

EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF BUILDINGS USING DYNAMIC LIFE CYCLE SIMULATION

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ABSTRACT

A building life cycle simulation tool has been developed and linked to thermal simulation, allowing energy use and other environmental impacts to be evaluated.

Existing building LCA tools are based upon a static method, considering yearly average processes and impacts. A dynamic method has been developed here in order to model the time variation of electricity production and allocate environmental impacts to different uses.

Results on a case study show an increase of environmental impacts up to 40% compared to the common static method. As a perspective, consequential LCA would be relevant to evaluate environmental consequences of technologies like electrical heating or heat pumps.

INTRODUCTION

Aside with stricter energy regulations, environmental consciousness is increasing in the building sector. Thermal simulation tools are now widely used to assist building designers in creating comfy and energy-efficient buildings. In such low energy buildings, the environmental impacts of the use phase are reduced and other phases become important, particularly the fabrication of the building products. LCA tools have therefore been developed, according to the ISO 14040 standard. This allows low energy and plus energy building 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.

In France in 2011 almost 60% of the total electricity production was consumed in buildings (RTE 2012). 33% of dwellings and 25% of office buildings are heated by electricity (ADEME 2012) and more than 45% of dwellings also use electricity to produce hot water (ADEME 2012). 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 (RTE 2012). 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 was to integrate 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. 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. Thanks to research projects like REGENER (Peuportier, Kohler, and Boonstra 1997), 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 (Peuportier et al. 2004).

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.m ² .yr
Damage to human health (HD)	DALY
Photochemical Oxidant Formation (smog) (POP)	kg C ₂ H ₄ -eq
Odour (O)	Mm ³

Linked to the thermal dynamical simulation tool COMFIE (Peuportier and Sommereux Blanc 1990),

the EQUER tool was developed to model the life-cycle of buildings, from construction to dismantling, through utilization and renovation phase (Polster et al. 1996; Peuportier, Thiers, et Guiavarch 2013). It considers twelve indicators, mostly from the CML2000 and Ecoindicator 99 methods to get a comprehensive set of environmental impacts (see table 1). It also includes an extension to urban district evaluation (Popovici 2005).

CONSTRUCTION OF HOURLY AND USE SPECIFIC ELECTRICITY MIXES

Modeling the production of electricity thanks to Fourier analysis

The French electricity grid manager (RTE) provides hourly production values for nuclear, hydro-electricity, gas, coal, fuel thermal plants, and other types. Only production units larger than 20 MW are accounted for. Gas and coal productions are grouped due to the low number of gas thermal plants: the gas contribution will be provided when this number will be larger than 3. 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 MétéoFrance).

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 discrete Fourier transform has been used (Fast Fourier Transform algorithm) since the signal is defined by discrete hourly production values.

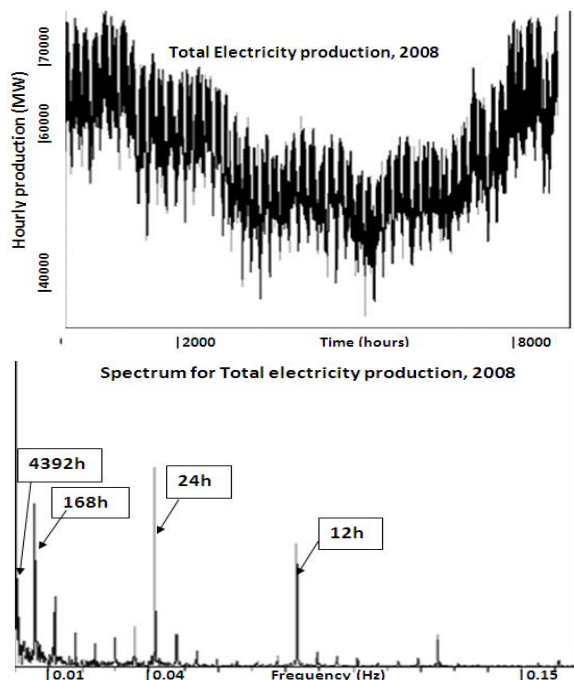


Figure 1: Electricity production curve and frequencies obtained by Fourier analysis

The result is shown on Fig.1: the main frequencies correspond to 12 h, 24 h, 48 h, 168 h (i.e. one week), 4392 h (half a year, 2008 being bissextile), and 8784 h (one year).

The model is based upon the Fourier analysis presented above: the electricity production is expressed as a sum of periodic functions corresponding to the identified frequencies (daily, weekly, seasonal and yearly variations). Due to the importance of the heating use, 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 (MétéoFrance 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:

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

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. Y_i are assumed constant. Linear functions are considered for $X_i(T_{av})$ and $Z(T_{av})$, except for the thermal production. Previous studies have shown that inertia phenomena may occur in such productions systems (Dordonnat 2009), therefore $X_i(T_{av})$ and $Z(T_{av})$ include terms depending on T_{av}^2 and T_{48} , average external temperature over the 48 preceding and following hours:

$$X_i(T_{av}) = A_i * T_{av}^2 + B_i * T_{av} + C_i * T_{48} + D \quad (2)$$

$$Z(T_{av}) = E * T_{av}^2 + F * T_{av} + G * T_{48} + H \quad (3)$$

Calculated and measured production values are shown on Figure 2: the global trend is consistent (average discrepancy of 4%).

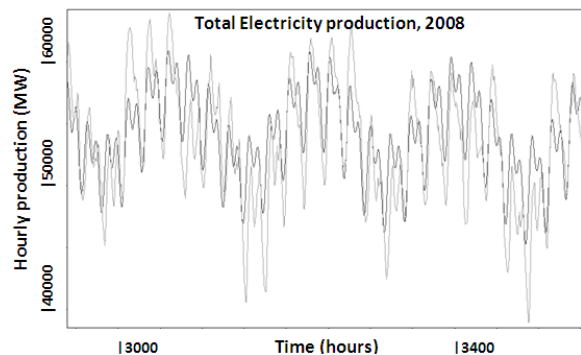


Figure 2: Comparison between measured (light grey) and calculated (dark) production values

The discrepancy is higher (11%) when comparing the year 2009 values (see the discussion section).

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

Impact Allocation model

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 impact 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 CO₂ emissions also for electric hot water production, though these high emissions are due to the seasonal peak induced mainly by the heating use. It seems therefore more precise to differentiate the production mix according to the different uses.

Assuming that the weekly minimum consumption (week-end nights) is related to heating, cooling and hot water, these 52 weekly values are used in a first step to identify production mixes for these three uses. A yearly constant mix is first identified according to the yearly minimum values of nuclear and hydro-power production, see next figure.

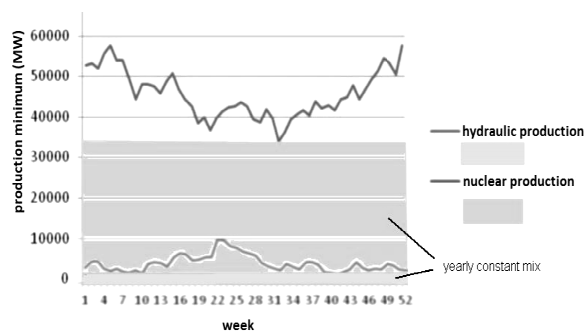


Figure 3: Identification of a yearly constant electricity production mix

This mix is used to evaluate the environmental impacts related to hot water production, the solar hot water contribution being marginal at the moment. The production values defining the mix also include other consumption types (industrial uses ...), not relevant in our study, but in a first approach a unique category is considered for all that is supposed to be "yearly" constant. 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 approach is applied at each hour to account for climatic variation within a week

(Peuportier et Herfray 2012). 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, as illustrated in Fig. 4.

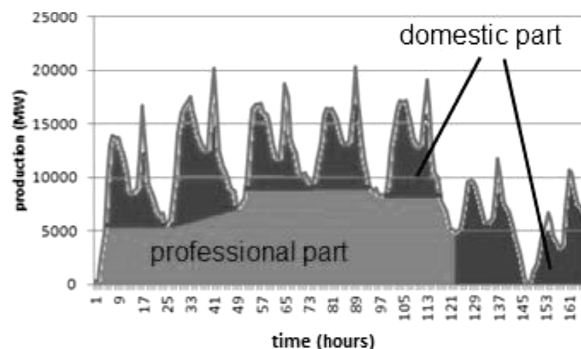


Figure 4: Schematic principle of the identification of domestic (dark) and professional (light) contribution

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 hourly production quantity for each production mean being considered as the sum of all specific production corresponding to each use category. The same grid efficiency is considered for all production types (9% losses).

INTEGRATION IN BUILDING LCA

The output of the model described above consists of 5 different hourly mix adapted to a typical year.

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

1. Seasonal consumption : Heating and cooling
2. Base load : Domestic hot water
3. Daily consumption : Domestic appliances
4. Weekly consumption : Professional appliances
5. Average hourly mix (not disaggregated by use), eg. for a local electricity production

Figure 5 shows examples of the model results aggregated on an hourly basis. The base load mix is constituted of nuclear and hydraulic (run-of water turbine) which are the main base load technologies feeding the French grid. The seasonal mix is based on nuclear and thermal plants: nuclear plants are seasonally adjusted to cover the overall increase of electricity demand in winter, but the climatic dependency is covered by coal and gas mainly. The share of hydraulic production is higher in daily and weekly mixes. This corresponds to hydroelectricity from dams which is the most reactive technology available. However, the amount available is not sufficient to cover the whole demand so that thermal plants fill the gap.

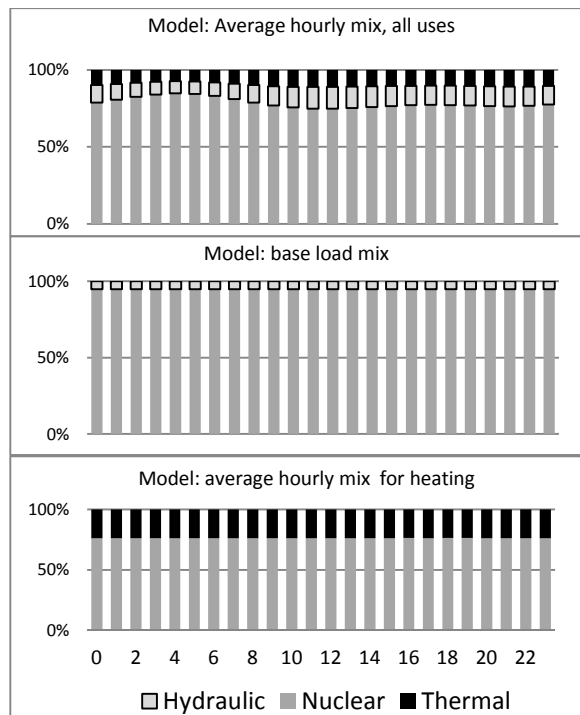


Figure 5: Results of the model presented as aggregated daily mixes

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.

To implement the mixes presented above in the LCA tool, we have to produce hourly consumption data for each use. Heating and cooling hourly consumption are provided by the thermal simulation tool COMFIE for each thermal zone.

When solar thermal panels are used, the extra electricity demand is given hour by hour in an output file of COMFIE. If no solar panels are installed, the global electricity consumption for water heating is calculated and homogeneously allocated to off-peak hour (from 10pm to 7am). This corresponds to the main technology actually used in France. The energy consumption depends on location (cold water temperature), number of people in the buildings, amount of hot water per person and hot water temperature (50°C). Grid and equipment losses are integrated.

The energy consumed for appliances generally contributes to heat the building, and this heat gain is defined in an hourly scenario in COMFIE. The EQUER interface allows the user to account for an additional electric consumption on an annual aggregated basis. This additional consumption is dispatched on hours of the day according to the hourly scenario provided by COMFIE.

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 panels for instance) are entirely allocated to the building. We do not consider a part being allocated to a potential user of the electricity production located outside the building parcel because the decision maker is the person who decides to integrate the PV system in the building: it is useful to help this person balancing avoided impacts resulting from electricity exportation and impacts resulting from the manufacture of the photovoltaic system.

In a first step of the algorithm, hourly electricity consumption patterns are defined, zone by zone and by use.

In a second step, the local electricity production is subtracted from each use, proportionally to the share of this use (at the hour considered) in the total electricity consumption.

Residual electricity consumption is evaluated using the mix associated to the considered use to calculate the share of each technology in its production (thermal, nuclear or hydraulic).

In a third step, residual production of local electricity is evaluated by the avoided impacts method. Each kWh of local electricity produced is considered as kWh not produced by the global mix of production, which reduces total environmental impacts.

CASE STUDY

This model has been tested on a case study. A simple family house has been chosen in this first step (Incas platform, near Chambéry). More details on Incas house can be found in (Spitz et al. 2012). It was built to respect the passive house standard. The heated floor area is 90m².

Using the thermal dynamical simulation tool COMFIE, the calculated heating load (19°C temperature set point) is 18 kWh/m²/year and the cooling load (26°C set point) is 4 kWh/m²/year.

Three renewable energy systems have been evaluated using the annual average and hourly electricity mix models:

1. 8m² of solar thermal panels, facing south, 71.7° slope
2. 39.3 m² of polycrystalline photovoltaic panels, facing south and with 26.5° slope
3. A wood cogeneration system for heating, with a global efficiency of 77,7%. We consider that for 1kWh of heat, 0,23 kWh of electricity is generated.

Electric air heating is used for space heating except for the “Cogeneration” alternative. 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 France (ADEME).

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.

For end-of-life, we simply assumed that all demolition waste is 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 (Ecoinvent 2010) for evaluation of environmental impacts.

RESULTS

Even if energy demand was reduced in this dwelling compared to an average dwelling in France, the use phase is still a major contributor to environmental impacts as shown on figure 6.

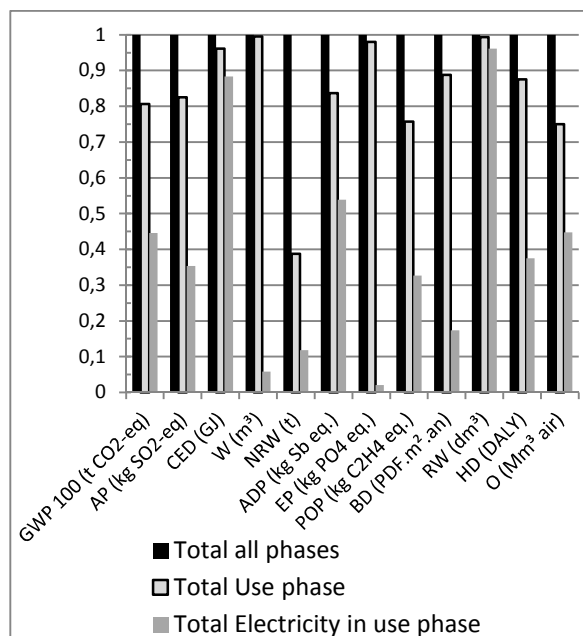


Figure 6: Significance of Use phase and Electricity consumption: Base case, annual mix.

Electricity use alone contributes for more than 30% of total for most environmental impacts (Water consumption, Non radioactive waste creation, Eutrophication potential and Biodiversity damage excepted). Similar calculation performed using the hourly mix model shows the same patterns, with slightly higher contribution of the use phase.

Evaluation of the INCAS House

Differences between the two methods are significant (figure 7): 40% discrepancy for abiotic depletion potential and global warming potential and 20% for radioactive waste production.

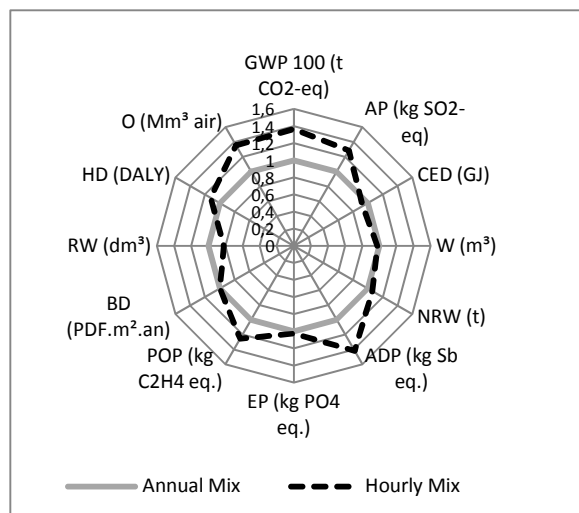


Figure 7: Comparison of LCA results using the annual and hourly model

Renewable energy systems reduce most environmental impacts, but production processes may increase indicators related to health and biodiversity. Balancing advantages and drawback is difficult because indicators are expressed in different units. Normalisation has been integrated in LCA in order to transform all indicators using the same unit: 1 equivalent person year. For instance if the average CO₂ emissions is 10t per person and per year and if 1000t CO₂ are emitted over the life cycle of the studied building, the corresponding normalized impact will be 100 eq person.year. The normalisation factors considered in this study are shown in table 2.

In our case, normalized values are very small for biodiversity and smog indicators, meaning that buildings are small contributors to these impacts. Therefore, they will not be included in the following graphs.

Table 2:
Normalization factors per person per year

Impacts	Value	Date	Source	
GWP 100 (t CO₂-eq)	8,68	1997	CITEPA	France
AP (kg SO₂-eq)	62,3	1997	CITEPA	France
CED (GJ)	177,87	1999	RECORD	France
W (m³)	339	1997	IFEN	France
NRW (t)	10,4	1997	ADEME	France
ADP (kg Sb eq.)	32,6	2001	Guinée 2001	Europe
EP (kg PO₄³⁻ eq.)	38,1	1997	IFEN	France
POP (kg C₂H₄ eq.)	19,7	1997	CITEPA	France
BD (PDF.m².an)	13700	2005	Jolliet 2005	Europe
RW (dm³)	0,51	1997	ANDRA	France
HD (DALY)	0,0068	2005	Jolliet 2005	Europe

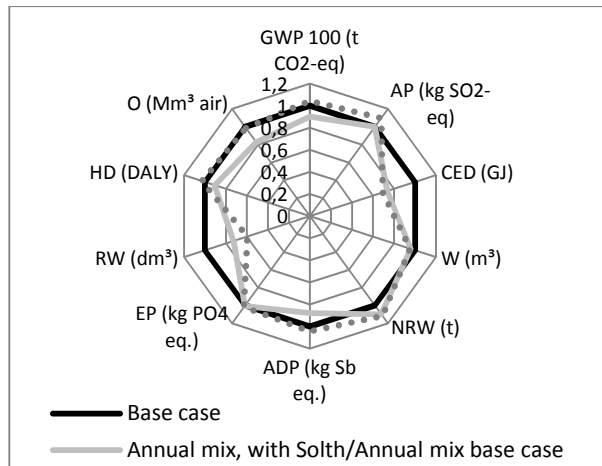


Figure 8: Evaluation of the INCAS house with the thermal solar system using the annual and hourly models

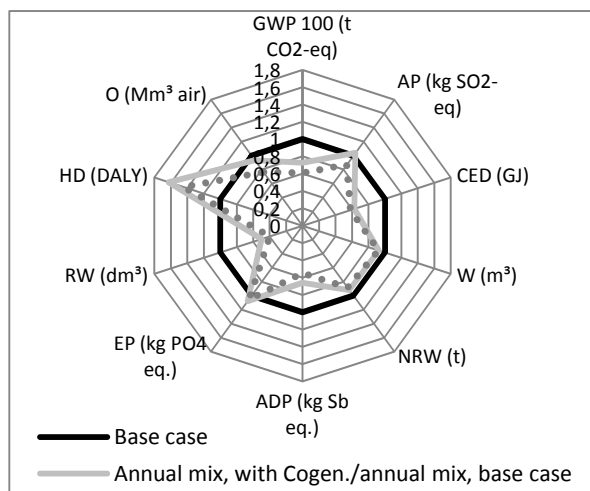


Figure 9: Evaluation of the INCAS house with the cogeneration system using the annual and hourly models

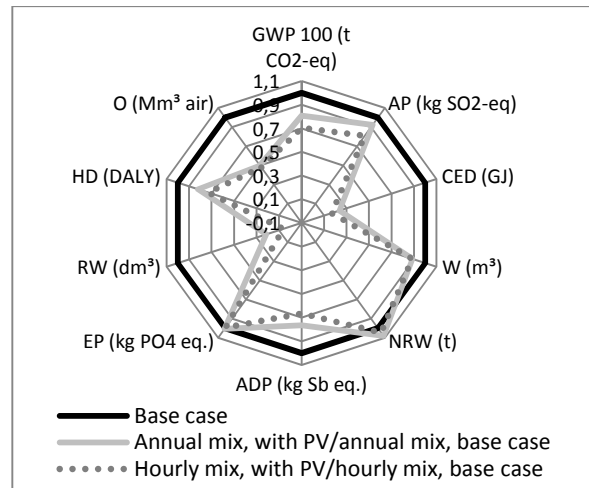


Figure 10: Evaluation of the INCAS house with the photovoltaic system using the annual and hourly models

Figures 8, 9 and 10 show how the normalized impacts of the house with and without the 3 integrated renewable energy systems, calculated using the 2 models.

The solar thermal system being used for water heating, which is considered in the model as a base load use, its environmental benefit is small using the hourly method, partly offset by environmental impacts related to the production of the collectors, except for radioactive waste and cumulative energy demand (figure 8).

Health damage is higher with a cogeneration system using both methods due to wood combustion emissions but the difference is smaller using the hourly model (figure 9). The cogeneration system produces electricity when the heating load is high, i.e. during peak demand so that the avoided impacts are higher (see also next section).

Integrating photovoltaic modules allow environmental impacts to be reduced, this reduction being larger using the hourly model (figure 10).

Photovoltaic and cogeneration electricity production

Cogeneration and photovoltaic systems can be seen as complementary technologies. Maximum daily production of photovoltaic modules appears usually at 12am. PV production is also higher in summer. On the other hand, cogeneration systems in buildings usually fit heating demand so that they produce more electricity in winter. It is seen by some researchers as a solution to reduce local blackout risk on electricity grid (Vuillecard et al. 2011).

Exported electricity produced by photovoltaic or cogeneration systems replaces standard technologies, and the corresponding avoided impacts are evaluated. Standard technologies have been identified at each hour using the electricity mix presented above, and this hourly mix model is compared to the average annual mix in fig. 11.

The use of an annual average mix underestimates the amount of electricity from thermal plants offset thanks to PV or cogeneration systems.

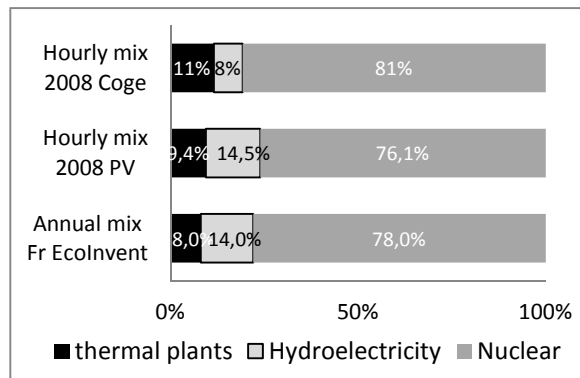


Figure 11 : comparison of the hourly mix and the annual average

As we have seen on the case study results, this has direct consequences on environmental assessment for these technologies.

DISCUSSION

The results show how important it is to consider time-variation in energy consumption and production. We can see differences up to 40% for some impacts on case studies. Using simulations instead of constant annual average is therefore justified.

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. Collecting data on a longer time period would improve robustness of the model. Moreover, 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 high 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.

Holidays are not taken into account. This introduces singularity neglected by the model.

Associating uses with temporal variation patterns could be refined; e.g. stand by consumption could be associated to a yearly constant mix instead of domestic or professional patterns.

Future evolution of the mix (planned closing 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 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 modelling technique aiming at evaluating consequences of a decision (Earles and Halog 2011; Ekvall and Weidema 2004; Zamagni et al. 2012). This method is of great interest when feedback loops of important magnitude occur between the studied system and background processes (e.g. electricity production). The study performed here is a first step towards integration of consequential parameters in life cycle assessment of buildings. Providing an hourly production mix can still be classified as attributional LCA. However, allocating impacts to each use implies to relate a use to a specific technology implying that the mix is a consequence of the use. This is a point of view similar to the marginal technology concept, which is at the basis of the consequential approach (Mathiesen, Münster, and Fruergaard 2009; Lund et al. 2010). After increasing the robustness of the model, further steps may include feedback loops such as modification of the general mix because of the influence of buildings (short-term, utilisation of installed capacities), scenarios integration (mid or long-term, influence on investment on new capacities), and economic parameters (electricity market merit order, elasticity).

CONCLUSION

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 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.

NOMENCLATURE

$P(t, T_{av})$: electricity production in terms of time t and average temperature T_{av} .

w_i : identified frequencies of electricity production

T_{48} : average temperature over the 48 preceding and following hours

$X_i(T_{av}), Z(T_{av})$: Calculated temperature-related parameters of electricity production

Y_i : constant parameter, not temperature dependent

A, B, C, D, E, F, G, H : parameters identified by a least-square method.

ACKNOWLEDGEMENT

This work follows research initiated by Gregory Herfray during his PHD thesis and was performed in the frame of the research Chair ParisTech VINCI "Ecodesign of buildings and infrastructure".

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