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Dynamic Life Cycle Assessment of the building electricity demand

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Abstract

The environmental footprint of the Swiss consumed electricity is not constant over the year. Indeed, the share of the energy production means varies throughout the days, weeks and months, as a function of the electricity demand, resource availability (hydro, solar) and the power plant availability (maintenance). Switzerland also balances its electricity grid with imports from neighboring countries. All these possible fluctuations imply a variable environmental footprint of the Swiss consumed electricity, which affect the environmental impact of the building electricity demand. So far, in Switzerland, the environmental accounting of the building energy demand considers yearly average impacts for the consumed electricity. The EcoDynBat project has developed a framework to collect and merge all the necessary data to conduct a Dynamic Life Cycle Assessment (DLCA) of the environmental impact for the Swiss building consumed electricity under different time steps. The resulting database and methodology has been applied to different profiles of building electricity demand, including buildings with heat pump and/or decentralized electricity production systems. The study evaluates the influence of different time step resolutions on the environmental impacts of the electricity demand in Swiss buildings. Results for the climate change impact show a variability going from 36 to 580 g of CO_2 eq/kWh for the consumed electricity when using an hourly resolution, during a one year period. This variability causes an increase in the impacts of up to 24% for space heating, when compared to the annual average impacts. Other electricity loads that do not have a seasonal profile are less affected by the time resolution. Nevertheless, observed trends suggest that an hourly resolution will be relevant to evaluate the potential environmental impacts of smart buildings.

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1. Scope

The Swiss electricity production strongly relies on hydro and nuclear energy [1], which are considered as energy sources with low carbon footprints [2, 3]. In previous decades, Switzerland was producing more electricity than needed and was deemed a net exporter. However, over time, the national electricity demand significantly increased and Switzerland became dependent on the imports from neighboring countries. These imports became especially significant during winter, when the higher seasonal demand (partially due to electric space heating) coincides with a reduced national renewable electricity production capacity (i.e. the hydroelectricity production is low because of the reduced snowmelt, while the photovoltaic production is low due to reduced solar radiation). Hence, Swiss production means and electricity imports are not constant over the year, but rather fluctuate, as illustrated in Figure 1 for the year 2018.

Figure 1 Profiles of Swiss production (top) and imports (bottom) in 2018 [4]

These variations in the electricity mix composition create fluctuations in terms of its environmental impacts. However, conventional LCA databases often only provide yearly average environmental impacts for the Swiss consumed electricity. For example, ecoinvent [2] calculates a climate change impact of 129 g CO_2 eq per consumed kWh, and KBOB [3] suggests an impact of 102 g CO_2 eq per kWh.

In addition to the variability of the electricity mix, the electricity demand of the Swiss buildings can vary significantly, because of the intra-day peaks or the seasonal effects. This fact causes an additional variability to the environmental impacts of the buildings. This aspect is particularly notable in buildings with important seasonal electricity demands, which occurs when electricity based heating systems are used (in particular heat pumps) and when decentralized electricity production systems are installed (photovoltaic production mostly occurring in summer). It becomes evident that considering the dynamic effects of the buildings is important, in order to increase the reliability of the resulting environmental impacts. Moreover, with the emergence of the smart-building concept, the dynamic consideration should also gain importance.

In this context, the EcoDynBat project, funded by the research program “Buildings and Cities” of the Swiss Federal Office of Energy (SFOE), has developed a framework for the collection of the necessary data, in order to calculate the environmental profile of the Swiss consumed electricity, using a Dynamic Life Cycle Assessment (DLCA), under different time steps. Then, based on the calculated environmental profile of the Swiss electricity mix, the impacts of different buildings have been calculated for different time steps (hourly, daily, monthly and annually) and various usages (space heating, domestic hot water, and other domestic appliances). Finally, the influence of the four time resolutions is quantified, on the environmental impacts of the buildings. By considering the difference with the annual calculation based on average annual values, the time resolution influence is therefore quantified.

2. Method

The overall EcoDynBat framework is presented in Figure 2 and described in the following sections.

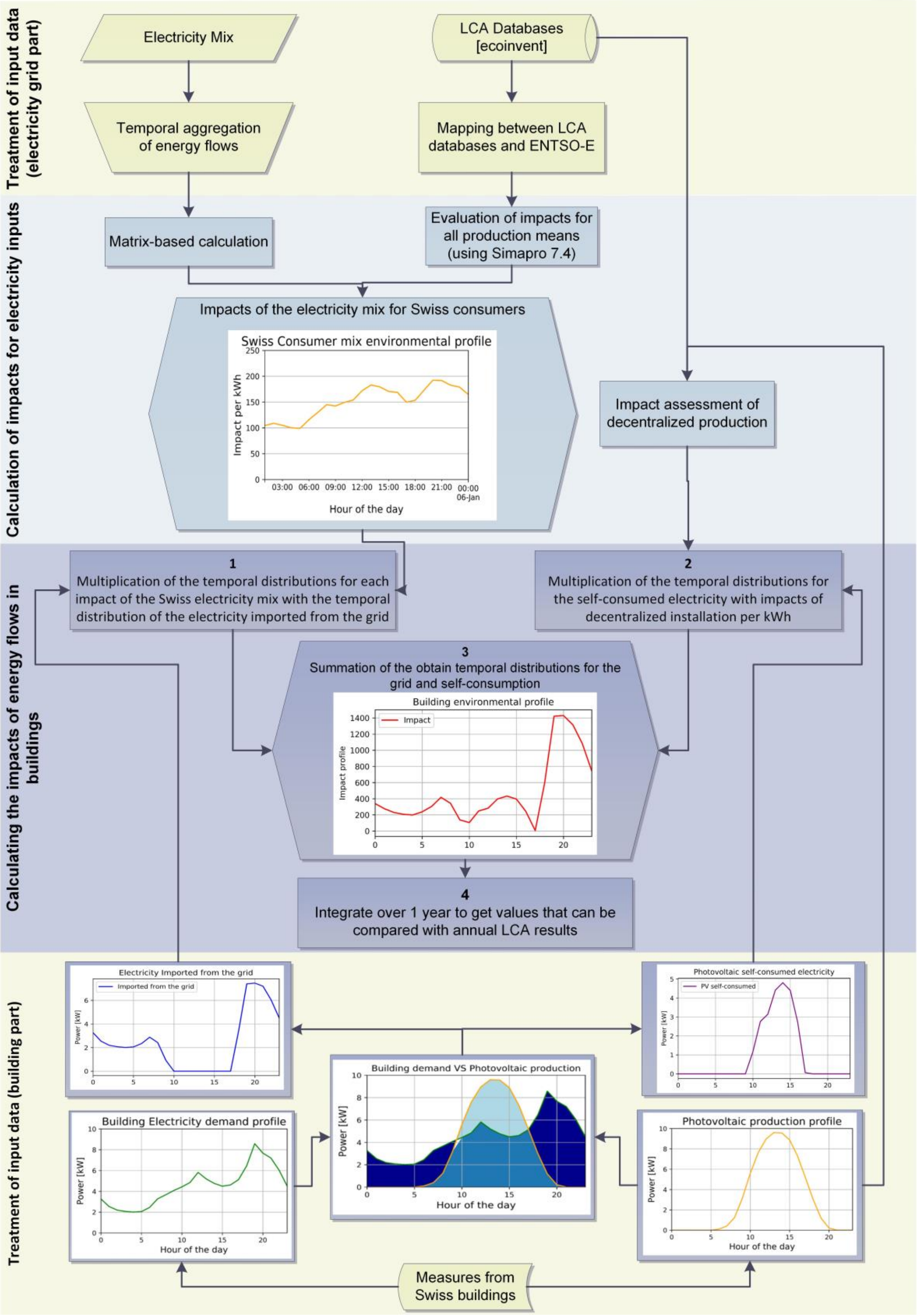

Figure 2 Overall calculation framework

2.1 Treatment of the input data

This section describes the process of obtaining and processing data, regarding the electricity production means at every time step, in order to form a harmonized dataset. To do so, the data from the ENTSO-E transparency platform [4] were collected for the production mix of Switzerland, Germany, France, Austria, Italy and Czech Republic. These five countries were preliminary selected, since they have the maximum influence on the environmental profile of the Swiss consumed electricity. Indeed, considering additional countries would increase the accuracy of the results by less than 2%. This would increase disproportionally the necessary calculation time and thus, they were excluded. The Czech Republic was considered in the geographical scope of the study, although it does not directly exchange with Switzerland. The reason lies in the fact that the Czech Republic indirectly influences the environmental impact of the Swiss electricity mix, due to its important exchanges with Germany and Austria. The bilateral exchanges between the six countries were also considered. Since ENTSO-E provides net exchanges (i.e. net differences between imports and exports), the raw exchange data from Swissgrid [5] were considered and incorporated in the dataset. In addition, the production data for each considered country was cross-compared with other data sources, and were found to agree well with each other. However, for Switzerland, the ENTSO-E production values were found to be lower than the national statistics [1]. A specific assessment over a few representative days was performed, showing that the ENTSO-E data underestimated the production of run-off river plants and other renewables (photovoltaics in particular). This gap is explained by the fact that ENTSO-E seems to consider only high voltage production means, while an important part of the generation from run-off river plants and other renewables sources is produced at lower voltage levels. Thus, this gap was filled with a production mix made of photovoltaics (PV) and hydro run-off plants according to the available data of typical days [1]. Based on these adaptations (raw exchanges and gap filling),as well as the addition of the transmission losses, it was possible to calculate, for each time step, the share of production means for the production of 1kWh, to be consumed in the Swiss network. Using a matrix-based approach (see details in [5]), it was then possible to asses, for each time step, the share of each production means per country.

At the building level, the electricity consumption data were collected for three usages of the different case studies: space heating, domestic hot water, and other domestic appliances. If available, the PV production was measured and the self-consumption was calculated, providing the consumed electricity share from the grid and from the PV installation for each usage. For the case studies, for which no PV installations were available, PV production models were developed, based on the work of Holmgren et al. [7].

2.2 Calculation of the impacts of the electricity inputs

Once the share of each production means is obtained, the environmental impacts of the produced electricity can be calculated. The production means in the ENTSO-E platform are less detailed compared to the ecoinvent database. For example, ENTSO-E gives information for the nuclear electricity per country, while ecoinvent provides information for the pressurized and boiling water reactor. In order to harmonize the different information levels among the sources, which is driven by the lowest detailed data source (i.e. ENTSO-E), a mapping file was created (see [6] for details).

In terms of decentralized electricity generation, the environmental impact of the PV electricity was then calculated according to the following equation:

$$\frac{\mathbf{Impact}_{\mathbf{PV\ electricity}}}{\mathbf{kWh}} = \frac{\mathbf{Impact}_{\mathbf{installation}_{\mathbf{manufacturing}}} + \mathbf{Impact}_{\mathbf{Installation}_{use\ phase}}}{\mathbf{Lifetime\ Production\ (kWh)}}$$

The lifetime production is, based on the electricity production measured or calculated for the case studies, multiplied by an estimated installation lifetime of 25 years. The impacts of the PV installation (manufacturing and disposal stage) and use-phase can be found directly in the ecoinvent database. From this step, the environmental input data of the produced electricity are calculated and the calculation of the building's electricity impacts can be continued.

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2.3 Calculating the impacts of electricity flows in buildings

The following calculation steps are carried out to obtain the impacts of the electricity consumption in buildings (see also Figure 1):

1. Multiplication of the different temporal distributions of the impacts of the Swiss electricity mix, with the corresponding temporal distributions of the electricity imported from the grid.
   ⇨ This step evaluates the impacts of the electricity used in buildings, when it is provided by the grid for every time step over the full period of assessment (i.e. one year).
2. Multiplication of the temporal distributions of the self-consumed electricity, with the impacts of the decentralized installations.
   ⇨ This step evaluates the impacts of the electricity produced by the decentralized installation, when it is used in the building for every time step over the full period of assessment (e.g. one year).
3. Summation of the obtained temporal distributions for the grid and self-consumption.
   ⇨ This step combines the impacts of all electricity uses in buildings, for every time step over the full period of assessment (e.g. one year). Values can be divided by the ERA (in m^2) of the building, in order to provide a functional unit, for comparing the results among buildings.
4. Integration of the dynamic impacts of the different time steps, over one year, in order to compare the annual impacts of the different time steps.
   ⇨ This summation of impacts over the full year is necessary for comparing the results for the various time step resolutions and quantifying the influence on the environmental impact accuracy. The annual results can also be compared with other “traditional” LCA calculations based on the ecoinvent or KBOB Swiss electric grid impact factors.

These calculation steps have been carried out with Python algorithms for each time step for both 2017 and 2018 because electricity data were available for this period. In EcoDynBat, four impact categories were assessed; Climate Change (GWP), Non-Renewable Primary Energy (NRE), Renewable Primary Energies (RE), and Ecological Scarcity (ES). The present paper presents the results of the climate change (GWP) and non-renewable primary energy (NRE) impact category.

3. Results

3.1 Environmental profiles of the Swiss consumed electricity

The resulting environmental profiles of the Swiss consumed electricity are presented per contributing country and main production categories, under a daily time step to simplify the graphic readability, in Figure 3.

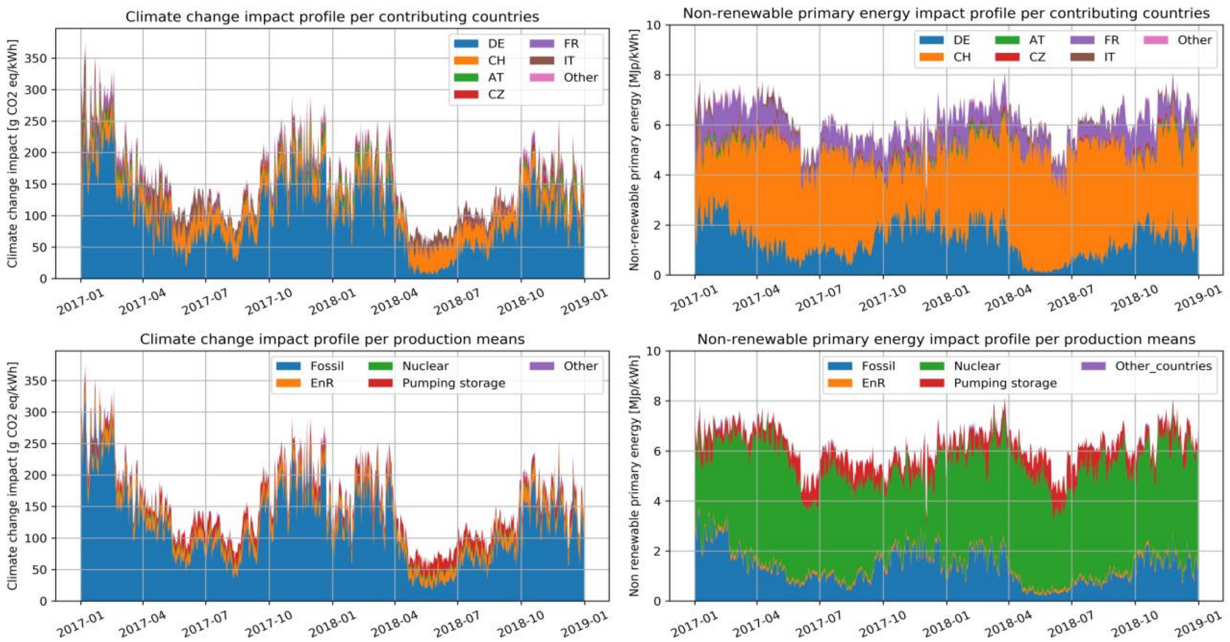

Figure 3 Profiles of environmental impacts for the Swiss consumed electricity (daily time step plot)

The environmental impacts of the Swiss consumed electricity present a high variability in the GWP impact category (from 36 to 580 g CO_2 eq/kWh on the hourly basis). From the observed profiles, it appears that the climate change impact category of the Swiss consumed electricity is highly sensitive to seasonal fluctuations. In winter, Switzerland relies more on imports, especially from Germany, while in summer there are less imports, leading to significantly lower impacts. In addition, the imports have a higher impact than the national production, since the German production mix relies significantly on fossil fuel technologies, which have a higher impact per produced kWh. Thus, there is a high correlation between the imports from Germany and the GWP of the Swiss consumed electricity. The other countries have less contribution on the GWP than Germany, e.g. France has a national production that heavily relies on nuclear energy, while Austria, Czech Republic, and Italy only provide a small quantity of electricity to Switzerland. As the GWP impact of the electricity is driven by the fossil fuel production means and the Swiss electricity production means have low carbon contents, the national production has a small contribution to the total impact.

The impacts of the NRE are still significant, but they present lower variability than those of the GWP impact category (from 2.9 to 12 MJp/kWh). For the NRE, Switzerland is the main contributor to the total impact. This observation is explained by the high share of the nuclear production on the national mix and the high share of the fossil fuel-based electricity imports, which both have a high NRE impact. Thus, along with Switzerland the other main contributing countries to the NRE impact are Germany and France.

3.2 Influence of different time resolutions

The case studies used to assess the influence of the time resolution on the accuracy of environmental impact calculations are presented in the Table 1. Four Single Family Houses (SFH, CS 1-4)), one Multi-Family House (MFH, CS-4) and one office building (CS-6) have been considered. Scenarios with and without PV have been considered for each building.

Case study	Description	Heating system	PV	Time step
CS 1 - 4	Single family house, ERA= 247m^2, construction year: 1975	Heat pump	10 kW	Annual, monthly, daily, hourly
			-	
	Single family house, ERA= 273m^2, construction year: 2000		10.7 kW	
			-	
	Single family house, ERA= 149m^2, construction year: 2000		7.4 kW	
			-	
	Single family house, ERA= 130m^2, construction year: 1987		6.6 kW	
			-	
CS - 5	Multi-family house, ERA= 2663m^2, construction year: 2013		20 kW	
			-	
CS - 6	Office building, ERA= 14’195m^2, construction year: 2013		230 kW	
			-	

Table 1 Case studies description

The relative time step influence, when compared to the annual results, is presented in Figure 4 .

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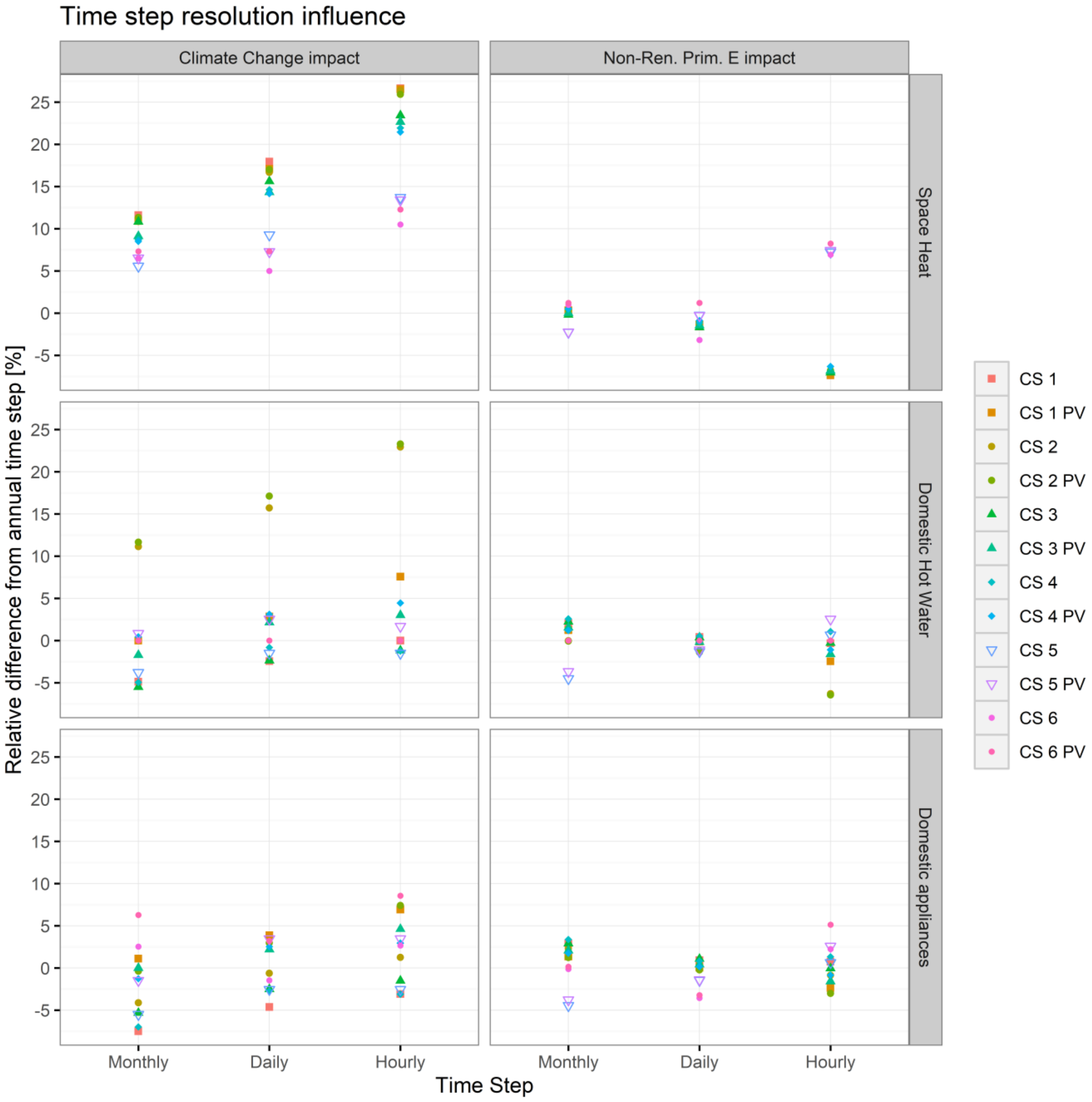

Figure 4 Relative influence of time steps compared to calculations on an annual basis

From Figure 4, it appears that the higher the time step resolution, the higher the relative difference. Therefore, using the hourly time step resolution, results in higher environmental impacts, than the other time step resolutions. Thus, when performing a DLCA calculation for the environmental impact assessment of the electricity demand for a building, the hourly time step appears to be the relevant resolution, for more reliable results that correspond better to reality and further decision making when energy optimization strategies are aimed. In addition, the comparison between the two presented indicators shows that the GWP indicator is more influenced than the NRE indicator, by the time step resolution. This observation is in accordance with the observation made for the electricity from the grid (Figure 3) for which more fluctuations are observed for the GWP. Thereby, in Switzerland, DLCA calculations should be prioritized when considering the GWP indicator. Regarding the different usages, the time step choice influences the most the electricity for space heating. This energy demand, contrary to the domestic hot water (DHW) and the other domestic appliances is highly seasonal and thus more influenced by the time step choice. The electricity demands of the DHW and the other domestic appliances are more stable over the year, for the case studies considered in EcoDynBat, and thus annual calculations appear to provide sufficient accuracy for their impact calculations. Finally, the comparison of the analyzed case studies showed that the single-family houses (CS 1-4) were more influenced by the time-step resolution than the multi-family house and the office building, since the latter were more energy efficient buildings. The consumption profiles (high seasonality for space heating, more important demand) for CS 1-4 seems to be the major explanation. In addition, larger buildings (CS5 and CS6) also exhibit less demand variability because of the scale effect.

Finally, for the case studies with PV installations, the influence of the time step is limited. Indeed, the PV electricity of each installation has a fixed environmental impact per kWh (see method section). Thus, when the consumed electricity from the grid (with variable impacts) is substituted by the constant impact of the PV, the sensitivity to the time step choice is reduced. Therefore, for buildings with no electrical storage and a high self-consumption rate, the use of DLCA for the calculation of the building electricity environmental impact is not recommended.

4. Discussion

Several observations have come out of the EcoDynBat project:

- There are some discrepancies in the different considered data sources for the electricity mix of Switzerland (ENTSO-E, SFOE, Swissgrid). It would be of interest to develop energy profiles for the Swiss production, imports and consumption mix, in order to develop reliable models that could be used for developing the mid-term Swiss energy strategy.
- Different modelling approaches are currently used for the environmental accounting of the consumed electricity. In EcoDynBat, the environmental impacts of the consumed electricity have been calculated for four time steps, considering the physical flows and exchanges among the neighboring countries. Other approaches consider the traded flows or the certificate of origin, which can significantly affect the results of the environmental impact assessment. Comparing, in detail, the environmental results for the different approaches and proposing a consensual approach for the Swiss environmental accounting of the consumed electricity would be of interest.
- The EcoDynBat results highlight the fact that dynamic aspects should be considered for the environmental impacts evaluated, using the GWP category.
- Seasonal demand profiles require considering intra-annual resolution for the environmental impact calculation. The appropriate metric to choose whether a DLCA is necessary or not has still to be defined. Based on the assessed buildings, it seems that constant usages over the year do not require a higher time step resolution than the currently annual average used
- Demand Side Management strategies and active energy solutions (electrical storage, peak shaving solutions, etc.) could increase the influence of the time-step, since the electrical uses would be dynamically managed in buildings. In addition, the management strategies could encompass the environmental aspect in order to minimize the impacts of the electricity consumption.
- The evolution of the Swiss electricity mix could also increase the time step influence. For that purpose, EcoDynBat considered a pessimistic scenario, for which the Swiss nuclear was only compensated by an increase in imports (no additional indigenous production). In this situation, the environmental impacts of the consumed electricity are significantly higher and the time step influence increases. Thus, developing dynamic environmental impact models for the future Swiss consumed electricity could be relevant.

5. Perspectives

The EcoDynBat project has developed a complete framework to collect and bring together the necessary data for the calculation of the environmental impacts of the Swiss consumed electricity. This framework is extensively presented in the report of project. Based on the “EcoDynBat dataset”, a matrix-based calculation approach for the environmental impact characterization of the consumed electricity was developed. This approach is of interest, since it consistently considers the variations of electrical flows (indigenous production, imports and productions of the neighboring countries) that are necessary to supply the Swiss electricity mix. Based on the calculation procedure, it is possible to point out which production means contribute most to the environmental impact of the Swiss consumed electricity in different periods. The calculation procedure could now be applied each year

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to observe the dynamic trend, regarding the environmental impacts of the Swiss consumed electricity.

Based on the obtained results, it appears more relevant to consider the dynamic aspect for the GWP category and for energy loads that substantially change during different seasons. In addition, it appears that future and currently emerging smart buildings with demand side management and active energy management systems could (1) be more influenced by dynamic environmental factors and (2) include dynamic factors, when developing control strategies that minimize the building's environmental impacts. Nevertheless, it would be necessary to quantify the impact mitigation potential when considering such aspects and, if proven relevant, it would be necessary to forecast the environmental impact of the Swiss consumed electricity, at least in the short-term.

References

[1] Office Fédéral de l'Energie (OFEN), "Statistiques Suisse de l'électricité 2018"

[2] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230

[3] KBOB, Données des écobilans dans la construction 2009/1:2016

[4] European Network of Transmission System Operators for Electricity (ENTSO-E)

[5] Heijungs R, Suh S (2002): The Computational Structure of Life Cycle Assessment. ECO-EFFICIENCY IN INDUSTRY AND SCIENCE, 11. Kluwer Academic, Dordrecht, The Netherlands, 241 pp

[6] Beloin-Saint-Pierre, D., P. Padey, B. Périsset, et V. Medici. « Considering the Dynamics of Electricity Demand and Production for the Environmental Benchmark of Swiss Residential Buildings That Exclusively Use Electricity ». IOP Conference Series: Earth and Environmental Science 323 (septembre 2019): 012096. https://doi.org/10.1088/1755-1315/323/1/012096.

[7] - W. F. Holmgren, C. W. Hansen, and M. A. Mikofski, "pvlib python: a python package for modeling solar energy systems," J. Open Source Softw., vol. 3, no. 29, p. 884, 2018.