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Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house

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ABSTRACT

The development of on-site renewable energy production and demand management in buildings calls for a deeper understanding of the interaction between building operation and the electricity grid. Electricity consumption in buildings varies in terms of seasons (heating and cooling), day of the week (professional activities) and hour of the day, which is also the case of on-site electricity production (e.g. photovoltaic systems). Centralised electricity production varies as well according to the demand (e.g. during peak hours). This research aims at improving the evaluation of potential environmental impacts of an energy efficient house attributable to electricity consumption and production by taking into account the temporal variation of the electricity production. Electricity end-uses and on-site electricity production were evaluated on an hourly basis in the case of an energy-efficient house. Another objective was to investigate the sources of errors in the assessment. Life cycle assessment was used to evaluate potential environmental impacts based on electricity production data for the year 2013 in France. Results were compared using an annual average electricity supply mix versus hourly data. This case study demonstrates that the use of an annual average mix instead of hourly mix data can lead to underestimation of potential impacts up to 39% for Abiotic Depletion Potential (ADP) and 36% for Global warming potential (GWP) when combining all end-uses. Increase of GWP and ADP when using hourly mix data is mainly explained by higher share of coal and gas power plant in the electricity mix in winter. This coincides with a higher electricity consumption of the studied house in this season due to space heating, electric back-up of the solar water heating system and a lower onsite production (photovoltaic system).

1. Introduction

In 2010, the residential and service sector accounted for around half of the world global electricity consumption, according to the IEA (2011). In countries with a high penetration of electrical heating, such as France, this share can go up to 68% (INSEE, 2012). Electricity-related impacts are important in the environmental assessment of buildings. The electricity consumption in buildings is highly variable, with seasonal variation due to space heating or cooling, weekly variation due to economic activities and daily variation due to home appliances and lighting. As a direct consequence, the electricity production mix is also variable because power generation technologies modulate in order to comply with the demand.

Electricity generation has been at the subject of numerous LCA studies investigating renewable energy (Pehnt, 2006; VarunBhat and Prakash, 2009; Zhai and Williams, 2010), nuclear power plants (Lenzen, 2008), and fossil fuel power plants (O'Donoughue et al., 2014). The choice of an electricity mix for an LCA study is a frequent challenge for the analyst (Dones et al., 1998; Frischknecht and Stucki, 2010). Specific seminars with both academic and operational experts have addressed this recurrent issue in LCA (Soimakallio et al., 2011). Recent literature reviews exposed the complexity of electricity mix assessment, with issues related to temporal differentiation, prospective study, attributional or consequential approaches (Soimakallio et al., 2011; Rehberger and Hiete, 2015).

Current practice in LCA is to use an annual average electricity supply mix based on a documented reference year (Itten et al., 2012a). This practice disregards the temporal variability of electricity production within a year. Development of on-site electricity generation such as photovoltaic systems integrated on building roofs and cogeneration units or innovative control in buildings (e.g. load shifting) increases the need for integration of electricity mix temporal variation in LCA. In a larger perspective, temporal

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differentiation is currently a prominent issue in LCA (Beloin-Saint-Pierre et al., 2013; Shah and Ries, 2009; Collinge, 2013).

This paper first intends to evaluate the magnitude of errors occurring when a yearly average mix is used instead of a temporally varying mix (hourly mix in this study). It follows research initiated by Herfray and Peuportier (Peuportier and Herfray, 2012) on dynamic LCA, and aligns with the framework defined for dynamic LCA by Collinge et al. (2013). Our second objective is to provide recommendations and insights for further research on this theme, towards the development of use-specific electricity mixes and consequential LCA.

The methodology is first presented. It explains how life cycle impact assessment of electricity supply was evaluated with two distinct methodologies. The first methodology represents current practice and uses a yearly average supply mix. The second evaluates impact assessment of the electricity supply at each hour of the year. A specific procedure was developed for impact assessment of one kWh supplied at low voltage level (below 1 kV). A case study is presented which compares the two approaches to evaluate potential environmental impacts related to electricity consumption and production in an energy-efficient single family house located in France. As detailed electricity production data are now freely available from the French network operator (RTE), we were able to compare precisely the discrepancy between the use of hourly mix data and the use of an annual average mix in building LCA for the year 2013 in France. Due to the availability of precise data for year 2013, fourteen production categories were considered in this paper. Limitations, uncertainties and recommendations are addressed in the discussion section followed by research perspectives.

2. Materials and methods

2.1. Life cycle assessment data for electricity generation technologies

The version 3.1 of the ecoinvent database (Frischknecht and Rebitzer, 2005; Treyer and Bauer, 2014) provides life cycle inventories (i.e. quantities of raw materials used, pollutants emitted to the air, water and ground) corresponding to 1 kWh of electricity produced by different technologies at high voltage level (above 24 kV). It also includes inventories for grid infrastructure (transmission and distribution network).

Life cycle impacts of 1 kWh delivered to the low voltage level (below 1 kV) by a given technology, I_i, include impacts related to electricity production using the technology and impacts related to the network infrastructure, as expressed in Equation (1).

$$I_i = C_f \times (ICV_i \times (1 + l) + ICV_{network,i}) \quad (1)$$

C_f is the characterisation factor matrix, ICV_{tech} is the life cycle inventory of a kWh produced by the technology “i”, $ICV_{network,i}$ is the life cycle inventory of electricity network infrastructure per kWh supplied in France and l is the level of losses. l represents electricity lost during transmission in the transport network (national and interconnection high voltage network), conversion and transmission in the distribution network (national low and medium voltage network, below 24 kV). 3% losses were accounted for the transport network and 6% losses for the distribution network according to data from the networks operators (RTE; ERDF). Twelve indicators commonly used for building evaluation were selected and evaluated according to equation (1) (see Table 1 and Peuportier et al. (Polster et al., 1996; PeuportierThiers, 2013)).

All technologies were considered to produce electricity at high voltage (above 24 kV), except for photovoltaic systems (considered to release electricity at low voltage). Infrastructure (high level transmission network, interconnection network with neighbouring countries, distribution network), SF6 emissions and electricity losses were integrated, following guidelines from Itten et al. (2012b). The list of technologies considered is given in Table 2.

The category thermal renewable technologies (REN Thermal) corresponds to a category used by default by the French transmission system operator (RTE), even if the integration of municipal waste production in the “renewable” category could be seen as inappropriate. The “coal and gas” category includes only production from centralised power plants whereas production from decentralised not dispatchable gas fuelled units such as heat and power units are included in the category “CHP gas”.

Pumped storage hydraulic impacts per kWh are equal to small dam electricity production impacts. Indeed, this value only takes into account impacts from infrastructure (dams) and network. The method to evaluate impacts induced by electricity consumption of pumped storage plants is explained in the supplementary information and is summed up in the next section.

Results of the impact assessment per kWh produced by each technology are given in the supplementary information. For most indicators, high discrepancies exist among technologies. For instance, more than one order of magnitude separates the GWP of run-of-river hydro and Coal&Gas centralized power plant.

2.2. Impact assessment of the electricity production according to the mix

Two approaches were used to evaluate life cycle impacts of 1 kWh of electricity supplied by the French electricity system on the low voltage level. These impacts correspond to the indicators listed in Table 1. Variables used in the following equations are listed and described in Table 3.

- Method 1: hourly mix evaluation. Impacts (I_{hourly}) at each hour h of the year 2013 of 1 kWh supplied by the grid are evaluated according to the electricity production mix at hour h.

$$I_{hourly} = \sum_{i=1}^{14} \left(I_i \times \frac{P_i}{\sum_{i=1}^{14} P_i} \right) + I_{step} \quad (2)$$

Where I_i is the life cycle impact assessment of technology i (evaluated using equation (1)) and $Prod_i$ the electricity production of technology i at hour h. I_{step} corresponds to impacts of electricity consumption by pumped storage hydraulic at hour h (see Equations 4)–(7)).

- Method 2: yearly average mix evaluation. Environmental impacts (I_{year}) of 1 kWh supplied by the grid is the sum of environmental impacts of each technology multiplied by its contribution in the mix.

$$I_{year} = \sum_{i=1}^{14} \frac{\sum_h P_{i,h}}{\sum_h \sum_i P_{i,h}} \times I_i \quad (3)$$

Results of the Method 2 calculation correspond to average impacts per kWh of Method 1 over the year, weighted by the total electricity production at each hour.

As stated before, a specific procedure was developed to assess environmental impacts related to electricity produced using pumped storage hydroelectricity. ecoinvent 3.1 inventory data for pumped storage accounts for the consumption of a certain amount of electricity. This electricity consumption is evaluated considering an efficiency rate of 70% of these plants and is supposed to be

Table 1
Environmental indicators.

Impact indicator	Unit	Reference
Cumulative Energy Demand (CED)	MJ	Frischknecht et al., 2007
Water consumption (Water)	l	Frischknecht et al., 2007
Abiotic Depletion Potential (ADP)	kg Sb-eq	Guinee, 2002
Non-radioactive waste creation (Waste)	kg eq	Frischknecht et al., 2007
Radioactive Waste Creation (Rad)	m^3	Frischknecht et al., 2007
Global Warming Potential (100) (GWP)	kg CO_2-eq	Solomon, 2007
Acidification Potential (AP)	kg SO_2-eq	Guinee, 2002
Eutrophication Potential (EP)	kg PO_4^{3-}-eq	Guinee, 2002
Damage caused to ecosystems (Bio)	PDF.m^2.yr	Goedkoop and Spriensma, 2001
Damage to human health (DALY)	DALY	Goedkoop and Spriensma, 2001
Photochemical Oxidant Formation (smog) (POP)	kg C_2H_4-eq	Guinee, 2002
Odour (Odor)	m^3 air	Guinee, 2002

Table 2
List of considered technologies.

Name	Share in the annual average mix in 2013 (%)	Description
REN – Thermal	1.1	Municipal waste (58%), Biomass (19%), Biogas (19%)
Coal & Gas	4.9	Centralised power plant from coal (70%) and gas (30%)
CHP Gas	1.9	Decentralised production, not dispatchable
CHP Fuel	0.5	Decentralised production, not dispatchable
Wind	2.9	1-3 MW wind turbines
PV	0.8	Open ground (37%), on-roof multi Si systems (43%) and small on-roof mono-Si systems (20%)
Run-of-river/small dams	8.9	Reservoir filling duration below 200 h
Nuclear	73.4	Pressurised water reactor
Large dams	3.6	Reservoir filling duration above 200 h
Pumped storage hydro	1.2	Electricity consumption of pumped storage excluded of the inventory
Peak	0.1	Fuel power plants, fuel and gas turbines
Imports	0.1	Belgium (50%), Germany (26%), Spain (21%), Switzerland (2%) and Italy (1%)
Others	0.6	Treatment of industrial gas: blast furnace gas (76%) and coal gas (24%)

produced by the average yearly mix for France. This introduces three issues:

- This average yearly mix does not correspond to 2013 data, but corresponds to the year 2008. This underestimates, for instance, the share of wind power in the French electricity mix.
- If an hourly calculation is performed using this inventory for pumped storage hydroelectricity, there is a double-counting of pumped-storage impact. It is first a consumption inducing an electricity production by other technologies during off-peak hours and then it is evaluated as a production with embodied electricity consumption during peak hours.
- Temporal variation of pumped storage is not taken into account: first, environmental impacts are balanced between off-peak and peak hours, whereas they should be allocated only at peak hours, and second, there is no differentiation based on the time of the year when the production occurs (e.g. winter versus summer).

Therefore, a procedure was developed for temporal allocation of environmental impacts related to infrastructure and electricity consumption of pumped storage. It allows allocating all impacts from pumped storage to peak hours: impacts from pumped storage infrastructure (power station and electricity network) and impacts from electricity requirements (occurring at off-peak hours, when pumped storage consumes electricity). The procedure is detailed in the supporting information.

2.3. Case study

The two methods presented above considering hourly or yearly average electricity mix were used to evaluate electricity related impacts of a single family house, part of the INCAS platform, located near Chambery, France. The INCAS platform has been set up by the national institute of solar energy in France (INES). Three test houses were built and fully instrumented to test models and improve building-integrated thermal and electrical systems.

Whole building LCA was performed using the EQUER (Polster et al., 1996) tool with a focus on the consumption and production of electricity during one year of operation of the energy-efficient single family house. Impacts related to manufacture of building materials and components, e.g., photovoltaic panels, are not

Table 3
List of variables for impact assessment of electricity production.

Variable	Description
i	Electricity production technology, listed in Table 2
h	Hour of the year (8760 in 2013)
I_{hourly}	Vector of impacts of 1 kWh supplied by the grid, evaluated for each hour of the year 2013
I_{year}	Vector of impacts of 1 kWh supplied by the grid, in average for the year 2013
I_i	Vector of impacts of 1 kWh produced by technology i and transmitted to the final consumer on the low voltage level (network and losses included, see equation (1))
$P_{\boldsymbol{i}}$	Electricity production of technology i at hour h, given by the French network operator, RTE
I_{step}	Impacts of electricity consumption by pumped storage hydraulic at hour h

included in the results presented here. The method is presented in PeuportierThiers (2013).

Electricity end-use (space and water heating, lighting, ventilation, household appliances) and electricity production of the photovoltaic system were considered. More details on INCAS house can be found in Spitz et al. (2012) and in a report from CEA (Commissariat à l'Energie Atomique et aux énergies alternatives (CEA), 2010). A 3 kWc nominal power photovoltaic system integrated in the roof (slope of 26°, south-oriented) was considered, which corresponds to a typical French domestic installation, instead of the system actually installed on the INCAS house. The annual consumption for specific electricity uses (lighting, ventilation, and domestic appliances) was set to 2500 kWh, corresponding to an average consumption per household in France (ENERTECH, 2013). Hot water was produced using a solar thermal system (solar fraction of 61%), complemented with electrical back-up. Electricity consumption (hourly load values) corresponding to different uses (electric heating, electric water-heating system) and electricity production by the photovoltaic system were calculated using the dynamical thermal simulation tool COMFIE (PeuportierThiers, 2013; Peuportier and Sommereux Blanc, 1990). Scenarios for specific electricity consumption (appliances and lighting) were derived from the national thermal regulation procedure RT2012. 2013 meteorological data were used to perform the simulation, ensuring consistency between building energy simulation and electricity mix data. Monthly end-uses and production in the low-energy house considered in this case study are reported in Fig. 1, resulting from energy simulation using a 15 min time step.

On Fig. 1, the energy provided by the thermal solar system is considered to avoid the use of electricity for water heating. The solar water heating production presented in Fig. 1 (in green (in the web version)) corresponds to the part of the water heating energy needs covered by the thermal solar system whereas the water heating category (in blue (in the web version)) corresponds to the total energy needs for water heating. The photovoltaic production represents 68% of the total yearly electricity consumption of the house. As can be seen in Fig. 1, the monthly balance is highly variable: the solar systems (photovoltaic and solar water heating) account for only 11% of the house energy requirements in December and 190% in July. In July, the onsite photovoltaic production exceeds electricity needs and a large part of the production is considered to be exported to the grid.

2.4. Impact assessment of electricity consumption and production

Impact assessment for each electricity end-use is evaluated as follows, for Method 1 (Equation (8)) and Method 2 (Equation (9)) respectively:

$$I_{EndUse-Method1} = \sum_{h=1}^{8760} I_{hourly} \times Conso_{EndUse} \quad (4)$$

$$I_{EndUse-Method2} = I_{year} \times \sum_{h=1}^{8760} Conso_{EndUse} \quad (5)$$

Where $Conso_{EndUse}$ represents the final electricity consumption of an end-use (e.g. electric heating) at hour h; I_{hourly} and I_{year} are calculated as defined in Equations (2) and (3).

In the French electricity system, the share of photovoltaic production in the hourly mix is low (maximum 6.4% in 2013), and the maximum wind power share is 13%. The total photovoltaic production represents around 1% of the total electricity production for year 2013. In French overseas territories (isolated electricity system, subject to grid stability problems), the local system operator has set a maximum of 30% for the share of intermittent source of electricity, such as photovoltaic and wind power (Drouineau et al., 2014). Metropolitan France is currently significantly under this limit (which could be increased as shown in Bouckaert et al. (2013)). Therefore we considered that all production from photovoltaic system can be efficiently used on the grid, which justifies accounting for avoided impacts when electricity is delivered to the grid.

In the assessment of the INCAS house, an hourly electricity balance is done: at each hour, the total electricity consumption (electric heating, back-up electricity consumption complementing the solar water heating system, appliances) is compared to the onsite production (photovoltaic system). Local electricity production is firstly consumed in the building and residual production at each

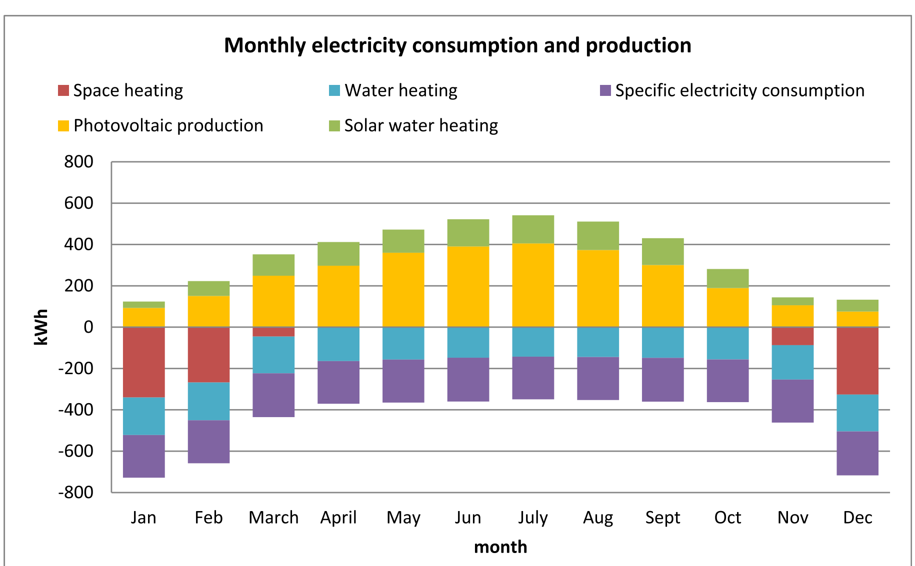

Fig. 1. Calculated monthly balance of electricity production and consumption in a low-energy house (INCAS platform, INES, Chambery, France) in 2013.

hour is exported to the grid and corresponds to an avoided centralised grid production. Impact assessment for the INCAS house combining consumption and production is expressed by the following two equations, for each method:

$$I_{INCAS-Method1} = \sum_{h=1}^{8760} I_{hourly} \times [Conso_{INCAS} - Prod_{INCAS}] \quad (6)$$

$$I_{INCAS-Method2} = I_{year} \times \sum_{h=1}^{8760} [Conso_{INCAS} - Prod_{INCAS}] \quad (7)$$

Where $Conso_{INCAS}$ is the total electricity consumption in the house at hour h and $Prod_{INCAS}$ is the total electricity production (here a photovoltaic system). At a given hour, if the onsite electricity production ($Prod_{INCAS}$) is higher than the building electricity consumption ($Conso_{INCAS}$), the residual electricity production results in avoided production from the electricity system (negative impacts). The residual electricity is considered to be exported to the grid and fully used by the electricity system. The related avoided electricity production is given by the supply mix at hour h.

3. Results

3.1. Variation of life cycle impacts of electricity supply using the hourly mix method

Using online data of hourly electricity production in 2013 (http://www.rte-france.com/fr/eco2mix/eco2mix) provided by the French network operator (RTE), environmental impacts per kWh at each hour of the year were evaluated, following equations (1)–(3) presented above. Mean value, minimum, maximum and relative standard deviation (RSD) for each impact are represented in Table 4.

Among the twelve evaluated indicators, four have a very small relative standard deviation (5% or below) and could be considered relatively constant along the year: Biodiversity (Bio), Cumulative Energy Demand (CED), radioactive waste (Rad) and water consumption. Three other indicators have a relative standard deviation below 20%: Human health impacts (DALY), Eutrophication (EP) and Waste.

The five remaining indicators have a relative standard deviations above 20% and up to 41% and 44% for GWP and ADP. Taking into account hourly variation of the mix is therefore justified if the studied electricity use (or production) is not constant over the year or if a demand management strategy (e.g. peak cut-off) can be implemented. This result is valid in the French context. Temporal variation of the global warming potential (GWP) indicator corresponding to the French electricity supply mix from January 1st to December 31st, 2013 is presented in Fig. 2 as an example. The GWP varies from 35 to 191 gCO2eq per kWh. An important seasonal variation is noticeable on Fig. 2, with a average of 124 gCO2eq/kWh for the January to March period and 63 gCO2eq/kWh for the June to August period. Weekly variations can also be noted, with variations from 35 CO2eq/kWh up to 100 gCO2eq/kWh in April and May. Daily variation range is usually around 20 gCO2eq/kWh. Variation of the GWP is a consequence of the variation of the electricity consumption: when the consumption is high (winter, week-days, daytime), an increase of gas and coal power plants production is needed to satisfy the demand. All variations (seasonal, weekly, daily) are significant and none can be considered negligible when compared to the others.

The two main findings of these preliminary results can be summed up as follows:

- temporal variations are important for several environmental indicators so they should be integrated in LCA;
- seasonal, weekly and daily variations are observed so the hourly time step should be preferred as it is the greatest common divisor.

3.2. Case study results

The comparison between the two methods presented above (hourly or yearly average mix) is shown in Fig. 3 for the twelve indicators and different electricity end-uses. Using an annual average mix can lead to noticeable errors, underestimating environmental impacts, particularly considering seasonal end-uses such as electrical heating and back-up of solar domestic hot water system (errors up to 20% for global warming potential and Abiotic Resource Depletion). Errors leading to overestimation can also be significant considering end-uses such as electric water heating with hot water storage because electricity is consumed during off-peak hours: Abiotic Resource Depletion and Global warming Potential was overestimated by 12%. Fossil fuels (coal and gas) produce less electricity during off-peak hours as the demand is lower, abiotic depletion and global warming potential are consequently lower at off-peak hours. This is valid for all seasons.

Electricity consumption and production have been grouped to represent the whole electricity balance of the INCAS house (consumption versus production). Impact assessment of the electricity consumption from space heating, electric back-up of the solar system providing hot water, and specific electricity were balanced with avoided impact from the photovoltaic production as presented in equations (6) and (7). Combining all uses, the discrepancy between the yearly annual mix and the hourly mix methods could be over 40%, for ADP and GWP indicators (see Fig. 3, f). In this final

Table 4
Yearly average mix and hourly mix impact assessment per kWh supplied in France.

Indicators	Unit	Average	Hourly mix, MAX (% of mean value)	Hourly mix, MIN (% of mean value)	RSD[a] in %
AP	kg SO2eq	5.5E−04	1.0E−03 (190%)	2.6E−04 (47%)	34
Bio	PDF.M^2.an	3.7E−02	4.1E−02 (109%)	3.4E−02 (90%)	3
CED	MJ	1.3E+01	1.4E+01 (108%)	1.1E+01 (82%)	3
Rad	m3	5.9E−08	6.8E−08 (116%)	4.7E−08 (79%)	5
GWP	kgCO2eq	9.1E−02	1.9E−01 (198%)	3.5E−02 (37%)	41
ADP	kgSbeq	7.4E−04	1.5E−03 (205%)	2.4E−04 (32%)	44
EP	kg PO4eq	1.1E−03	1.6E−03 (150%)	7.9E−04 (72%)	13
DALY	DALY	2.4E−07	3.0E−07 (128%)	1.8E−07 (75%)	11
Odor	m3air	7.0E+02	1.2E+03 (177%)	3.6E+02 (52%)	33
Waste	kg	5.8E−02	8.3E−02 (145%)	3.9E−02 (67%)	19
POP	kgethyleq	2.5E−05	4.7E−05 (186%)	1.2E−05 (47%)	34
Water	l	5.9E+00	6.8E+00 (114%)	4.7E+00 (80%)	4

[a] Standard deviation divided by the mean value.

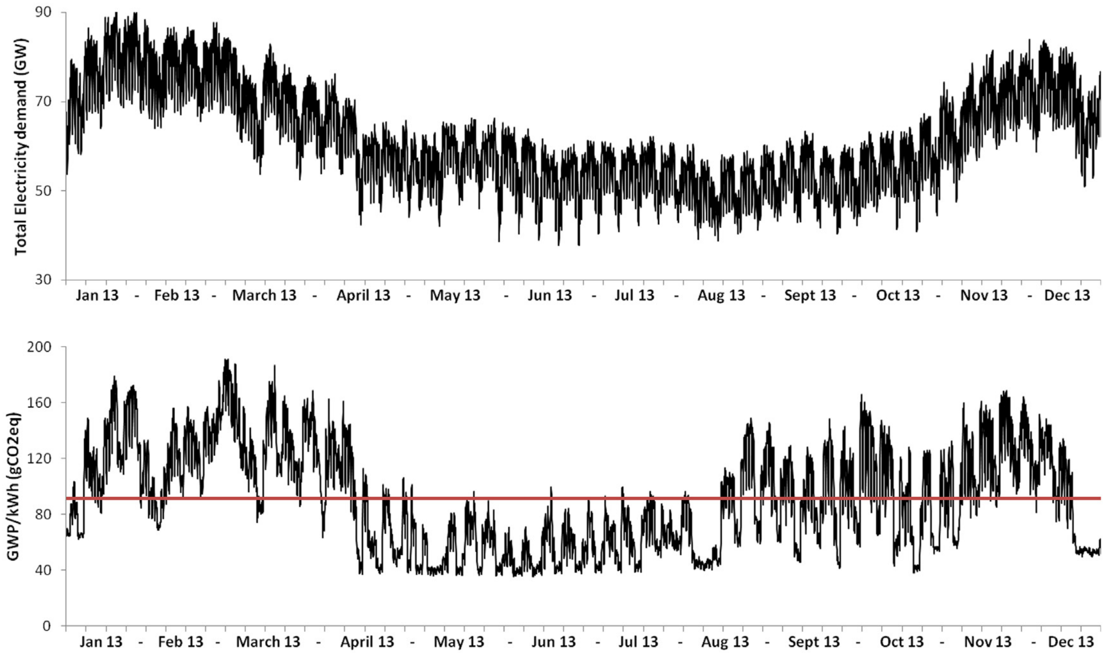

Fig. 2. Total Electricity consumption in France in 2013 (top) and Global Warming Potential (GWP) per kWh (bottom) in 2013 (France). Temporal variation of GWP are represented by a black line and the yearly average value by a red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assessment, discrepancies between end-uses do not compensate, and onsite electricity production from photovoltaic system introduces negative impacts (avoided production from the network). This increases the differences between the two methods.

Discrepancies between the two methods are related to production technologies with variation across the year. Fig. 4 illustrates these variations for electricity use for end-uses.

Indeed, we can first notice that the share of nuclear power ('Nuc') is always above 70% with a 6.4% variation between the lowest and the highest share. Gas CHP plants production is high in winter and low in summer due to specific contracts enhancing the price of electricity during the heating period (from November to end of March) (RTE, 2012), which explains the differences between electricity mixes related to photovoltaic system production (avoided impacts) and space heating. Photovoltaic production from the network is not used to satisfy water heating electricity needs as the storage water heater system runs in the night, during off-peak hours (ADEME, 2015) (Fig. 4, Domestic hot water). The modulation of the electricity production between day and night, or winter and summer leads to an important variation of electricity impacts as what was shown on Fig. 2 for Global Warming potential. It interacts with end-use when they have a high temporality or seasonality, such as Domestic Hot Water (night), or Heating (winter) for instance.

4. Discussion

This study helps to evaluate the range and sources of errors due to the use of a yearly average mix instead of an hourly mix representing daily, weekly and seasonal variation of the electricity production. The results show that accounting for temporal variation of electricity would greatly improve reliability and comprehensiveness of life cycle assessment of electricity-related impacts. Errors due to the use of a yearly average mix have been estimated for an energy-efficient house and could be above 30% for global warming potential and abiotic resource depletion. This research represents a first step toward accounting for load shifting and more generally smart grid and smart building benefit in life-cycle assessment. Load shifting is considered as an important driver of the needed energy transition. It could among other things ease intermittent power integration and improve network reliability (Bouckaert et al., 2013). But its potential environmental benefits are not assessed when a yearly average mix is used because the electricity mix would be identical with and without load shifting. This study also illustrates the importance of hourly evaluation of renewable onsite electricity production in life cycle assessment. An original impact adjustment method is suggested to better take into account environmental impacts of electricity storage, a group of technologies that is expected to further grow in a near future.

However, results cannot be directly used as such, e.g in a building design tool. 2013 is a real year, with deviation from annual average conditions, including higher temperatures, more precipitations, in a weak economic growth context. This induces an electricity production that is not representative of other years: for instance hydraulic production was 12% higher than average. There is a need for a representative hourly mix that would be averaging climatic and economic fluctuations of real years, because decisions made in the design of a building will have consequences over a long period. This is why energy calculations are based upon meteorological years, corresponding to long term averages (e.g. 20 years).

Results of end-use electricity mixes are also not applicable to other case studies. Hourly electricity loads are specific to each project and not linearly derivable. For instance:

- Assessment of an old building with a high heating load will emphasise the share of heating-related impacts in the global assessment and could lead to different results (longer heating period, higher load during cold wave, different thermal mass effects…).
- Location of the house, shading, window size, etc. will affect heating consumption but also water heating (cold water temperature) and lighting consumption.
- Hourly specific electricity consumption depends (at least) on the use of the building (residential, office…) and number of occupants.

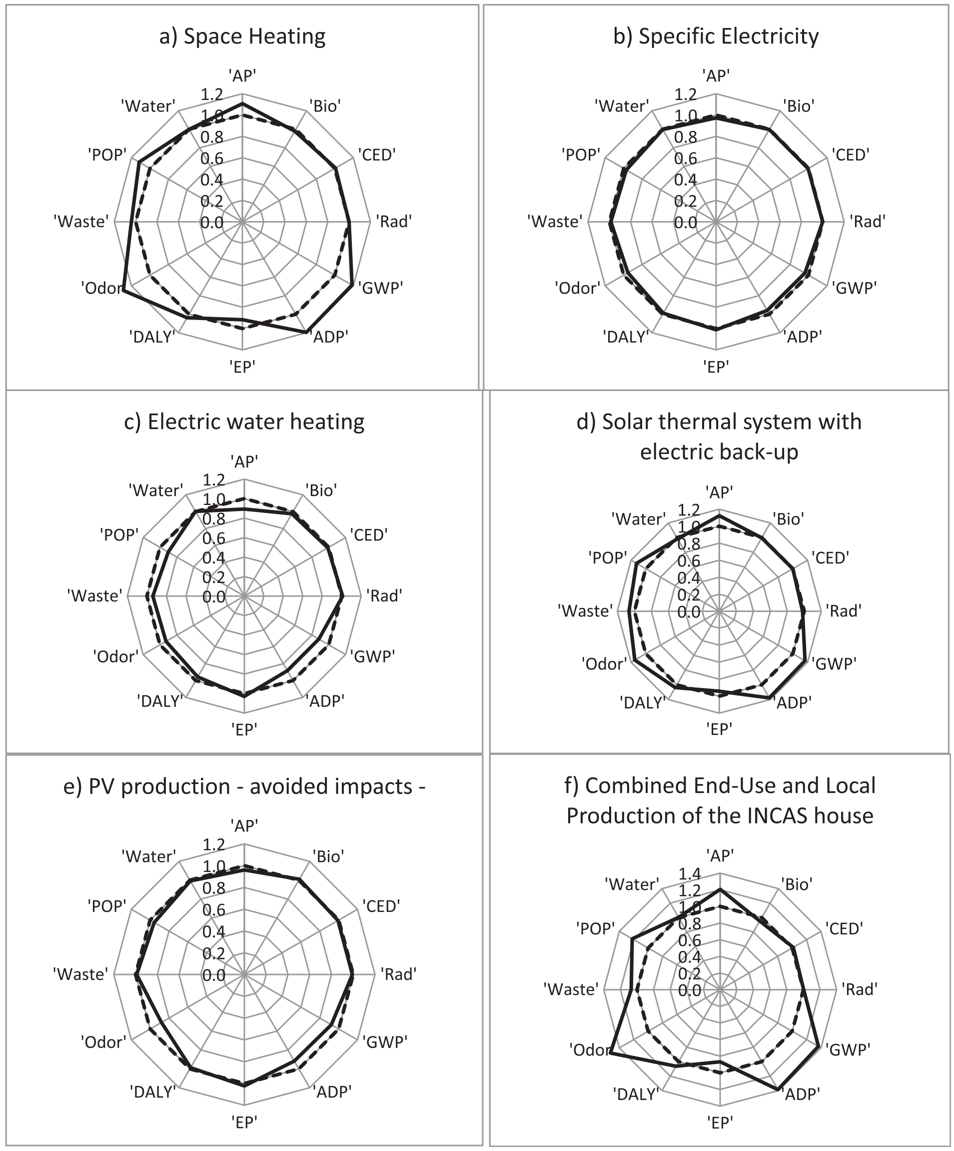

Fig. 3. Impact assessment of electricity consumption and production in the INCAS house. Comparison between an hourly mix (plain line) and a yearly average mix method (dotted line).

- Photovoltaic production depends among other things on the orientation, slope and shading of the roof.

Ensuring consistency between building energy simulation and electricity mix evaluation is important: consuming electricity during peak hours of a cold wave or being able to offset or delay this consumption influences to a large extent the environmental performance of the assessed building. This was taken into account in this evaluation but raises challenges for the development of typical hourly electricity mix data corresponding to a typical meteorological year.

The same hourly mix was used to evaluate all different end-uses. However, a seasonal use such as electric heating induces a seasonal peak demand that leads to an increase of production from fossil thermal plants such as gas and coal power plants. Less seasonal uses such as domestic hot water consume electricity all year round and during the night and could be then considered as covered only with base load technologies. Thus the authors consider that the specificity of the different end-uses was not fully taken into account by the method presented here.

Indicators used are not fully in line with recent recommendation from the JRC (EC-JRC, 2010). New methodologies developed could be used to update the set of evaluated indicators when they are fully operational. This could improve overall results, decreasing uncertainties and increasing comprehensiveness of the assessment. For instance, the scarcity of water resources has been neglected. New methodologies exist (Berger et al., 2014; Boulay et al., 2015) to overcome this important shortcoming; however they were not fully operational at the time of study. The model for eutrophication does not distinguish marine and freshwater eutrophication (EC-JRC, 2010), the model for abiotic depletion aggregates fossil and mineral resources. This is the result of a trade-off between aggregation uncertainties and number of evaluated environmental indicators. Spatial differentiation has been recognised to be an important issue for photochemical oxidant formation (Hauschild, 2006), but the methodology used does not account for it. The IPCC 2007 (Solomon, 2007) method was used to evaluate global warming potential even though a more recent version of the method was available (Stocker, 2014). The implementation of the latter was not fully implemented in ecoinvent 3.1 at time of study and potential changes made on

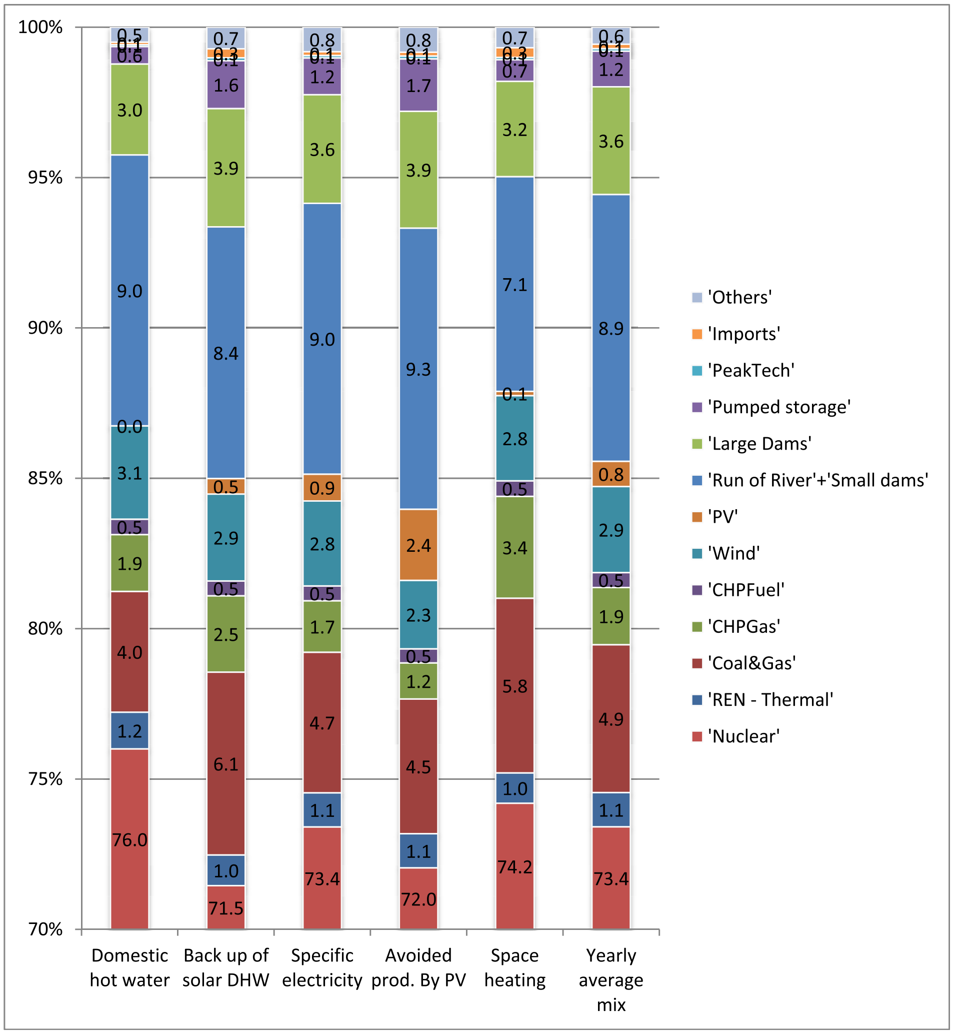

Fig. 4. Average computed electricity mix per end-use and yearly average mix for 2013. For better readability Fig. 4 shows only 30% of the electricity mix (from 70 to 100%) as nuclear energy covers always more than 70% of the electricity mix. The vertical axis thus starts at 70%.

biogenic carbon accounting lead us to keep the previous version of the indicator. Two endpoint indicators are included here (damage to human health and damage caused to ecosystem) to ease interpretation of results. However, large uncertainties are related to endpoint indicators (Bare et al., 2000) and no method is currently recommended by the JRC (EC-JRC, 2010).

Life cycle assessment is frequently used as an aided design tool for building projects (PeuportierThiers, 2013; Basbagill et al., 2013; Chouquet, 2007). The construction of a new building or retrofitting operations could be seen as a marginal change of the overall electricity consumption, e.g. by increasing heated or lightened surfaces, or decreasing energy consumption thanks to better wall insulation. In this context, the use of marginal instead of average electricity mixes as proposed by approaches such as consequential LCA (Ekvall and Weidema, 2004) would improve relevance of the environmental assessment by taking into account actual production constraints on the electricity system. For instance, at a given installed capacity, non-dispatchable or saturated power cannot increase its production to satisfy an increase of electricity consumption.

Another important parameter that was not studied is the time horizon. Buildings are supposed to last several decades, during which the electricity mix could face important changes. As a research perspective, different scenarios of electricity mix evolution could be used to perform sensitivity analysis.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.11.052

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