

Considering the dynamics of electricity demand and production for the environmental benchmark of Swiss residential buildings that exclusively use electricity

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Abstract. The environmental impacts of buildings can significantly vary with the dynamics of their energy demand and production. Significant variations have been modelled for buildings in the U.S., France, Denmark and Switzerland but the levels of variation are different between these countries. This difference can be explained by factors like the existing energy sources, the availability of renewable energy and the importation of electricity from nearby countries. With its high share of renewable energy and significant electricity exchanges with neighbouring countries, Switzerland presents a specific case where benchmark values from dynamic life cycle assessment should be well understood. The project's goal is to provide results from a dynamic life cycle assessment with a detailed study of the influence from temporal fluctuations in the national electricity production, electricity imports, decentralised generation and electricity demand from buildings. Additionally, consequences of changing the temporal precision (i.e. hourly, daily, monthly and annual) of energy dynamics are analysed. This assessment is conducted with demand and production estimations for the design of a residential building in Switzerland. Disparities of results are assessed for all temporal precision levels with a comparison to the values that are obtained with the current national methodology which operates with values based on average annual electricity production. Results thus suggest some methodological recommendations to develop the temporal aspects of the environmental impact assessment methodology for the Swiss building sector.

1. Introduction

Numerous life cycle assessment (LCA) studies of buildings have shown that energy demand, during their use phase, is often a key source of environmental impacts over their full life cycles. When combined with the inherent temporal variability of energy sources (e.g. gas, coal, photovoltaics), this observation raises the question of considering the energy dynamics to improve the representativeness of environmental impact assessment in LCA studies. Models of energy dynamics in recent LCA studies have mapped prospective scenarios of the future [1, 2], replicated the intra-annual electricity production variations [3-11] or simulated impact changes over time [12, 13].



When looking more specifically at the question of intra-annual variations of energy demand and production, the importance of such dynamics on LCA results have been investigated since 2013 mainly in the US [3-5], France [6-8], Denmark [9] and Switzerland [10, 11]. These studies have evaluated the impacts of rather recent residential [6-8, 10, 11], commercial [9] and institutional [3-5] buildings. The level of temporal precision on energy models varies between studies with hourly [5-11], daily [9] and monthly [3-5] averages and the effect of varying precision levels has been evaluated once [9] for Denmark. Overall, these “dynamic” LCA studies confirm that some environmental impacts might be reduced or increased substantially when compared to results from models which consider the average annual energy production mixes and demand from buildings.

While past studies clearly support a more regular account of energy dynamics in LCA of buildings, many aspects are still ambiguous for the specific case of Switzerland therefore raising some questions. First, how different would results be when compared to the current Swiss evaluation standard [14] which is based on annual averages for the electricity mix? Second, what is a useful level of temporal precision to describe energy production and consumption when considering a representativeness-to-effort ratio? Third, what is the importance of limiting the details on dynamic models of neighbouring countries when looking at the choices made in the recent Swiss studies [10, 11]? Further evaluations are therefore required to explore and answer these questions and they shape the goals of this work.

2. Case study

A project for a residential building near Fribourg in Switzerland is used as a case study to answer the three questions on energy dynamics from the introduction. This building is meant for three inhabitants and possesses an energy reference area (ERA) of 199 m². Standard appliances (i.e. oven, washing machine, dryer, dishwasher, domestic hot water and pumps), lighting equipment and an air-to-water heat pump are considered to evaluate the electricity demand of this single-family home. The building is also equipped with a roof-integrated photovoltaic (PV) installation of mono-crystalline technology with a peak power of 4.5 kW facing east.

The Swiss society of engineers and architects provides the SIA 2024 standard [15] which has been used to evaluate the hourly energy demand for the considered home during a “typical” year. This temporal curve of energy demand has been calculated by adding the provided curves for the standard appliances, lighting and heating. The “typical” heating needs for the year are based on the building components and climatic data from the SIA 2028 standard [16] which is the reference in the Swiss building sector for new projects. The home’s energy demand amounts to about 8725 kWh/year (i.e. 43.85 kWh/year·m² of ERA). The hourly energy production from the PV installation is calculated with hourly solar irradiation levels in Fribourg for a full east orientation and 45° inclination during a “typical” year. The results, while more detailed, are coherent with values that are obtained from the PVopti Excel tool [17] which is widely used for projects that respect the MINERGIE® certification. The PV installation of this building is expected to produce about 3792 kWh/year (i.e. 19.06 kWh/year·m² of ERA). The hourly energy demand and production for a “typical” year are presented in figure 1 (from January 1st to December 31st).

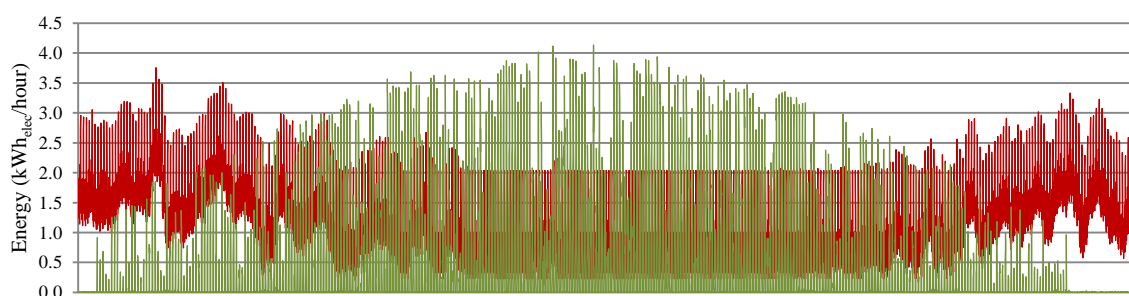


Figure 1: Building’s hourly energy demand (red) and PV production (green) over a “typical” year

3. Scope of study

Many different modelling choices have been made to evaluate the potential environmental impacts of the home's energy flows and how different temporal precision levels will affect them within the LCA framework. This scope of study therefore lists all the key aspects which should be considered in the analysis of results and commonly found in LCA studies.

3.1. Functional unit

The chosen function unit (FU) for this assessment is the m^2 of ERA used during a year which represents the indoor floor area of heated rooms inside the buildings. The evaluated potential environmental impacts values are therefore given per $\text{m}^2 \cdot \text{year}$ to present results for new homes which respects the Swiss energy standard.

3.2. Limits of the home's model

The focus on dynamics of energy demand and production for a Swiss residential building justifies the use of a model which concentrates on some components of the building's life cycle. Indeed, the only change between all considered options for this study is the temporal precision of electricity flows during the use stage. Modelling efforts are also directed on intra-annual variations meaning that no evolution on the long-term is considered and thus, analysis centres on variations of impacts for three "typical" years (i.e. 2016, 2017 and 2018). Figure 2 shows the boundary of the modelled system and offers a correspondence with stages defined in the EN 15804 document [17]. The model also details the energy sources of neighbouring countries (i.e. Austria [AT], Germany [DE], Italy [IT] and France [FR]) with a high level of temporal precision (up to hourly variation). The white boxes of figure 2 are defined as system processes since they list all the natural resource extractions and pollutant emissions that are related to the production of 1 kWh of electricity with these sources in respective countries.

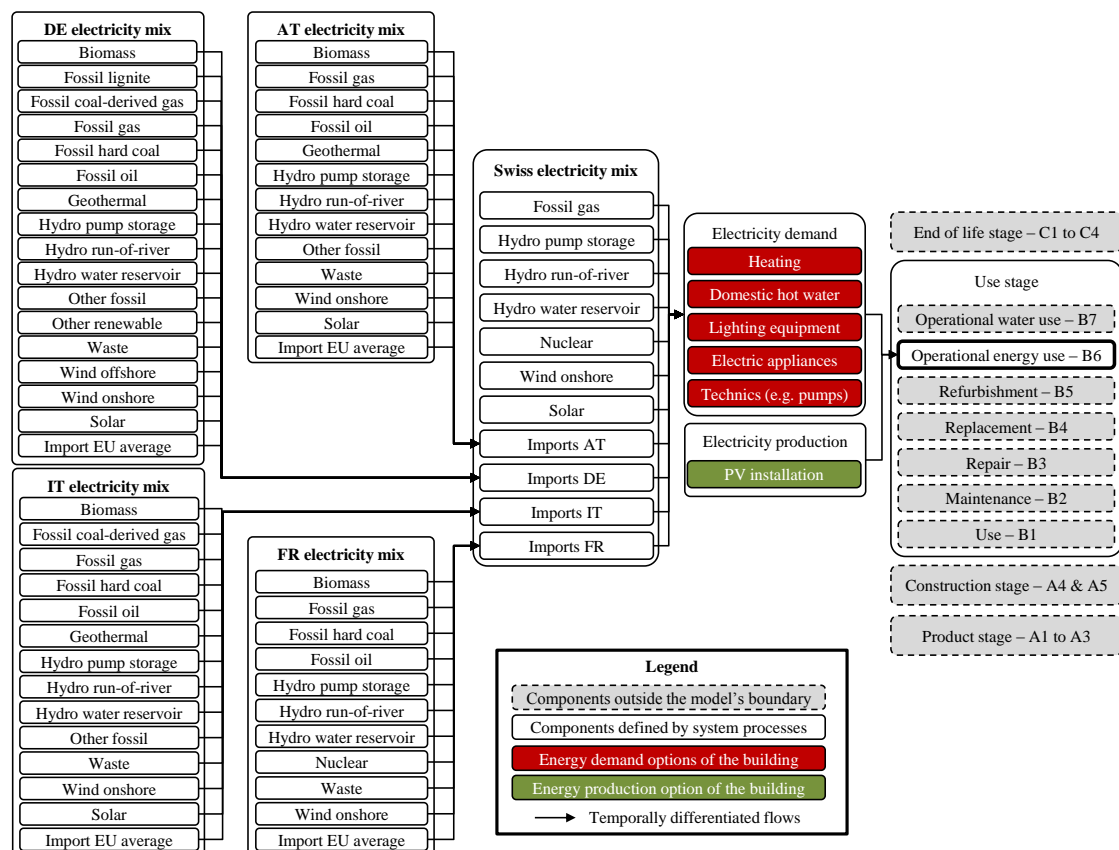


Figure 2: Considered components of the home's model with temporally differentiated flows

3.3. Sources of data

The model of figure 2 is informed mainly by two data sources: the ENTSO-E website and the ecoinvent LCA database. The ENTSO-E website [18] offers statistics on historical electricity generation from different energy sources and importation. The ecoinvent database [19] presents information that can be translated into potential impacts for these energy sources and the European average electricity mix. Combining these two sources of information requires some assumptions.

3.3.1. The ENTSO-E website: It was launched on the 5th of January 2015 and sources its information from electricity transmission system operators (TSOs) or other qualified third parties. The ENTSO-E transparency platform, in accordance with EU Regulation 543/2013, offers information on generation, load, transmission and balancing of 36 countries across the European continent (with Switzerland). The generation data describes the electricity mixes, with the different sources that are presented in figure 2, and informs on exchange values for importation and exportation between countries. The temporal precision of generation statistics varies between 15, 30 and 60 minutes depending on the data provider. Some gaps in the data can be observed which explains why this study only considers the period between 2016 and 2018. This interval of three years permits an analysis with four levels of precision: hourly, daily, monthly and yearly. Figure 3 presents an example of the provided information for the hourly electricity generation in Switzerland for one day (highest precision available).

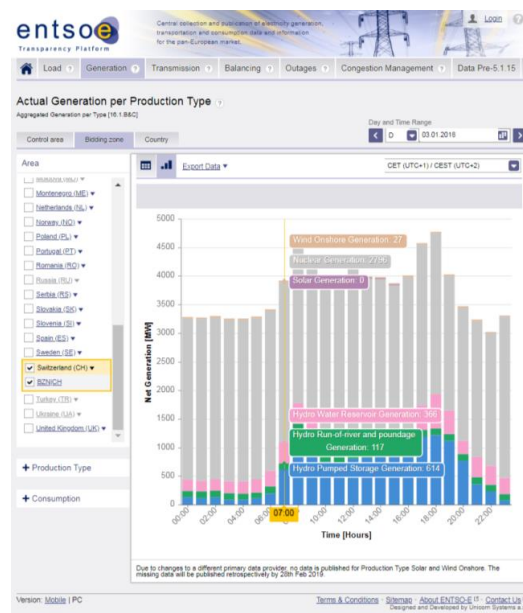


Figure 3: Example of information from the ENTSO-E website for the Swiss electricity mix

3.3.2. The ecoinvent v3.4 cut-off database: The organisation behind the ecoinvent database was founded by institutes of the Swiss Federal Institute of Technology (ETH) domain and the Swiss Federal Offices. It became a not-for-profit association in 2013. One of the core principles of this information source is “thrust in transparency” which means that it offers a comprehensive and detailed description of human activities and their effects (e.g. impacts) on the environment. Many processes of different electricity sources (e.g. coal and nuclear power plant production) are available for countries around the world. Such processes describe supply chains (i.e. link with other processes of human activities) and their elementary flows (i.e. extraction of natural resources and emission of pollutants). For all the relevant energy sources of this case study, the descriptions of processes (i.e. datasets), from version 3.4 cut-off, have been transformed into 4 potential environmental impacts (see subsection 3.4) per kWh of produced electricity with the help of the SimaPro v8.5.2.0 software.

3.3.3. Mapping connections between the data of ENTSO-E and ecoinvent. The differences in structures and levels of detail to describe the energy sources in the ENTSO-E and the ecoinvent database force the creation of a mapping structure to link environmental impacts (based on ecoinvent) to the energy sources statistics of ENTSO-E. These important modelling choices are necessary to calculate the potential environmental impacts of the Swiss electricity mix when ENTSO-E data is used for each hour of the day. Some assumptions on the shares of different technologies from ecoinvent (e.g. boiling or pressured water reactors) that relate to a common energy source in ENTSO-E (i.e. nuclear) were therefore made in this study. Table 1 presents these shares for the Swiss electricity mix. Mappings were carried out for all neighbouring countries (i.e. AT, DE, IT, FR) and readers are invited to contact the corresponding author if they would like to have access to this information. Table 1 shows that the ecoinvent database offers varying levels of details on technologies and it is important to mention that these levels of detail changes between countries.

Table 1: Mapping of links between energy sources for ENTSO-E and ecoinvent database

Energy sources in ENTSO-E	Energy sources as defined in ecoinvent v3.4 cut-off	Shares (statistics from 2014)
Fossil Gas	Natural gas, 500kW electrical, lean burn	100.00%
Hydro Pumped Storage	Hydro, pumped storage	100.00%
Hydro Run-of-river	Hydro, run-of-river	100.00%
Hydro Water Reservoir	Hydro, reservoir, alpine region	100.00%
Nuclear	Nuclear, boiling water reactor	47.35%
	Nuclear, pressure water reactor	52.65%
Wind Onshore	Wind, <1MW turbine, onshore	5.48%
	Wind, >3MW turbine, onshore	9.59%
	Wind, 1-3MW turbine, onshore	84.93%
Solar	Photovoltaic, 3kWp facade installation, multi-Si, laminated, integrated	3.74%
	Photovoltaic, 3kWp facade installation, multi-Si, panel, mounted	3.74%
	Photovoltaic, 3kWp facade installation, single-Si, laminated, integrated	2.48%
	Photovoltaic, 3kWp facade installation, single-Si, panel, mounted	2.48%
	Photovoltaic, 3kWp flat-roof installation, multi-Si	11.35%
	Photovoltaic, 3kWp flat-roof installation, single-Si	7.47%
	Photovoltaic, 3kWp slanted-roof installation, a-Si, laminated, integrated	0.43%
	Photovoltaic, 3kWp slanted-roof installation, a-Si, panel, mounted	6.32%
	Photovoltaic, 3kWp slanted-roof installation, CdTe, laminated, integrated	6.90%
	Photovoltaic, 3kWp slanted-roof installation, CIS, panel, mounted	0.86%
	Photovoltaic, 3kWp slanted-roof installation, multi-Si, laminated, integrated	3.74%
	Photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	28.96%
	Photovoltaic, 3kWp slanted-roof installation, ribbon-Si, laminated, integrated	0.29%
	Photovoltaic, 3kWp slanted-roof installation, ribbon-Si, panel, mounted	4.02%
	Photovoltaic, 3kWp slanted-roof installation, single-Si, laminated, integrated	2.44%
	Photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	14.79%

3.4. Considered impact categories

The goal of comparing results from a dynamic assessment of energy flows with different temporal precision levels with the current Swiss standard based on annual averages (i.e. KBOB [14]) imposed the choice of three impact assessment methods that are used in this standard. The greenhouse gas (GHG) emissions (in kg of CO₂ eq.) were calculated with the characterisation factors (CFs) of the IPCC2013-100 year v1.03 method [20]. The renewable and non-renewable primary energy (in MJ primary) were computed with the CFs of the CED v2.05 method [21]. The environmental loading points (in UBP) were determined with the CFs of the ecological scarcity (ES) 2013 v1.05 method [22]. All these methods are available in the SimaPro v8.5.2.0 software.

3.5. Calculations of energy dynamics in a Swiss residential building

Once all the data has been obtained from the different sources and processed with a LCA software, it becomes rather straightforward to merge the temporally differentiated information of energy demand with the potential environmental impacts of the Swiss electricity mix for different hours, days, months and years. Then, the environmental impact of energy production from the PV installation is accounted while making the assumption that auto consumption is a priority. This means that only excess demand from the building will be covered by the Swiss electricity mix. The environmental impacts of electricity production from overproduction of the PV installation are not accounted in the impacts of the building (i.e. when production is higher than demand in figure 1). This modelling choice is explained by the idea that the Swiss grid, which uses this overproduction, should assume the impacts for its other customers. It should also be mentioned that the environmental impacts of 1 kWh of PV electricity is computed from the environmental impacts of the installation divided by its electricity production (in kWh) over its full life cycle (e.g. 0.093 kg of CO₂ eq./kWh over 25 years). The following equation explains the calculation for any time period (e.g. an hour of day or a month).

$$Impact_{\Delta t} = P_{PV,\Delta t} \cdot EIF_{PV} + [(D_{House,\Delta t} - P_{PV,\Delta t}) \cdot EIF_{CH-mix,\Delta t}]_{if D > P}$$

Where:

$Impact_{\Delta t}$ is the impact of energy consumption for the selected time period Δt

$P_{PV,\Delta t}$ is the production of electricity from the PV installation during Δt

$D_{House,\Delta t}$ is the electricity demand from the different devices in the building during Δt

EIF_{PV} is the environmental impact factor of the PV electricity, which does not change

$EIF_{CH-mix,\Delta t}$ is the environmental impact factor of the Swiss electricity mix during Δt

4. Results and discussion

Figure 4 presents the potential impacts of the annual energy flows (i.e. demand and production) per m² of ERA for the four categories of the Swiss standard when system dynamics are considered. The dotted red lines are also offered to present the environmental impacts that are obtained when values of the Swiss standard (i.e. KBOB) are used (e.g. 0.102 kg of CO₂ eq./kWh for the Swiss electricity mix).

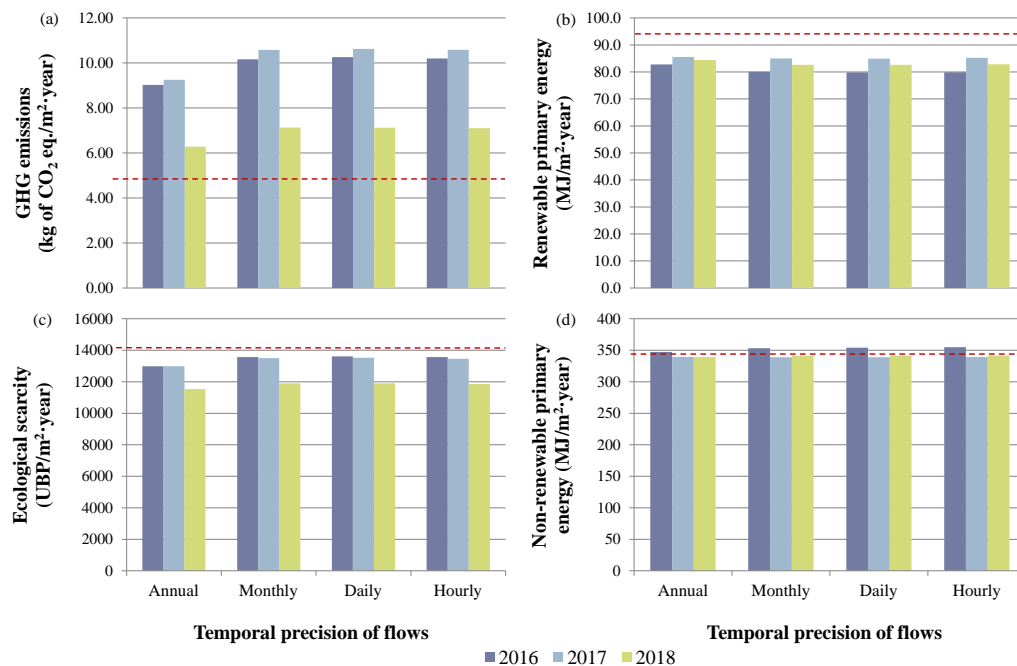


Figure 4: Potential environmental impacts from energy flows in 1 m² ERA for 2016, 2017, 2018

Results in figure 4 only show a significant divergence between the dynamic assessment and the outcomes of the Swiss standard evaluation tool (i.e. KBOB) for the GHG emissions (i.e. $> +65\%$). The three other impact categories present smaller differences (-12% on average for (b), -7% on average for (c) and -1% on average for (d)). To go beyond this simple observation, two alterations between the annual static and dynamic models are presented in table 2 to show their importance on these observed total differences. It becomes clear that the change of background database ($\Delta 1$) and the description of the electricity mix ($\Delta 2$) have opposing effects on the three categories with relatively small variation (i.e. b, c and d). Table 2 also illustrate that both alterations have similar levels of importance when absolute difference are considered between the dynamic and standard results.

Table 2: Main contributors to the differences between the dynamic and standard results of KBOB

Categories of environmental impacts	Step-by-step analysis					Share of absolute difference	
	ecoinvent v2.2+ (KBOB)	$\Delta 1$ database	ecoinvent v3.4 (static)	$\Delta 2$ electricity mixes	Dynamic annual (2016)	$\Delta 1$	$\Delta 2$
(a) GHG emissions (kg CO ₂ eq./m ² _{ERA} ·year)	4.40	+23%	5.42	+67%	9.03	31%	69%
(b) Renewable primary energy (MJ/ m ² _{ERA} ·year)	94.0	+19%	112	-26%	82.8	44%	56%
(c) Non-renewable primary energy (MJ/ m ² _{ERA} ·year)	347	-22%	272	+28%	347	46%	54%
(d) Ecological scarcity (UBP/ m ² _{ERA} ·year)	14065	-22%	11026	+19%	13151	59%	41%

Additionally, a relatively important variation of impacts between the annual average values and more precise options (i.e. monthly, daily, hourly) can be observed in figure 4 for GHG emissions ($+14\%$ on average) and ecological scarcity ($+4\%$ on average). Conversely, results for primary energy use (renewable and non-renewable) are not varying much with an increase of the temporal resolution. The same results show that most of the change for GHG emissions and ecological scarcity can be observed with the use of a monthly precision. This implies that a more detailed model will not change the conclusions of the environmental assessment for the analyses residential building which is representative of future single family housing in Switzerland.

The results of figure 4 also show that differences in electricity production between the years of a building use phase might relate to higher impact variability than the assessed intra-annual variations. Indeed, there is a much larger difference of impacts between 2017 and 2018 (i.e. -32% kg of CO₂ eq. and -11% UBP) than for any of the observed changes with different levels of intra-annual precision. A detailed analysis of the model clearly indicates that this difference is mainly explained by the reduced importation of German electricity during the beginning of 2018. Such an outcome stresses the need to consider the future of the Swiss electricity mix to obtain representative environmental assessments of buildings. Furthermore, it highlights one limitation of this study concerning the small amount of available historical statistics (i.e. 3 years) in comparison to the expected lifetime of buildings (i.e. 60 years). It is also worth mentioning that a detailed description of production sources for neighbouring countries was necessary to make this observation.

To go further on the question of a relevant complexity level for the model of energy sources in neighbouring countries of Switzerland, a comparison of results from this study and those of a recent publication [11] is necessary. In this publication, the temporal variations in primary energy use and GHG emissions have been modelled for the Swiss grid, but this model uses average values to describe the GHG intensity of France, Germany and Austria, while neglecting Italy. On this aspect, the complexity of the model is lower than the one that has been used in this study (see figure 2). The authors of this publication then obtain a level of GHG emission, based on hourly data, which is increased by 1.9% when compared to the result of a calculation with an annual average. This variation is significantly lower than what has been obtained in this study (i.e. $+12\%$) which might partially be explained by the difference in the studied cases (i.e. buildings), but that also showcase the effects of considering a complex model of electricity importations.

5. Conclusion

A LCA study of a Swiss residential building has been conducted with different levels of temporal precision (i.e. hourly, daily, monthly and yearly) to model the potential environmental impacts of the dynamics of its energy demand and production during its use stage. When compared with values from the currently used standard in Switzerland, the results from this study show a significant difference for GHG emissions which can be explained by the use of different sources of data for energy statistics and environmental information. The comparison of results from models with different levels of temporal precision confirms previously observed variations, but also demonstrates that monthly precision is sufficient to make a representative assessment of new single-family housing in Switzerland. The separation of yearly demand and production for 2016, 2017 and 2018 then shows that prospective modelling might be more relevant than intra-annual precision to offer representative assessment. Finally, the consideration of temporal variation from energy sources in neighbouring countries reveals its importance when compared to models which considers average European electricity production.

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