Illustration of methodological challenges in energy and environmental assessment of buildings

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Abstract: *A life cycle approach (LCA) is now commonly used for the environmental assessment of buildings. However, different methodological rules are currently found in the literature to estimate the energy and LCA balance for the use stage e.g. from an annual assessment to a one hour time step assessment. Another critical issue is related to the assessment of new low energy buildings equipped with on-site renewable energies. In this study, first, the consequences of using different Life Cycle Inventory (LCI) calculations for the electricity mix are analysed. Then, the consequences of using different allocation rules for the on-site renewable energy produced by PV panels are assessed. The results on a single individual house showed that the use phase results are very sensitive to the allocation rules. Regarding the temporal aspects, this study highlights the differences between dynamic and static approaches for both energy and LCA calculations. Finally, recommendations are given to improve the reliability of building LCA tools.*

Keywords: Life cycle assessment, energy efficient building, building environmental assessment, renewable energy, time step

1. Introduction

The building sector is a major contributor to the environmental impacts including climate change, energy consumption, waste generation and air pollution [1]. The environmental stakes are particularly important in construction because any initial decision has always long-term consequences. One of the methods suggested to evaluate such environmental impacts is Life Cycle Assessment (LCA). LCA provides a holistic approach that is based on studying "the whole industrial system involved in the production, use and waste management of a product or service" [2]. Although LCA first emerged from the packaging industry, it has gradually spread into many sectors, including the construction industry and led to the development of several building LCA tools with their own data, methodologies and environmental indicators [3].

Currently, environmental authorities and policy makers use LCA to choose environmental strategies. A critical issue in the building sector concerns the assessment of nearly zero energy building (nZEB) and plus energy building i.e. over the year, they should produce more energy than they consume. Most of these buildings are or will be equipped with on-site renewable energy production e.g. PV panels, solar thermal panels, wind power, geothermal heating to fulfil the current and future regulations. For instance, in France, all new buildings should be plus energy buildings in 2020 [4]. On the one hand, solar decentralized renewable energy production units can annually produce more energy than the building energy consumption. On the other hand, they may produce energy while the users of the building do not need it e.g. during the day when the users are out of the building (respectively they may not produce energy while the users need it e.g. during the evening).

This statement questions the way the energy production/consumption and the LCA calculations are conducted e.g. in early design or in more detailed assessment. Indeed, no consensus exists on the way to account for the onsite energy production in LCA. Recently, the EN 15978 standard "Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method" recommends differentiating the energy consumed on site, the energy imported from the grid and the energy exported to the grid, separately from the LCA results. In the same time, the standard does not provide any guidance of the choice of the time step for the assessment and recommends to fully allocate the environmental impacts of the on-site energy equipment to the building [5]. Though harmonizing the LCA rules for the European construction sector, the EN 15978 standard can have some consequences in decision making (e.g. encourage or discourage the use of PV in new buildings) that need to be studied in more details.

In this paper, the goal is to understand 1) the influence of the time step used for the energy and LCA calculations and 2) the influence of the rules for handling the on-site energy production on the impact assessment results of near zero energy building (nZEB) and plus energy building located in France. The next sections present the methodologies tested and the building case study. Results are reported in section 4.

2. Methodology

2.1. Three methods for handling energy and LCA calculation time step

Today, the energy balance (i.e. differentiation between energy consumed on site, exported and imported) for a building is commonly available at the hourly time step e.g. if directly from dynamic thermal simulation results. Common practive consists in using annual energy balance from the thermal regulation. In this study, both annual and hourly energy balance results are used for the following French regulated uses: heating, cooling, domestic hot water, lighting, auxiliaries, ventilation and other uses of energy e.g. appliances (not regulated). Then, for electricity uses, the energy input data are combined with LCA data describing the impacts of electricity consumption.

Previous works have shown the variability of environmental impacts of the French electricity grid mix depending on the day, the week or the month in a year [6]. As all uses of electricity in a building are variable during the year (e.g. for heating or lighting), both hourly and annual LCA data for electricity consumption are considered to assess the sensitivity of the time step from an attributional LCA point of view.

These two types of data for the assessment of energy and LCA are then combined as illustrated in Table 1 and in Figure 1. In this study, case B is assumed to be the most accurate assessment while Case C represents common practice (i.e. hourly energy results, aggregated to the year and then LCA calculation with annual electricity mix) and case A may be considered as the simplest option.

Table 1: Energy and LCA data configurations

	Annual energy balance	Hourly energy balance
LCA data based on annual electricity mix	**Case A**	**Case C**
LCA data based on hourly electricity mix	**-**	**Case B**

2.2. Three methods for handling on site energy production in LCA

As stated earlier, the European LCA standard, EN 15978, advices to communicate next to the LCA results, the amount of energy produced on site and allocate the entire energy production system to the building. Nevertheless, for plus energy buildings, it is clear that from a LCA point of view, it is a multifunctional system because buildings become energy producer. Therefore, according to ISO 14044 [7] and ILCD Handbook [8], in attributional LCA (describing the environmental life cycle of the product and not its consequences), two other approaches could be used to deal with this issue: the system expansion, also called avoided burden approach or the co-products allocation. The avoided burden approach considers exported energy as energy not produced by the grid which then results in avoided impacts (proportionally to the average contribution of each energy carrier). All impacts related to the energy system are allocated to the building. Regarding the co-products allocation method, the exported energy is considered as a co-product of the building and the impacts of the on-site production system are affected to the building with a ratio (denoted X in Figure 1) according to the energy consumed on site.

In this study, these three approaches are considered and are illustrated for a building with photovoltaic (PV) panels in Figure 1.

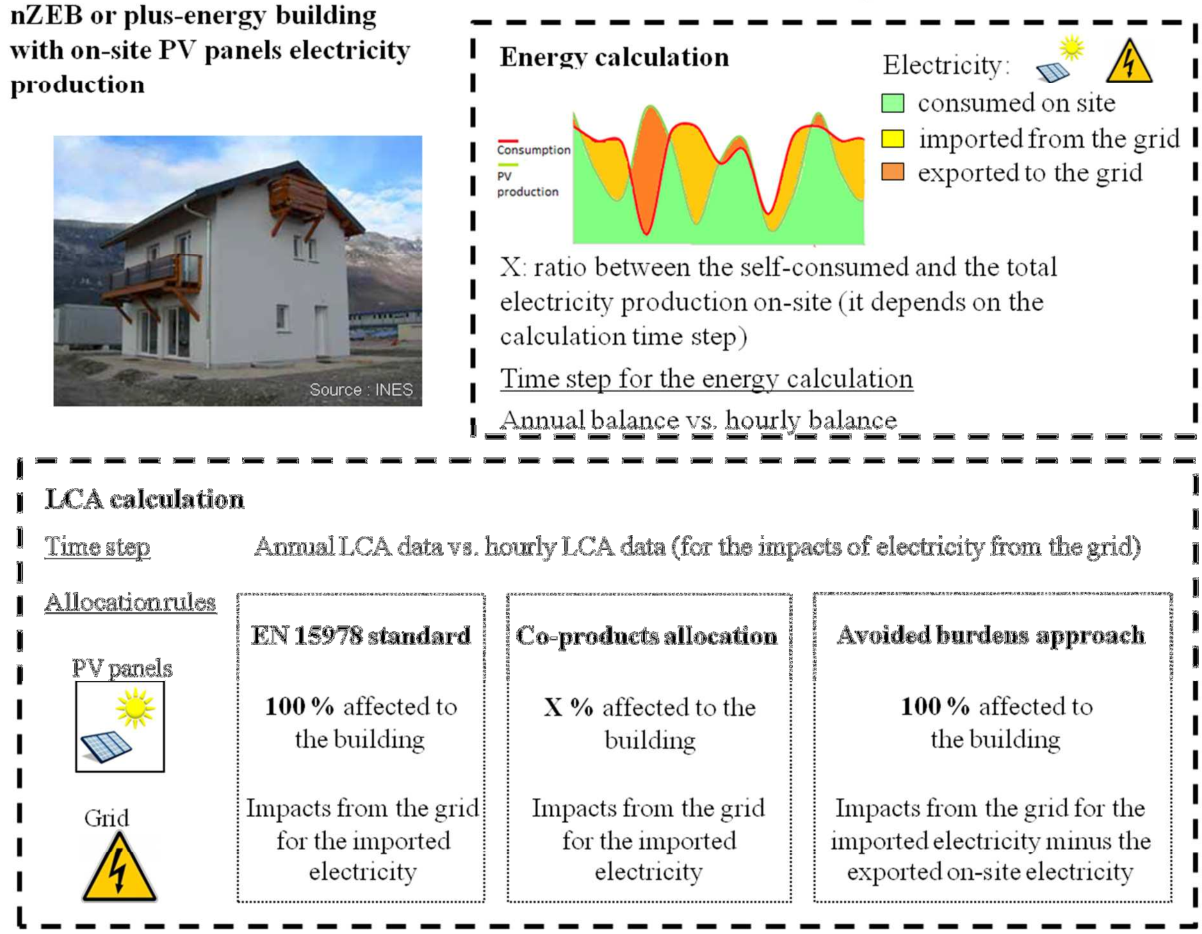


Figure 1: Representation of the methods for handling on site energy production for building equipped with photovoltaic panels.

3. Application to a building LCA case study

In order to test the different methodologies presented in section 2 (cf. Table 1 and Figure 1), a single family house from the INCAS platform, near Chambery, in France, has been chosen as a case study. The INCAS house complies with the passive house standard and has a net floor area of 122 m². Spitz et al. described it in more details [9].

In this study, different alternatives of the house are tested: the INCAS house without PV panels, the house equipped with 40 m^2 of PV panels and the house equipped with PV panels and 4 m² solar thermal panels (used for the hot water needs). The first house is used as a reference case; the second alternative is representative for nZEB and the last one of plus energy buildings.

3.1. System boundaries

The LCA of the buildings include the impacts of three contributors according to the EeBGuide guidance [10]: the building products and equipment from cradle-to-grave i.e. production, transportation to the site, use and replacement, end-of-life (modules A, B, C of EN 15978), the impacts related to the operational energy regulated uses (module B6 of EN 15978 , energy needs at the meter), the operational water uses (module B7 of EN 15978), and the specific uses of electricity such as appliances in the building (module B6 of EN 15978). The reference study period for the house is set at 50 years.

3.2. Operational energy use data

The dynamic thermal simulation tool COMFIE was used as well as the 2012 meteorological data of the Bourget-du-Lac (location of the INCAS house). Four inhabitants are considered, consuming each 100 L of cold water and 40 L of hot water per day. The heating demand is covered by an electric air heater and the hot water by an electric storage heater running during the night. In the alternative where solar thermal panels are used, an electric heater is used instantaneously as backup. For the other electrical needs (lighting, ventilation and domestic appliances), the annual consumption is determined using a ratio of 2500 kWh, average consumption per household in France [11]. They are supposed to be hourly distributed along the year according to the house occupancy.

The heating demand is low and equal to 7.5 kWh/m²/year. The overall energy needs of the building are 52 kWh/m²/year in 2012, 40 kWh/m²/year when the house is equipped with solar thermal panels for the hot water and the overall PV production is 41 kWh/m². Figure 2 presents the variability of the total electricity consumption and production for the two alternatives of the INCAS house: nZEB and PEB.

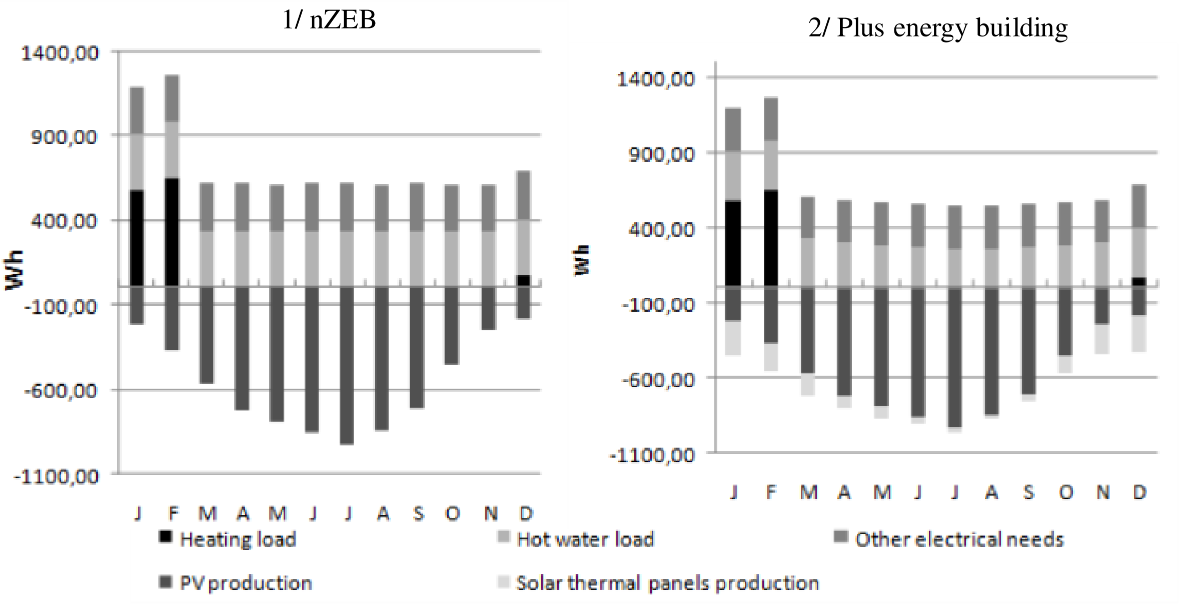


Figure 2: Average monthly final electricity consumption and production in 2012 for the INCAS house with (1) photovoltaic panels and electric heater storage and (2) the house with photovoltaic panels and solar thermal panels (2).

Hourly 2012 production data from the French electricity grid manager (RTE) were used for calculating the hourly and then the annual electricity mix. The energy carriers of the electric mix are break down by technology type: nuclear, gas, coal, fuel thermal plants, hydro-power, wind energy, solar energy and thermal renewable energies (biomass, biogas and industrial waste) as well as electricity import and export with neighbouring countries. For each energy carrier, recent, LCI data from ecoinvent v3 [12] was associated to rebuild an hourly and annual electric mix. The national electricity mix is considered in this study because European environmental objectives (e.g. reduction of energy consumption and CO_2 emissions) are fixed on national bases.

3.3. Building products and technical equipment data

The data describing the LCA impacts of products are taken for all the scenarios from the INIES database [13]. These are Environmental Product Declaration (EPD) from cradle-to-grave [14]. Each EPD has a service life data reported by manufacturers and a scenario for the transport to the building site, its implementation and its end-of-life. For the photovoltaic panels and solar thermal panels, the data used are extracted from ecoinvent v2.2 database [15]:"3 kWp slanted-roof installations, multi-Si, laminated, integrated on roof". Their life time is assumed to be 30 years and the amount is adapted to match the peak power (5 kWp).

3.4. Impact assessment

Seven indicators were used based on the French and European standards for LCA in the construction sector. Table 2 presents the names and units of these indicators.

Table 2: List of environmental indicators considered in this study

Indicators	Units
Non renewable energy	kWh
Water consumption	L
Waste (hazardous and non hazardous)	kg
Radioactive waste	kg
Global Warming potential	kg eq-CO_2
Acidification potential	kg eq-SO_2
Photochemical ozone formation potential	kg eq-C_2H_4

4. Results

4.1. Contribution analysis

Figure 3 shows the LCA results of the reference case (INCAS house without photovoltaic panels) with the annual electricity mix and the electricity consumption of 2012 (Case C). As it is an energy-efficient building located in France, the electricity consumption during the use phase is only a major contributor of two indicators: Non Renewable Energy (83 %) and Radioactive Waste (62 %). It also represents a substantial share of Water consumption and Climate change impacts, respectively 42 % and 39 %.

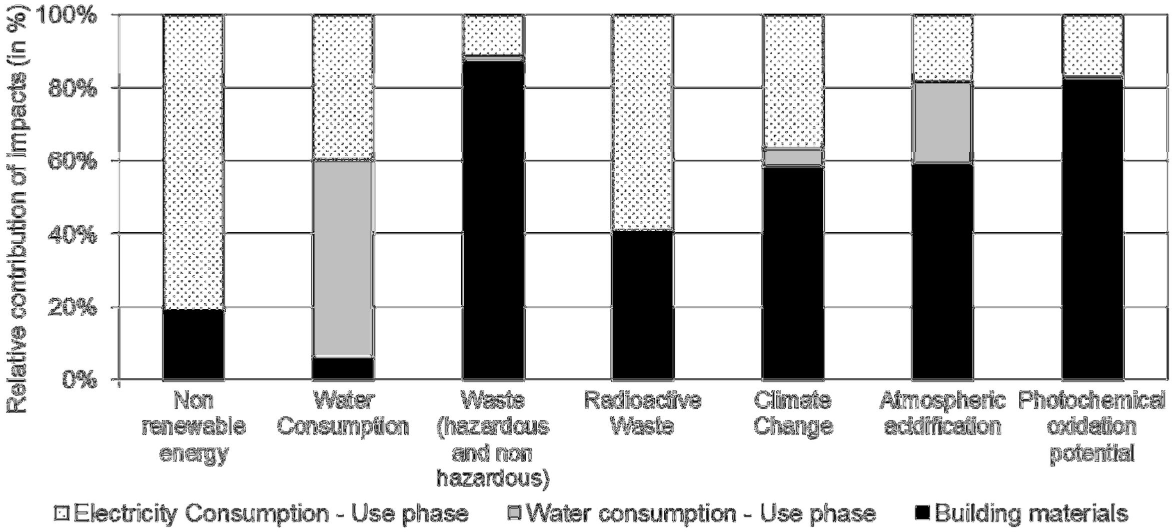


Figure 3: LCA results for the reference INCAS house (without photovoltaic panels) – annual electricity consumption and annual mix 2012 (Case C)

4.2. Import/export energy calculation time step

Table 3 shows huge differences in electricity consumed on-site, imported and exported when the energy balance is done with a yearly or an hourly time step. For instance, the self consumed energy ratio calculated annually is closed to 100 % for both houses whereas it falls to 22 % for the nZEB case and 34 % for the plus energy building case. All methods for handling on site energy production in LCA use these results.

Table 3: Differences between a yearly and an hourly calculation

		nZEB	Plus energy building
Yearly calculation	Electricity consumed on-site (kWh)	5054	4923
	Electricity imported from the grid (kWh)	1241	0
	Electricity exported to the grid (kWh)	0	131
	Self consumed energy ratio	100 %	97%
Hourly calculation	Electricity consumed on-site (kWh)	1121	1708
	Electricity imported from the grid (kWh)	5175	3215
	Electricity exported to the grid (kWh)	3934	3346
	Self consumed energy ratio	22 %	34 %

4.3. Influence of methods for handling on site energy production

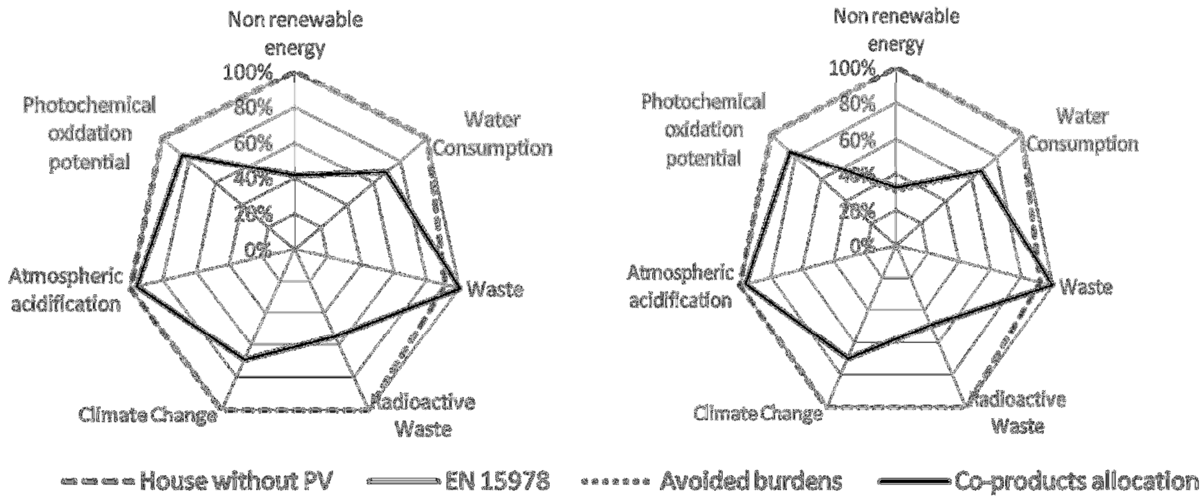
Figure 4 presents the results for the cases A, B, C (see Table 1) of the three different methods for handling on-site energy production in LCA for the nZEB and for the plus energy building.

For case A, the three methods for handling on site energy production give the same results whatever the alternative (nZEB or plus energy building). Indeed, the amount of exported electricity is small and the self consumed energy ratio is around 100 % (cf. Table 3). These two factors are the ones inducing differences between methods. For the variant comparison, all methods show that the house with PV panels has a better environmental profile than the house without PV panels except for the hazardous and non hazardous waste indicator.

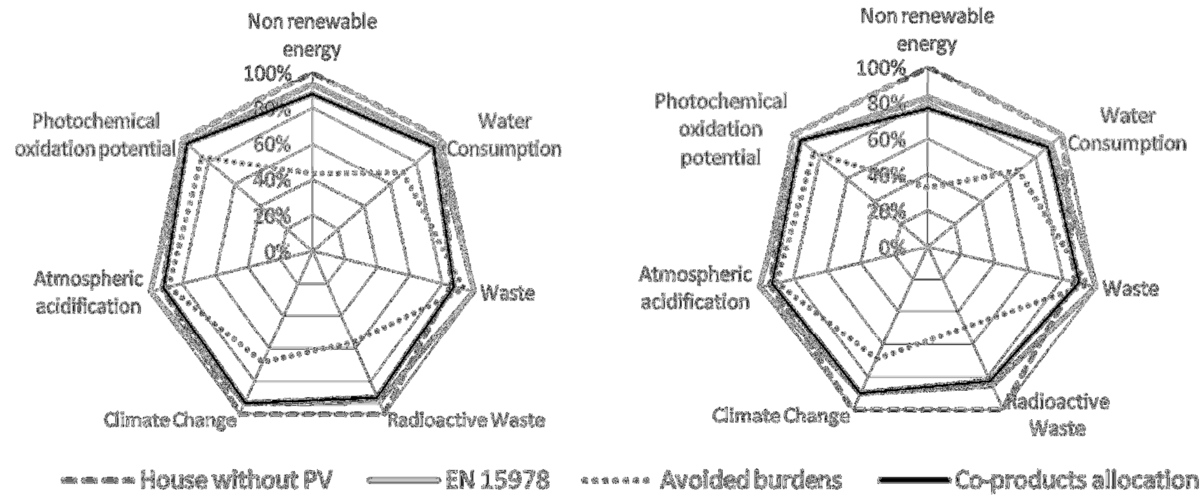
For case B, the differences between methodologies are significant (up to 58 %), especially for the plus energy building. The co-products allocation gives results close to the ones of the house without panels. Similar results are found for the EN 15978 allocation method. Regarding the avoided burdens approach, the results, whatever the building type: nZEB or plus energy, are much smaller especially for the Non renewable energy and Radioactive waste indicators. In fact, the amount of exported electricity is high: more than the half of the imported electricity for the nZEB case and higher than the imported electricity for the plus energy building case (cf. Table 3). Hence, the impacts of electricity consumption are significantly reduced for the avoided burden approach (compared to the reference case) and as seen in Figure 3, the most sensitive indicators to this change are Non renewable energy and Radioactive waste.

For case C, differences between methodologies are smaller than in case B and the results are similar for the nZEB building than those of the reference house (without PV panels). For plus energy building alternative, all methods give smaller results than the reference case. The avoided burden has much smaller impacts than the co-product allocation but only for the non renewable energy indicator. Unlike case B, the radioactive waste results are not very different for the allocation methods. Similarly to case B, the amount of exported electricity is part of the explanation; however, the annual electricity mix does not allow taking into account which energy carrier of electricity is avoided. In case B, mainly nuclear electricity is avoided (depending on the exportation hours) whereas in case C, it is the average energy carrier mix which is avoided i.e. less nuclear electricity is avoided.

Case A 1/ nZEB 2/Plus energy building



Case B 1/ nZEB 2/Plus energy building



Case C 1/ nZEB 2/Plus energy building

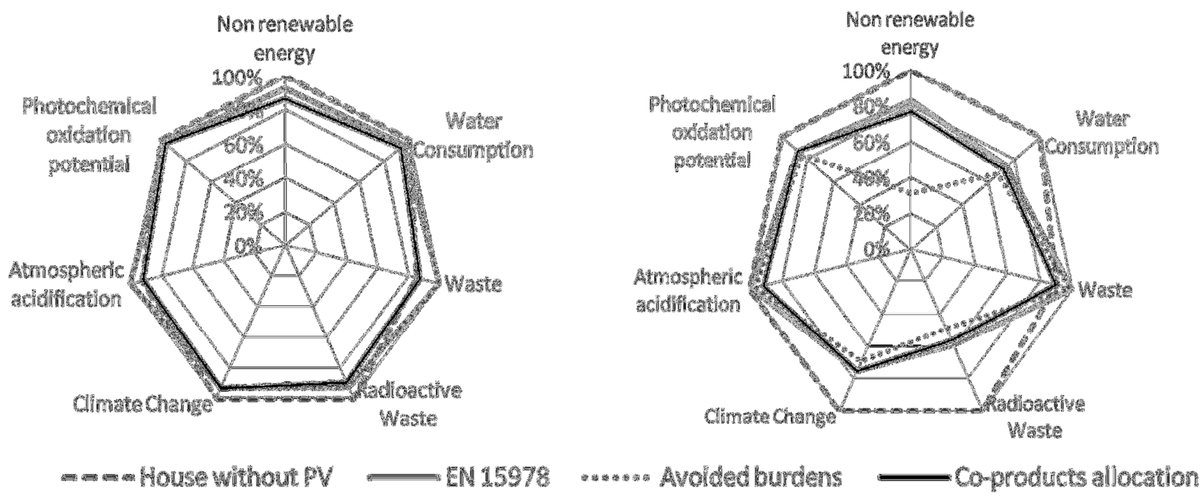


Figure 4: Comparison between the different methodologies for the INCAS house in the configuration nZEB and plus energy building for the annual calculation (A), hourly calculation (B) and hourly energy balance used with annual electricity mix (C). The house without photovoltaic panels is used as reference.

5. Discussion and conclusion

In this study, it was found that differences between methodologies are more important for the plus energy building than the nZEB. Similarly, using an hourly electricity mix led to different results than an annual mix. More differences are also found between the avoided burden and co-product allocation methods when using an hourly electric mix. This is more critical for LCA indicators sensitive to the nuclear and fossil fuel energy carriers' shares of the French grid mix (radioactive waste, climate change).

For these dwellings with photovoltaic panels, it is important to calculate the energy flows at hourly level at least Moreover, choosing an hourly or an annual electricity mix to perform the LCA influences the results; the hourly electricity mix takes into account the variability of production during the year and, will be more accurate physically speaking.

For the different methodologies, between the house with and without panels, the ranking will be the same. However, the numerical results are really different. The avoided burden methods give smaller results for the indicators: typically around 40 % for Non renewable energy, 70 % for Climate change, 55% for Radioactive waste and 70 % for Water Consumption whereas the EN 15978 and the co-products allocation give closer results, typically around 80%.

Furthermore, absolute value for each method depends strongly on how much specific electricity is required yearly by inhabitant: in this study, 20 kWh/m^2 compared to total energy needs of 52 kWh/m^2 and how it is distributed along the time.

Finally, each methodologies, has its own motivation. The EN 15978 gives some advantages to the building exported energy and some advantages for the one that will use this exported energy. The co-products allocation evens out the impacts between the building producing energy and the building consuming the exported energy. The results are more balanced than for the EN15978 method. For the avoided burden approach, the building producing energy is advantaged without implying relations with neighbouring buildings. It considers all environmental benefits and impacts allocated to the producing building, following the idea that the decision maker (the one that have chosen to install the PV panels) is responsible for related impacts and benefits.

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