model is based on two main parameters: temperatures and frequencies of uses. However, these two parameters are not completely independent, which means that a part of variation linked with temperatures is allocated to frequencies. The reference temperature is calculated on the basis of three meteorological locations in France. This number could be increased, e.g. the grid manager (RTE) uses 32 locations in its model. There is work in progress to build up a new reference temperature based on 8 locations. Holidays are not taken into account, which introduces some singularity neglected by the model.

Future evolution of the mix (planned dismanling of obsolete plants for instance, planned construction of new capacities) has not been taken into account. This is of importance considering that average lifespan of buildings is around 80 years but it is also very uncertain. Therefore LCA results are more reliable for short term periods, e.g. dividing the total impacts by the duration of the period provides yearly impacts and this value is more reliable for the next years than for a far future.

Consequential LCA is defined as a modeling technique aiming at evaluating consequences of a decision (Earles et Halog 2011; Ekvall et Weidema 2004; [13]. This method is of great interest when feedback loops of important magnitude occur between the studied system (here a building or urban settlement) and background processes (e.g. electricity production). The study presented here is a first step towards integration of consequential parameters in life cycle assessment of buildings. After increasing the robustness of the model and integrating new dataset available, further steps may include feedback loops such as modification of the general mix because of the influence of buildings (short-term, utilization of installed capacities), scenarios integration (mid or long-term, influence on investment on new capacities), and economic parameters (electricity market merit order, elasticity).

Conclusion and perspective

Choosing an hourly or annual production mix model to perform building life cycle assessment has a large influence on impact evaluation. Technologies such as photovoltaic modules, heat pumps, cogeneration, solar domestic hot water systems, or new control strategies influence the electricity consumption and production over time. Using an annual model is therefore not precise, and life-cycle simulation is more adapted.

A consequential LCA method could be further developed to better understand feedback loops mechanisms between the building sector and the overall electricity production system. Economic mechanisms, resources constraints or scenarios may be added. This would allow a better understanding of short and long-term environmental consequences of electricity consumption, and more globally improve the reliability of building eco-design tools.

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