Rapport final du 20.12.2020

EcoDynBat – Final Report

Dynamic Life Cycle Assessment of Buildings

Date: 15.06.2020

Lieu: Berne

Prestataire de subventions:
Office fédéral de l'énergie OFEN
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CH-3003 Berne
www.ofen.admin.ch

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Numéro du contrat de l'OFEN: SI/501814-01

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Zusammenfassung

Das Projekt EcoDynBat (Dynamic Life Cycle Assessment of Buildings) untersuchte den Einfluss der zeitlichen Auflösung auf die Genauigkeit der Berechnungen der Umweltbelastung des Schweizerischen Netzstromes und damit des Stromverbrauches in Gebäuden mittels dynamischer Ökobilanz (Dynamic Life Cycle Assessment, DLCA). Das Projekt wurde von HEIG-VD, EMPA und SUPSI durchgeführt. Um die Projektziele zu erreichen, wurde ein Berechnungsverfahren der notwendigen Daten definiert sowie ein methodischer Rahmen für die Ökobilanz-Resultate des Stromes festgelegt. Diese Rahmenbedingungen werden im vorliegenden Bericht dargestellt und können bei zukünftigen Studien zu diesem Thema eingesetzt werden. In einem ersten Schritt wurden die notwendigen Daten für die ökologischen Berechnungen gesammelt. Die gesammelten Daten repräsentieren stündliche Informationen von der Stromproduktion, Importen und Exporten sowie vom Stromverbrauch in der Schweiz und ihren europäischen Nachbarländern. Nach einer Validation der Informationen wurde diese in einem "EcoDynBat"-Datensatz aggregiert, welcher die Herkunft des in der Schweiz konsumierten Stroms zu jedem Zeitpunkt basierend auf einem physikalischen Flussansatz angibt. Durch die Anwendung der Methode der Ökobilanz wurde für diese Daten das Umweltprofil des Schweizer Strommixes in einer stündlichen, täglichen, monatlichen sowie jährlichen Betrachtungsweise berechnet. Die Auswirkungen wurden für vier Kategorien berechnet: Klimawandel, erneuerbare und nicht erneuerbare Primärenergie sowie die ökologische Knappheit (Methode der Umweltbelastungspunkte, UBP), wobei insbesondere beim Treibhauseffekt signifikante jährliche und halbjährliche Schwankungen sichtbar wurden (Jahreswert 2018 = 138g CO_2-Äq/kWh, mit stündlichem Min/Max-Bereich von 35 bis 385g CO_2-Äq/kWh).

In einem nächsten Schritt wurden diese Umweltprofile zur Untersuchung des Einflusses der zeitlichen Auflösung auf die Genauigkeit der Berechnung der Umweltbelastung durch den Strombedarf bei Gebäuden verwendet. Dazu wurden mehrere Fallstudien gemacht, und in jeder wurden unterschiedliche Konfigurationen für die technischen Anlagen (wie Wärmepumpe, Photovoltaikanlage, Mikroblockheizkraftwerk, usw.) berücksichtigt. Die Ergebnisse zeigten, dass die Granularität der zeitlichen Auflösung Einfluss haben kann für saisonale Energiebedarfsprofile (wie z.B. Raumheizung). Im Gegensatz dazu wird die Genauigkeit der Auswirkungen des relativ konstanten Strombedarfes nur geringfügig beeinflusst durch die gewählte zeitliche Auflösung. Verschiedene Sensitivitätsanalysen bestätigten, dass die Wahl einer stündlichen Auflösung für den saisonalen Strombedarf kritisch ist, wenn dieser den Bedarf an konstantem Strombedarf deutlich übersteigt. Abschliessend wurde der Einfluss der zeitlichen Auflösung im Hinblick auf die Umweltvorteile einer kombinierten Verwendung von Photovoltaik und stationäre Batterien bewertet. Die Ergebnisse für den Treibhauseffekt zeigten, dass bei einer stündlichen Auflösung die Umweltvorteile für das untersuchte Gebäude mit dem aktuellen Strom mix der Anlage abnehmen. Alles in allem offeriert das EcoDynBat Projekt einen generellen Überblick über die Thematik der dynamischen Ökobilanz am Beispiel des Strombedarfes von Gebäuden, ausgehend von der Datenerfassung dieses Strombedarfes, dem methodischen Rahmen für die Ökobilanz-Berechnungen, den Auswirkungen des Schweizer Stromnetzes, sowie den Auswirkungen durch den Strombedarf auf der Gebäude-ebene.

Résumé

Le projet EcoDynBat (Ecobilan Dynamique de l'électricité) a eu pour objectif d'étudier l'influence du pas de temps sur la précision des calculs d'impacts environnementaux de l'électricité consommée par les bâtiments en Suisse. Ce projet a été réalisé par la HEIG-VD, l'EMPA et la SUPSI. Pour réaliser l'objectif du projet, un cadre méthodologique et une structure de calcul a été définie. Celles-ci sont clairement explicitées dans le présent rapport et pourront être réutiliser pour de futures étude sur le sujet. Ensuite, les données nécessaires au calcul ont été collectées. Les données collectées comportent les informations horaires sur la production, les imports/exports et la consommation énergétique des pays Européens. Ces informations ont ensuite été caractérisées et validées puis agrégées dans un jeu de données « EcoDynBat » fournissant à chaque pas de temps l'origine de l'électricité consommée en Suisse selon une approche de flux physiques. Par la suite, la méthode de calcul EcoDynBat a été appliquée à ce jeu de données et a permis d'obtenir le profil environnemental (indicateurs sur le changement climatique, l'énergie primaire renouvelable et non-renouvelable ainsi que le score écologique – ecological scarcity) horaire, journalier, mensuel et annuel de l'électricité consommée en Suisse. Ce profil a été étudiée en détail et a montré de large fluctuations aussi bien interannuelles qu'intra-annuelles. Ces profils environnementaux ont ensuite été employés pour étudier l'influence du pas de temps sur la précision des calculs environnementaux de la demande électrique de bâtiments. Plusieurs cas d'étude ont été réalisés et, pour chacun d'entre eux, différentes configurations des installations techniques (utilisation d'une pompe à chaleur, installation photovoltaïque, micro-cogénération etc.) ont été considérées. Les résultats montrent que la précision temporelle peut être influente dans le cas d'une demande énergétique saisonnière (p.ex chauffage des bâtiments). Alternativement, la précision du calcul les impacts des demandes électrique en ruban sur l'année n'est que très peu affectée par le choix du pas de temps. Finalement, des analyses de sensibilité ont été réalisées. Celles-ci ont confirmées que le choix du pas de temps horaire pouvait devenir nécessaire dans le cas de demande électrique saisonnière et lorsque celle-ci surpasse largement la demande en ruban. Des travaux ont aussi été mené pour étudier l'influence de la prise en compte d'une résolution temporelle horaire dans le calcul des bénéfices environnementaux liés à l'utilisation d'un système technique {photovoltaïque + batterie stationnaire}. Les résultats ont montré que la prise en compte du pas de temps horaire réduit le bénéfice environnemental (indicateur sur le changement climatique) de ce type d'installation technique pour le cas d'étude considéré et pour le mix électrique actuel (pour l'indicateur en énergie primaire non-renouvelable, il apparait que ce type d'installation technique réduit l'impact). Il démontre néanmoins qu'avec les évolutions attendues du mix électrique Suisse, il est nécessaire d'étudier maintenant les bénéfices environnementaux de ces systèmes plus en détails. Le projet EcoDynBat a donc permis de couvrir largement la question de l'ACV dynamique de la demande énergétique des bâtiments, du concept méthodologique jusqu'aux résultats en passant par la collecte et le traitement des données.

Summary

The EcoDynBat project (Dynamic Life Cycle Assessment of buildings) studied the influence of the time step on the accuracy of the environmental impact calculations of the Swiss grid electricity and consequently the consumed electricity in buildings, through a Dynamic Life Cycle Assessment (DLCA). This project was carried out by HEIG-VD, EMPA and SUPSI. In order to achieve the project's objective, a calculation procedure for the necessary data was defined and a methodological framework for the LCA of the electricity impacts was determined. These frameworks are clearly explained in this report and can be used in future studies on this topic. In the beginning, the necessary data for the environmental calculation were collected. The collected data provide hourly information on the energy production, imports/exports and energy consumption of Switzerland and its neighboring European countries. This information was then characterized, validated and aggregated in an "EcoDynBat" dataset that indicate the origins of the electricity consumed in Switzerland, according to a physical flow approach, at each time step. Then, using these data and the LCA framework, the environmental profile of the Swiss grid electricity was calculated, under an hourly, daily, monthly and annual time step. Its impacts were calculated for four impact categories, i.e. climate change, renewable and non-renewable primary energy and ecological scarcity, while significant inter and intra-annually fluctuations were found in particular for the climate change indicators (annual value for 2018 = 138 g CO_2 eq/kWh, hourly min/max range from 35 to 385 g CO_2 eq/kWh). Thereupon, these environmental profiles were used for the investigation of the time step influence on the accuracy of environmental calculations of the electricity demand of buildings. Several case studies were used and for each one of them, different configurations of the technical installations (heat pump, photovoltaic installation, micro-cogeneration, etc.) were considered. The results showed that the time step resolution can be influential in the case of seasonal energy demand profiles (e.g. space heating). On the contrary, the accuracy of the impacts of relatively constant electricity demand profiles is only slightly affected by the choice of the time step. Different sensitivity analyses, concerning the time step resolution confirmed that the choice of the hourly time step is critical in the case of seasonal electricity demands and in case that this demand significantly exceeds the demand of constant electricity need. Finally, the influence of the time step resolution was evaluated, concerning the environmental benefits of the combined use of a photovoltaic and a stationary battery. The results showed that for the studied building and the current electricity mix, the environmental benefits of this installation diminish when, taking into account the hourly time step for the case of the climate change indicator. Therefore, the EcoDynBat project offers a global view of the problematic of the dynamic LCA, regarding the electricity demand of buildings, i.e. starting from the data collection of the electricity demand, the LCA methodological framework, the impacts of the Swiss grid electricity and the impacts of the electricity at the building level.

Take-home messages

- A computational method for the data collection in a dynamic state for the Swiss grid electricity has been set. The method offers a dataset of the energy production of Switzerland and its neighboring European countries, as well as the physical flows between them. There are different sources for these data, however, effort should be made, in future, to make the data coherent, across the various sources;
- The climate change impact of the Swiss grid electricity is highly variable within the year (intra – annual variability) due to the important differences of the imports in summer and winter, but also from one year to another (inter – annual variability), because of the national production means availability. The variability is less pronounced for other impact indicators (non-renewable primary energies and ecological scarcity);
- Regarding the time step resolution influence on the accuracy of the environmental impact calculations of the building energy demand, only the seasonal demands are affected (mainly for the climate change indicator). The impacts of the space heating demand, when covered by a heat pump are higher for the hourly electricity impact calculations than for the annual ones. Relatively constant demands are conversely not affected. Since building have both seasonal and constant demands, the overall time step influence is moderate, for the considered case studies;
- A Dynamic Life Cycle Assessment for the environmental impact calculations of the building energy demand should be considered, especially for the new generation of smart buildings that include energy management, storage and control technologies.

Foreword

The majority of the studies related to the environmental impacts, using a Life Cycle Assessment (LCA), for the electricity consumption assume a constant impact profile, for the consumed electricity. However, it is widely known that the electricity supplied from the grid does not derive, by the same energy mix, annually or even hourly. The electricity from the grid depends, for example, on the production means availability, the primary resources (wind, solar) and the level of the electricity consumption, as well. Thus, the environmental impacts vary accordingly to the variation of the electricity mix. Therefore, the EcoDynBat project offers insights into the problematic of the dynamic environmental impact assessment of the grid electricity mix and into the way that the dynamic electricity impact profile influences the environmental impacts of the buildings, as well. This report presents the results from the different work-packages of the project, starting with the management summary. Finally, annexes are also included, in order to provide additional information on the calculation procedures and the results.

Management Summary

The main goal of the Ecodynbat project is to evaluate the influence of the time step of the Swiss grid electricity, on the environmental impacts of the building electricity demand. In the beginning, a literature review was conducted, concerning the DLCA at the building level. The collection of the data, regarding the electricity flows followed, while the DLCA framework of the Swiss grid electricity was defined, as well. After the dynamic impact assessment of the Swiss grid electricity, the environmental impacts of the electricity demand, at the building level were calculated for four different time steps of the grid electricity. In the end, sensitivity analyses were conducted, in order to define the how the variability of different parameters, influence the environmental impact results.

Diagram below shows the flow of the project and the different WPs. A dedicated chapter is provided, for each of the WPs, attached to the present report. The following part summarizes the work, findings and recommendations of the WPs. The details are then available in the chapters. The annexes of each chapter are provided at the end of the document.

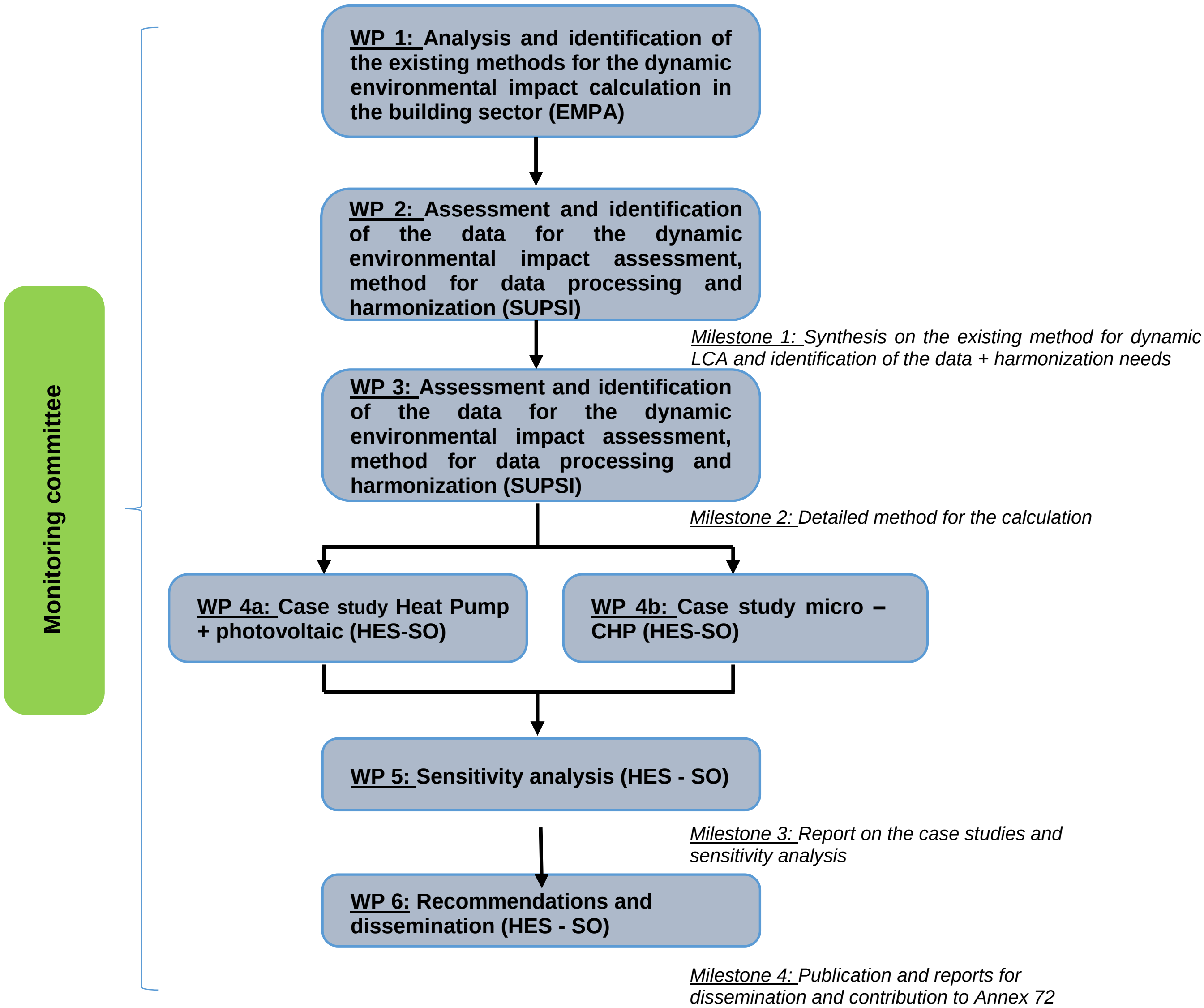

Figure 1: EcoDynBat structure

WP1: Literature review on DLCA for buildings

This work package provides a literature review on the dynamic life cycle assessment (DLCA) methods, concerning the environmental evaluation of the energy flows in buildings. More specifically, it includes the studies, focused on the development and application of the dynamic modeling and assessment of the environmental impacts of the electricity uses at the building level. This work was conducted in 2018 and approximately 40 documents were identified as being relevant to the DLCA for buildings.

The literature search was divided into four subjects, i.e.: (1) existing DLCA approaches for buildings, (2) computational options for DLCA, (3) methods for PV production, (4) other relevant studies and (5) case studies at the international level. One of the existing DLCA approaches is the matrix-based computation, according to which all the building flows should be described as time series. Other methodologies include the application of time functions for LCI flows, for which there is a need for a time – varying LCA databases. The studies that employed a matrix – based computation, applied different categories for time-series, as for example the building energy consumption – production, the supply chain dynamics, the degradation of the materials, the inventory dynamics, etc. Concerning the computational structure, two methods were identified in the literature, i.e. the matrix – based and the Enhanced Structure Path Analysis (ESPA). In addition, the literature search showed that there is a consensus of the LCA experts, concerning the methodology of the DLCA of the PV installations, which was established in 2016. Finally, the main observations of the DLCA of case studies showed that special attention should be given in the data sources, the energy flows of the building operation, the intra-annual variations, the national particularities and the temporal resolution of the energy flows.

WP1 Findings & Recommendations

The literature review of the WP1 leads to the identification of the main aspects and key elements that should be considered in the application of the DLCA in buildings. Thus, based on the scientific experience, the following recommendations are presented, when a robust DLCA on buildings is aimed.

Energy modelling

Concerning the energy modelling, it is recommended to give a special focus to:

- the intra-annual variations (short-term) of the energy flows;
- the detailed energy production of neighboring countries for the modelling of the Swiss imports;
- ensure the consistency to other assessment methods of the model, i.e. :
    - Electricity mixes and
    - Decentralized production;
- the use of site specific data, if available;
- the transparent and detailed description of the data sources;
- minimization of the amount of temporal simplifications;
- neglect the time - lag in:
    - Background databases and
    - Decentralized renewable energy production.

For the computational structure

Concerning the computational structure, it is recommended to:

- use matrix-based calculations to obtain DLCIs:
    - Can also be applied on processes instead of emissions.

WP2: data collection of the Swiss grid electricity

The WP2 includes the collection of all the necessary data for the characterization of the Swiss electricity mix. For this, data concerning four aspects of the Swiss electricity mix were collected, i.e. data for the national production mix, the international exchanges (imports – exports), the grid distributions and conversion losses. Different sources were analyzed, for their appropriateness concerning the project's objectives, for all the neighboring countries of Switzerland, i.e., the Swissgrid, the SFOE, the RTE (France), the E-Control (Austria), the Fraunhofer Institute (Germany), the Terna (Italy) and the ENTSO-E (European level). The analysis revealed that the most relevant source was the ENTSO-E database, which provides the hourly production mix for all the European countries, as well as the imports and exports, between the countries.

However, for the case of Switzerland the ENTSO-E data presented some differences, when compared to the Swissgrid data. Thus, a 'harmonization framework' was developed, see Figure 2, in order to cover these discrepancies. Hence, taking as a basis the ENTSO – E database, four adjustment rules were applied, in order to create the electricity flows of the Swiss grid. The rule zero, concerned the fill of the missing values, the first rule had to do with the addition of a missing amount of energy, not taken into account in the ENTSO-E database, the second rule concerned the replacement of the net exchanges of the ENTSO-E to the gross exchanges of the Swissgrid (i.e. separated imports – exports), while the third rule had to do with the addition of the grid losses to the ENTSO-E, provided by the SFOE.

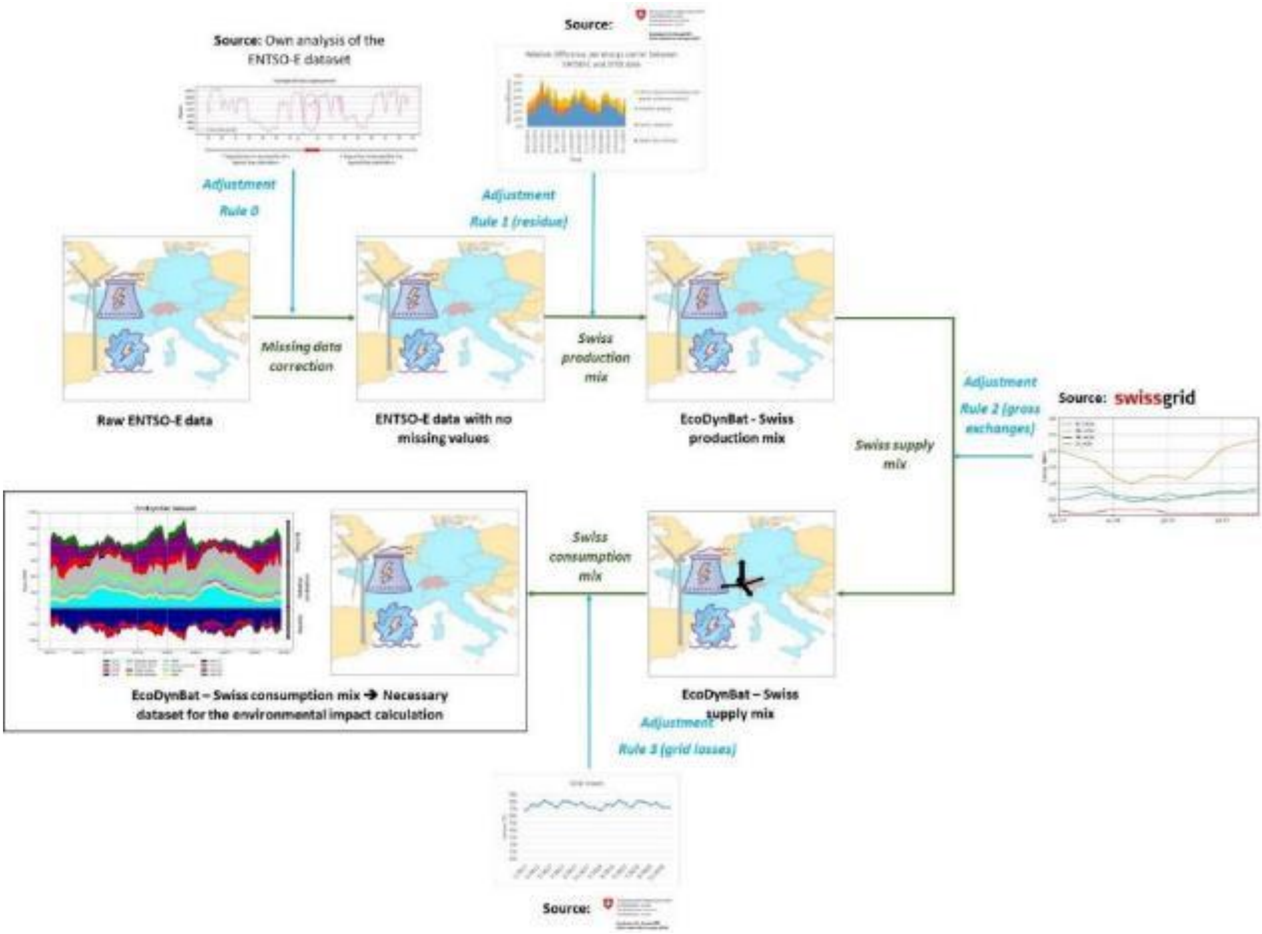

Figure 2: Harmonization framework for the development of the EcoDynBat dataset

Like that the Swiss electricity mix was created, see Figure 3. It becomes clear that there are important fluctuations over time (inter – and intra – annual variations). Indeed, in winter, the imports (mostly from Germany) contribute to the national demand, while in spring and summer, Switzerland produces more, because of the higher hydro-electric production, and thus during this period Switzerland relies less on imports from Germany. The last part of WP2 included the development of the PV, heat pump and micro – cogeneration (micro – CHP) models. The PV model provides the hourly PV production, taking into account a selected peak power, as well as the building location and the roof availability (surface, inclination, orientation, shadings). Furthermore, the heat pump model provides the electricity needs of a theoretical heat pump, while the micro-cogeneration (micro-CHP) developed model (for both combustion-based and fuel cell systems), enables the estimation of the electricity and heat that could be provided by a micro-CHP.

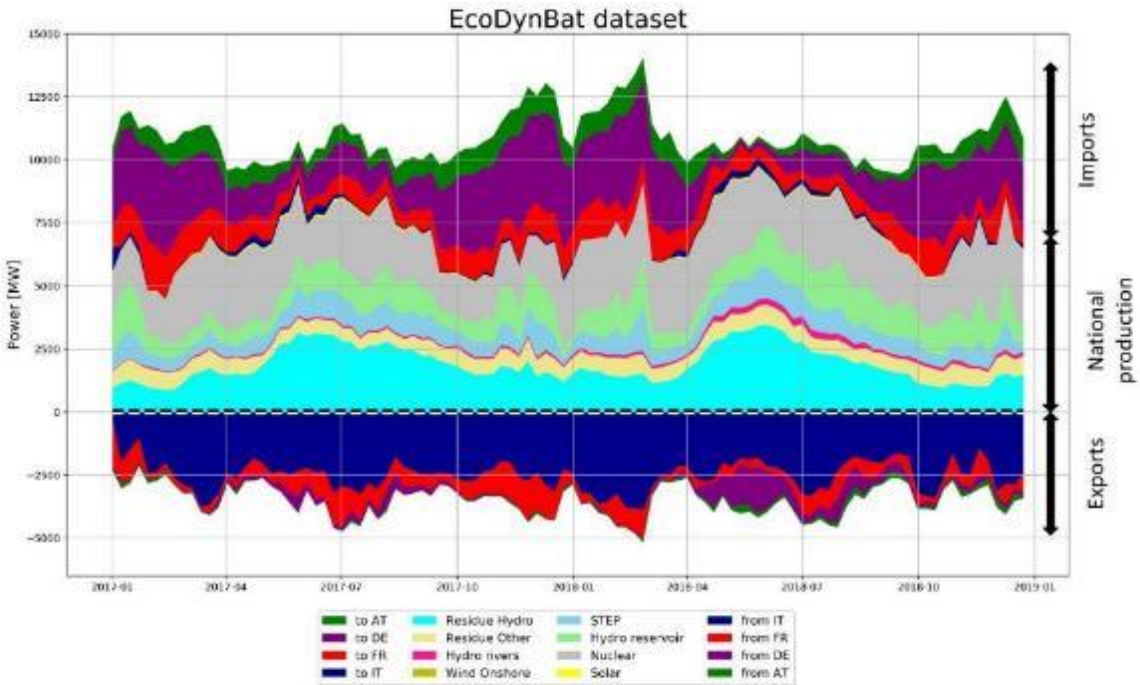

Figure 3: Example of the EcoDynBat dataset for the period 2017-2018

WP2 Findings & Recommendations

The data analysis of the electricity flows and the knowledge obtained from the synthesis of the Swiss electricity mix, led to the following recommendations, necessary for the harmonization of the Swiss energy strategy.

1- The Swiss electricity mix presents important inter- and intra- annual fluctuations. The energy flows are a dynamic phenomenon and these variations can be eventually diminished or increased in the near future. It is thus, important to take into account the dynamic effects of the electricity mix, in future studies.

2- Switzerland is is producing a large share of its consumed electricity. Nevertheless, its mix fluctuates over the year. In winter an important share of electricity is imported from its neighboring countries (mostly Germany), Conversely, in spring and summer, Switzerland relies mostly on its own production being mostly hydro and nuclear electricity.

3- The synthesis of the Swiss energy mix, using different data sources, showed that there is a lack and a need of a platform on a national level, for the Swiss electricity mix, on an hourly basis. This platform should be transparent and can be eventually linked to the Swissgrid and SFOE sources. Like that, all the necessary data could be gathered in a consistent way and could be used for further studies on the national production and consumption. Thereby,, there would be a harmonized framework for the Swiss electricity mix, which can contribute to a coherent Swiss energy strategy.

4- The differences on the electricity mix, between the ENTSO-E and Swissgrid data are of importance and should not be neglected. It is necessary to fill this gap, in order to provide an accurate dataset on a European level. Within the EcoDynBat project a first contact has been made with Swissgrid and it becomes necessary to continue these discussions in the future.

WP3: DLCA methodology

This work package presents the methodological framework for the dynamic life cycle assessment (DCLA), of the energy flows in Swiss buildings. The scope of this WP is to define the boundaries of the analysis and the representation of the energy flows. A list of modeling choices complement this information and offer a clear explanation of the limits of the analysis and the potential future improvements of this framework, if more information becomes available. A systematic description of the computational structure is also proposed to help readers, to use the developed algorithms of the DLCA for other buildings, if needed. The following tables summarize the key modeling assumptions and the main steps of the computational structure.

Table 1: Key modeling assumption for the EcoDynBat framework (see chapter 3)

Scope definition (Chapter 3, sub-section 2.1)

- **The functional unit is the m^2 ERA for 1 year of energy use in the assessed building**
- **The model of the system considers:**
    ○ **20 different production means in 6 countries**
    ○ **The infrastructure to transport electricity**
    ○ **The transport losses of the electricity to the grid**
    ○ **Decentralized production in the building**
    ○ **All electricity uses in the building**
- **The modeling approach for the electricity mix is based on production and imports**
- **The input data comes from WP2, the KBOB database and the ecoinvent database**

Key modeling assumptions (Chapter 3, sub-section 2.2)

- **Focus on intra-annual variations with a resolution up to the hourly time step**
- **Use of site-specific information on building, if available**
- **Attributional modeling perspective**
- **Choice of 4 impact categories:**
    ○ **Global warming potential (GWP)**
    ○ **Renewable cumulative energy demand (CED$_{renew}$)**
    ○ **Non-renewable cumulative energy demand (CED$_{non-renew}$)**
    ○ **Ecological scarcity (UBP)**
- **Neglect the existing time-lag in background database and the electricity infrastructure**

Table 2: Main steps of the computational structure (see chapter 3)

Treatment of input data (Chapter 3, sub-section 3.1)	
-	**Temporal aggregation of information to provide different temporal resolution levels**
-	**Mapping for the connection between LCA databases and ENTSO-E data structure**
Calculation of impacts for the electricity inputs (Chapter 3, sub-section 3.2)	
-	**Matrix-based calculation of all production means in important countries**
-	**Impact assessment for all production means in the framework**
-	**Impact assessment for decentralized electricity production**
Calculating the impacts of energy flows in buildings (Chapter 3, sub-section 3.3)	
-	**Evaluation of impacts from the use of electricity from the grid**
-	**Evaluation of impacts from the self-consumed electricity in the building**
-	**Combination of impacts from all energy flows in the building**
-	**Summation over the assessment period for comparison with “standard” LCA results**

WP3 Recommendations

Based on the WP3 research work, the following steps are proposed, for the dynamic calculation of the environmental impacts of the building electricity demand :

1- Calculation of the impacts of the Swiss electricity mix, for different time steps, over a long period (i.e. one year). In this step the temporal distributions of the electricity mix, calculated in WP2 can be multiplied with the temporal distributions of different impact categories;

2- Calculation of the impacts of the electricity produced on site, by the decentralized installation. In this step the temporal distributions of the self – produced electricity can be multiplied with the impacts of the decentralized installations, using the models, developed in WP2;

3- Summation of the aforementioned impacts;

4- Comparison of the impacts obtained, using the annual time step from the DLCA to the existing traditional methods, i.e. KBOB, ecoinvent.

The general recommended methodology for the DLCA calculation in buildings is summarized in Figure 4.

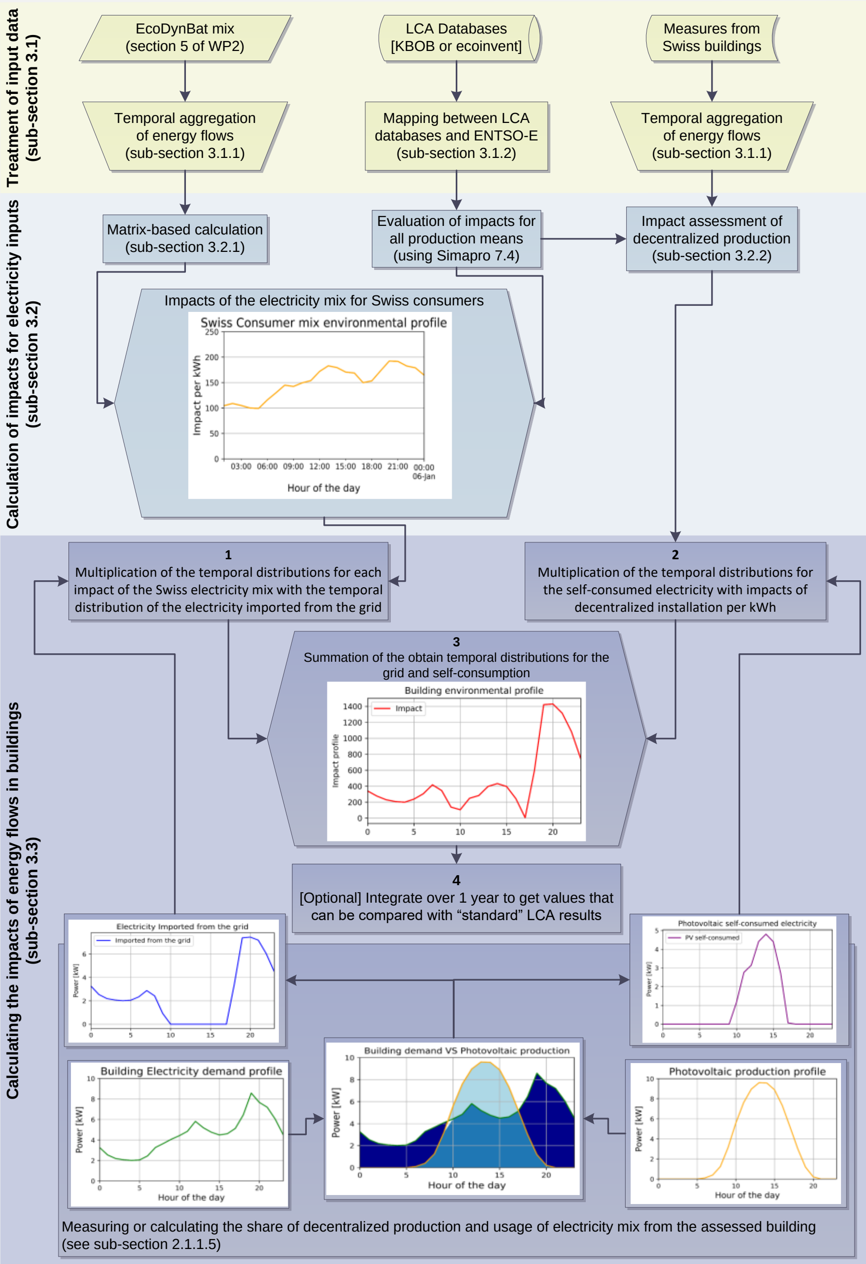

Figure 4: DLCA computational structure

WP4: environmental assessment of the building electricity needs

WP4 is focused on the characterization of the time step influence on the environmental impacts. For this reason, this WP includes two parts; WP4 – a and WP4 – b. The WP4 – a includes the environmental impact assessment of the Swiss electricity mix, for four time step resolutions and impact categories. Based on the data collected and the methodological framework, the environmental profile of the Swiss electricity mix has been computed, assessed and compared to the other existing sources (ecoinvent, KBOB). After this assessment, the impact calculation of building case studies follows, considering different energy supply configurations (equipped with/without heat pump, HP or, PV), for four time step resolutions and impact categories. Finally, the WP4 – b includes the environmental impact assessment of building case studies, equipped with micro-CHP (combustion-based and fuel-cells) that operated with a variable share of bio-methane, in order to cover different configurations of this decentralized electricity production system.

WP4 – a: Impacts of grid electricity mix and evaluation of case studies

Figure 10 presents the impacts of the electricity mix for two years, four time step resolutions and four impact categories. The results showed that the variability of the climate change indicator was found to be more important, than of the other environmental impact categories. For this indicator, peaks are observed mostly in winter, because of the increased electricity imports from Germany, which have a high carbon footprint. The renewable primary energy indicators vary less, throughout the year and exhibit higher intra-day variability, than seasonal variability. The intra-day variability is related to a higher share of imports from France (mostly at night), which rely on nuclear energy. Finally, the ecological scarcity indicator exhibits an intermediate behavior, between the climate change and the primary energy indicators. Indeed, it shows seasonal fluctuations, but in a smaller range than the climate change indicator, and also important intra-day fluctuations.

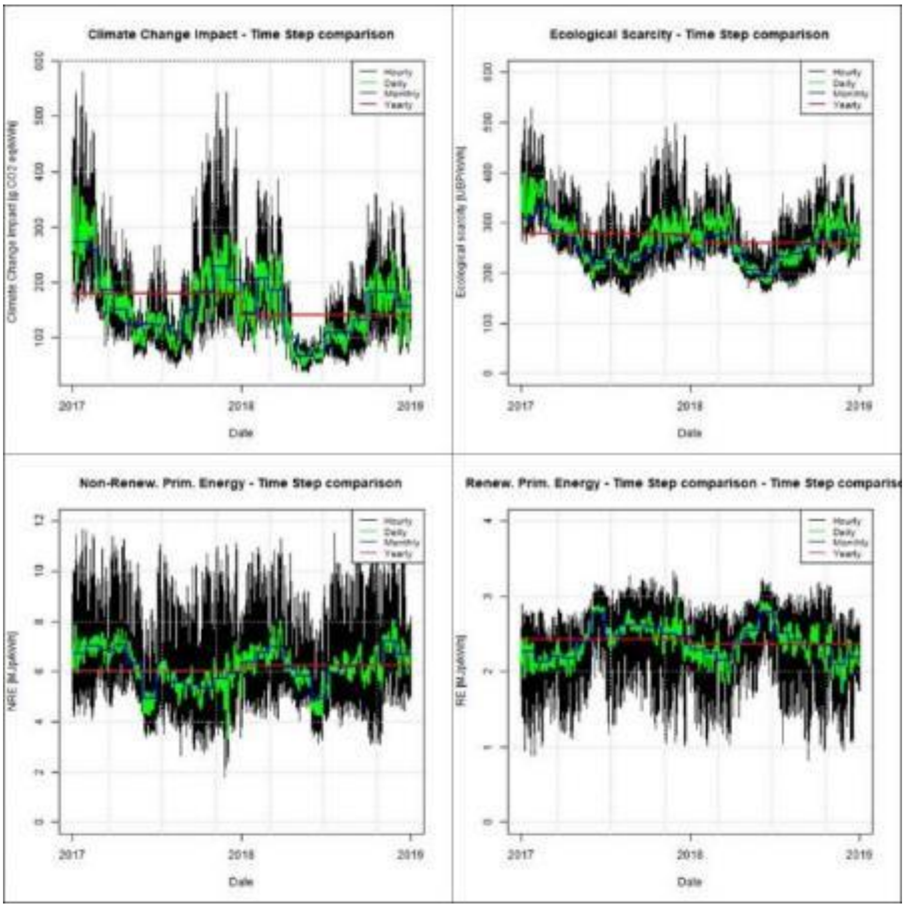

Figure 5: Impacts of the electricity mix, for the four studied time steps and indicators.

The assessment of the electricity mix has also revealed that there is important inter-annual variability, especially for the climate change impact. Indeed, between 2017 and 2018, the climate change indicator decreased, because of the higher availability of the Swiss nuclear production. It leaded to reduced imports and thus to a lower impact of the electricity mix.

The comparison of the environmental impacts of the electricity, obtained through the EcoDynBat, to existing reference methods (KBOB and ecoinvent v3.4) has shown important differences. One explanation of these differences lies on the fact that the compared methods considered, production mixes from different years. However, the main source of the differences was found in the calculation approach of the imported electricity. Within EcoDynBat, the physical flows were considered for the impact calculation and the impacts of the Swiss imported electricity are equal to the average impact of the electricity produced and imported by the neighboring countries. In KBOB and ecoinvent, the calculations are based on the certificate of origin. With this approach, the imported electricity is partially apportioned to specific production means, having a lower impact footprint, than the average value considered in EcoDynBat.

The time step influence was evaluated through the environmental impact calculation of six building case studies, for a total of 20 different building configurations. The results of the relative time step (taking as reference the annual time step) are displayed in Figure 6 for the climate change impact. The case studies have shown that the time step influences the most, the climate change indicator. The variability is important when considering grid electricity for the heat pump operation. The seasonality of the demand appears to be responsible for this trend and is coherent to the observations, made for the impact of the Swiss electricity mix. For the electricity consumption related to the domestic uses or the domestic hot water (DHW) needs, the time step resolution appears to have a small influence.

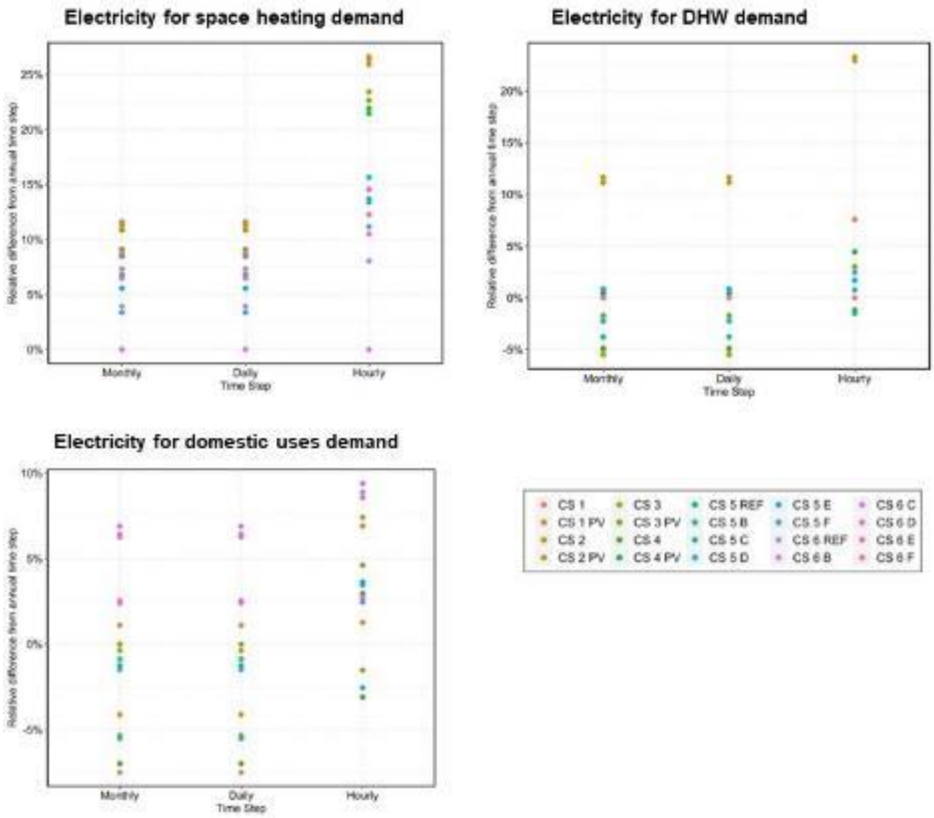

Figure 6: Time step influence results from chapter 4-a (climate change impact)

WP4 – b: Environmental impacts of micro - CHP

The environmental impacts of building case studies, equipped with a micro-CHP unit have been assessed. Two micro – CHP systems were used; combustion – based and fuel-cell systems, operated with different bio-methane shares (from 0% to 100%). For the 100% supply scenario, the time step influence was found to be negligible since a large share of the electricity demand is covered by the micro-CHP units (70% for the combustion-based approach and almost 100% for the fuel-cell solution). In this case there is no seasonality of the demand, since the space heating demand is supplied by heat produced, either by the micro-CHP or by the backup gas boiler, for which the impacts are constant, over the year.

The micro-CHP impact assessment has shown that there is a significant influence of the production allocation choice, regarding the biogas impact. Indeed, there are two ways of considering the biogas impact. Either the production process is considered, as a waste treatment and the biogas itself has no impact, or, it is considered, as a recyclable product. For this latter case, the environmental impacts can be significant. This assumption, completely, reverse the environmental impacts of the buildings that are equipped with a micro-CHP unit. When the biogas is issued from a waste treatment, the use of a micro-CHP with bio-methane, reduces the building energy demand impact for all indicators. In addition, increasing the share of bio-methane increases the benefit of the micro – CHP and thus, its use should be promoted. Conversely, when the biogas is considered as a recyclable product, the environmental impacts, related to the building energy demand are, higher than the reference case, for the climate change and the ecological scarcity indicators, but lower for the primary energy indicators. In addition, increasing the bio-methane share implies an increase of the impacts. Thus, for this assumption, the micro-CHP should be avoided.

WP4 Findings & Recommendations

The WP4 section on the evaluation of the grid electricity mix and the time step influence on the case studies led to the following recommendations:

1- The electricity mix shows an important inter – annual variability. Thus, the uncertainty of the impacts of the electricity mix should be quantified and taken into account in further studies of DLCA of the electricity mix. In addition, the uncertainty of the evolution of the electricity mix should be considered, when evaluating the dynamic impacts for long periods of time.

2- Including DLCA results in the energy management control of smart – buildings could help to the mitigation of the building energy demand.

3- It would be necessary to compare the various LCA approaches, regarding the environmental impacts of the Swiss grid electricity and decide which method better represents reality. Indeed, there are different methods or they are under investigation and the results of the impacts evaluation vary significantly.

4- The DLCA of the Swiss electricity mix can be used for the impact evaluation of other sectors, as for example the transport (e-mobility) and the tourism.

5- The hourly environmental impacts of the Swiss electricity mix can be used in order to further develop the national electricity strategy, since the hourly evaluation offers a clear image of the electricity mix.

6- The environmental assessment of the case studies showed that the time step resolution is significant for highly seasonal demands. Thus, the investigation concerning the time step resolution is necessary, when evaluating the impacts of a seasonal demand.

7- For constant or low fluctuating electricity demands, the annual time step is proved relevant and there is no need for a DLCA.

8- In cases that the micro – CHP covers a high share of the electricity, the time step resolution is not influent and annual values can be used for the impact calculation. For low electricity shares and high seasonal profiles, the choice of time step resolution should be investigated.

9- It is important to clarify the questions of the biogas impact allocation, since based on the allocation rule the micro – CHP should be either promoted (if biogas is considered as issued from a waste treatment) or avoided (if the biogas is considered as a recyclable product).

WP5 : Sensitivity Analysis

WP5 is focused on the sensitivity analysis of the time step resolution. Like that the conclusions, concerning the time step influence on the environmental impacts can be studied in a broader context and thus, generalized. Three sensitivity analyses were conducted on the: a) the energy storage, b) time step influence of one building case study and c) time step influence of the different building case studies. Finally, a theoretical study was performed, concerning the maximum observed time step influence, under a varying seasonal energy profile.

Sensitivity analysis of energy storage

The first sensitivity analysis studied the variability of the environmental impacts of the electricity consumption, of a case study, when different technical and environmental aspects are varied, i.e. the system design of PVs and batteries, the control approach of the battery discharge, the time step in combination to the energy storage, the grid mix (including a scenario without nuclear production in Switzerland), and the impact categories.

The results of these simulations show that the environmental benefits of batteries in Switzerland are currently limited for the climate change impact category, in particular, due to the low carbon footprint of grid electricity. In summer, the battery use is not beneficial, since the hourly impacts of the Swiss electricity grid are low at that period. Thus, taking an hourly time-step resolution of the climate change indicator for the batteries, rather than an annual value, increases the annual emissions. This seasonality cannot be captured, by an annual approach, since the annual impacts of the self-generation and storage systems are always lower, than those of the grid electricity. Hence, there is always a clear advantage of these systems, which however does not correspond to reality. In addition the use of a control strategy that avoids consumption from the grid, during the peak times of the environmental impact, improves moderately the environmental benefit, compared to the traditional battery management. However, the results reflect a specific case study of an energy-efficient building and it is not clear if this would be the case for different building consumption profiles, or with different control approaches and objectives. The hypothetical scenario, with no Swiss nuclear production and no additional national production means to compensate, highlighted the role of energy storage. With this scenario, the grid impacts are found to be higher, compared to the current grid mix and therefore the benefits of the battery are significantly higher. The long-term strategy of reducing the GHG emissions, by promoting the installation of PV systems and batteries in the Swiss building stock,is found to be beneficial. The advantages of complementing a PV system with a battery are also apparent when considering the non-renewable primary energy indicator. In such cases, the use of energy generated from a photovoltaic system, and stored in the battery, consistently and significantly reduced the environmental impact of the electricity consumption.

Sensitivity analysis of the time step

These sensitivity analyses aimed at quantifying the shares of the environmental impact variance, induced by the time step resolution and other parameters, like the photovoltaic production, the inter-annual variability, and the building load profile. The two first sensitivity analysis were made with Global Sensitivity Analysis (GS). The 1st GSA first assessment considers only the variability induced for one building model, while the 2nd GSA considers different building configurations. The 3rd sensitivity analysis assesses the influence of the load profile seasonality coupled with the time step influence by a Monte Carlo Analysis

These assessments have shown that the time step choice has a limited influence on the environmental impact variability. Considering only one building, the time step parameter has the highest influence on the climate change impact category, but remains limited (max 11%). For this impact category, the influence of the time step remains lower than the inter-annual variability of the consumed electricity impact. The ecological scarcity and primary energy indicators are mostly influenced by the photovoltaic peak power. For these three indicators, the inter-annual variability of the grid electricity impact has a small influence on the impacts since, the impacts of the Swiss grid electricity fluctuate less inter – and intra – annually. The second GSA has been performed in order to broaden the scope, by considering the influence of various building load profiles. When including this additional parameter, both the inter-annual and the building choice parameters dominate the others. In addition, there is a large joint influence between these two parameters (high total Sobol indices). For this model, the time step influence becomes marginal.

Concerning the seasonality assessment (third sensitivity analysis), a theoretical model was developed, which considered different configurations of the seasonality of the load profile. This model has been set, in order to estimate the maximum range of the time step influence, as a function of the seasonal demand profile (including its duration and amplitude). This assessment has confirmed that the relative difference between hourly and annual calculations is the highest, for the climate change indicator, when the seasonality of the demand profile is important (i.e. low duration and high amplitude, compared to the constant demand part). The other indicators are less influenced, than the climate change. Both the seasonal duration and the seasonal ratio (ratio of seasonal consumption over a constant demand) strongly affect the relative time step difference. The seasonal ratio influence confirms that the constant electricity demand tends to flatten the relative time step difference. Thus, for high shares of constant demand, considering hourly calculation does not seem relevant.

WP5 Findings & Recommendations

The WP5 section on the sensitivity analyses on the energy storage and the time step influence led to the following findings and recommendations:

1- Further investigation of the energy storage should be performed, by analyzing different building case studies, with energy self – generation and storage systems (both thermal and electric systems), in order to clarify the influence and the potential of the energy storage, as well as the control strategy on the environmental mitigation of the Swiss building stock. For this assessment the hourly time step resolution is relevant.
2- The assessment of the influence of the time step should be further considered, when studying the environmental impacts of the electricity consumption of smart-buildings, with a self-generation, storage system and active Demand Side Management strategies.
3- The environmental assessment of the stationary batteries for building applications should be accurately defined in future, as well as their benefits and drawbacks, since until now the assumptions from the automotive industry are used.
4- The first sensitivity analysis showed that the parameter of the inter – annual variability is the most influential on the impacts and thus it should been taken into account, when evaluating the impacts over a long period of time.
5- From the first sensitivity analysis it was shown that the time step influence is higher for the climate change impact, than for the other indicators and thus, the choice of the time step is relevant should be performed, by evaluating this impact indicator.
6- The second sensitivity analysis showed that the most influential parameters on the environmental impacts are the building load profile and their inter – annual variability. Thus, it is recommended that for future predictions of the impacts of the electricity mix, the inter – annual variability to be taken into account. Uncertainty profiles or scenarios for the electricity grid impacts could be defined, as well as for the building load profile, as a function of external forecasted parameters (external temperature, population, development of productions means, etc.).
7- The seasonality assessment verified that load profiles with high seasonality are the most influenced by the time step resolution. Thus, a special investigation should be done for these types of profiles, concerning the time step.
8- The time step influence should be investigated over a bigger group of buildings, or on the archetypes of demand profiles, in order to consolidate the findings of the sensitivity analyses.

General Report - Table of Contents

Project ECODYNBAT

Dynamic Life Cycle Assessment of Buildings

Chapter 1: Literature review (WP1)

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Summary

This document presents the literature review on the dynamic life cycle assessment (DLCA) methods, applied to buildings. It focuses, more specifically, on the key aspects of the temporal considerations, concerning the modelling and the assessment of the environmental impacts of the energy flows in buildings. This work was divided in five sub-taksi.e. (1) exchange of information between partners, (2) existing DLCA frameworks for buildings, (3) computational options for DLCA, (4) methods for decentralised energy production and (5) case studies at the international level. Modelling assumptions and choices are analysed with an explanation of their relevance for the EcoDynBat project. The main conclusions can then be used to guide the work in the other work packages of the project.

Résumé

Ce document présente la revue de littérature sur la méthode de l'analyse dynamique du cycle de vie (ADCV) lorsqu'elle est appliquée aux bâtiments. L'emphase de l'analyse porte sur les aspects clés des considérations temporelles pour la modélisation et l'analyse des impacts environnementaux des flux d'énergie dans les bâtiments. Ce travail est divisé en cinq sous-tâches pour la revue des : (1) échanges d'information entre les partenaires, (2) cadres d'études ADCV pour les bâtiments, (3) options de calcul pour l'ADCV, (4) méthodes pour la production d'énergie décentralisée et (5) cas d'études au niveau international. Les hypothèses et choix méthodologiques sont analysés avec une explication de leurs pertinences pour le project EcoDynBat. Les conclusions principales pourront ensuite être utilisées pour guider le travail des autres étapes du projet.

Zusammenfassung

Dieses Dokument enthält einen Überblick über die Literatur zur DLCA-Methode (Dynamic Life Cycle Assessment) bei der Anwendung auf Gebäude. Es konzentriert sich insbesondere auf die Schlüsselaspekte zeitlicher Überlegungen zur Modellierung und Bewertung der Umweltauswirkungen der Energieflüsse innerhalb von Gebäuden. Diese Arbeit wurde in fünf Teilbereiche unterteilt, um Folgendes zu überprüfen: (1) Informationsaustausch zwischen Partnern, (2) vorhandene DLCA-Rahmenbedingungen für Gebäude, (3) Berechnungsoptionen für DLCA, (4) Methoden für die dezentrale Energieerzeugung und (5). Fallstudien auf internationaler Ebene. Modellierungsannahmen und -entscheidungen werden mit einer Erklärung ihrer Relevanz für das EcoDynBat-Projekt analysiert. Die wichtigsten Schlussfolgerungen können dann verwendet werden, um die Arbeit in den anderen Arbeitspaketen des Projekts anzuleiten.

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Abbreviations

ALCA: Advancing Life Cycle Assessment Group

APOS: allocation at the point of substitution

CF: Characterization Factor

DLCA: Dynamic Life Cycle Assessment

DLCI: Dynamic Life Cycle Inventory

DLCIA: Dynamic Life Cycle Impact Assessment

Empa: Swiss Federal Laboratories for Materials Science and Technology

GHG: Greenhouse Gas

GWP: Global Warming Potential

HEIG-VD: Haute École d’Ingénierie et de Gestion du Canton de Vaud

HES-SO: Haute École Spécialisée de Suisse Occidentale

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LESBAT: Laboratoire d’Énergie Solaire et de Physique du Bâtiment

SUPSI: Scuola Universitaria Professionale della Svizzera Italiana

TD-LCI: Temporally Differentiated Life Cycle Inventory

TS-CF: Temporally Specific Characterization Factor

WP1: Work Package 1 – Review of methodologies

WP2: Work Package 2 – Input data with temporal variability considerations

WP3: Work Package 3 – Development of a DLCA framework for the project

WP4: Work Package 4 – Case studies

WP5: Work Package 5 – Sensitivity Analysis

WP6: Work Package 6 – Recommendations and dissemination of results

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1. Context of the EcoDynBat project

The Swiss building sector currently uses databases (e.g. KBOB), methods (SIA 2032, SIA 2039, SIA 2040 technical books), tools (e.g., Bauteilkatalog, Lesosai) and labelling systems (Minergie-Eco, SNBS) that are built on the principles of the life cycle assessment (LCA) methodology. LCA studies of buildings can, thus, be done using these data, methods and tools to assess the environmental impacts of buildings and to identify how they can be reduced.

Such LCA studies aggregate many impacts over the life cycle of buildings (cradle-to-grave perspective) to offer useful knowledge on their environmental sustainability. These comprehensive models of buildings are very valuable to understand future environmental consequences of today's decisions, but often overlook the inherent variability of flows during the life cycle. Figure 7 presents the stepwise calculation that is based on a simplified "steady-state" model of human activities following an attributional modelling perspective[1].

Full life cycle of the building (e.g. 60 years)

1) Aggregation of equivalent processes happening over the life cycle for a building (functional unit = FU)

$$\int_0^{t\,(e.g.\,60\,years)} Process\ flows\ in\ the\ supply\ chains = List\ of\ processes\ (Qt.) = LP(Qt.)$$

2) Multiplication of all processes with extractions of natural resources and emissions of pollutants

+

Summation of identical extractions and emissions from different processes (elementary flows)

$$LCI(life\ cycle\ inventory) = \sum_i \sum_j \sum_{Processes} LP(Qt.) \times \left(extractions_i + emissions_j\right)$$

3) Summation of matching environmental impacts (EI) from different elementary flows using characterisation factors (CFs)

$$Results\ from\ an\ LCA = EI = \sum_k CF_k \times LCI(k)$$

Matrix-based computation

$$|\mathbf{EI}| = \underbrace{[\mathbf{CF}] \times \underbrace{[\mathbf{B}] \times \underbrace{([\mathbf{I}] - [\mathbf{A}])^{-1} \times |\mathbf{FU}|}_{1}}_{2}}_{3}$$

Where:

EI is the vector of different environmental impacts
CF is the matrix of characterisation factors
B is the matrix of elementary flows for all processes
I is the identity matrix
A is the matrix of process flows for all supply chains
FU is the vector defining the functional unit

Figure 7 : Structure for the stepwise calculation of impacts in the LCA framework

Information on the timing, when processes occur throughout the life cycle is lost, during the first step. The aggregation of elementary flows, in the second step, also removes any knowledge on when extractions and emissions of processes are occurring. The modelling of potential impacts, in the third

[1] "The attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle). [Sonnemann, G., B. Vigon, S. Valdivia and M. Rack (2011). Global Guidance Principles for Life Cycle Assessment Database - "Shonan Guidance Principles". SCP document. E. David and K. Larry. Geneva, UNEP - SETAC: 158.].

step, is thus provided for unspecific periods. These simplifications reduce the calculation time and are in line with the initial character of the LCA methodology, according to which the LCA is a macro-environmental method that does not consider time and spatial variation. However, this aspect raises some concerns when the systems and impacts vary significantly over the life cycle; expected for systems, like buildings that have long operational periods.

Indeed, the following examples of variations and evolutions in the model come to mind:

- Evolution of products for future replacements during the use of the building
- Changing electricity infrastructure and production options
- Intermittence of energy production for renewable sources
- Variation of the share of energy sources used to produce electricity at every moment of the day
- Modification of energy use in buildings over the day
- Alteration of environmental impacts from pollutants when they are emitted at different moments
- (For instance, photochemical oxidants can double their effect between winter and summer (Shah and Ries 2009))

The aspects from the previous list warrant a complexification of LCA calculations to consider the most important sources of variability in the environmental impacts of buildings. The conceptual strategy to account for such changes is presented in figure 8.

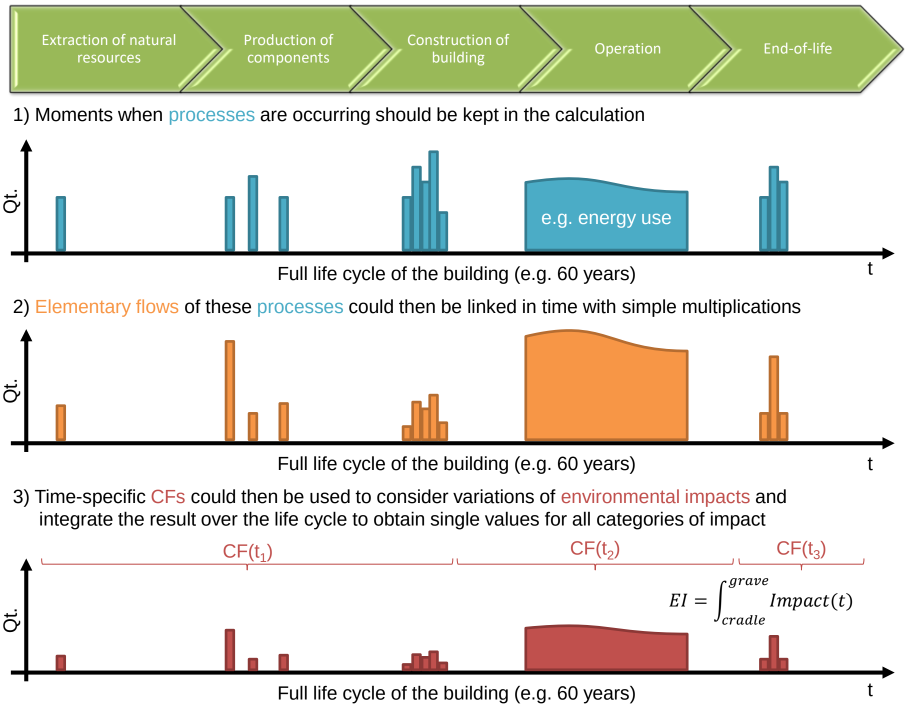


Figure 8: Conceptual representation of temporal considerations in LCA calculation

As Ffigure 8 shows, the basic ideas for the dynamic environmental assessments are rather straightforward, but their implementation is not typical in the field of LCA, which suggests the need to look for new methodological approaches. The following chapters, thus, explore the recent scientific literature and give insights into the requirements for dynamic LCA (DLCA) of buildings in Switzerland.

The comprehensive literature review of DLCA of buildings in the chapter 1 identifies key ideas for the consideration of the time parameter in the environmental assessments. This could then, specifically, contribute to the EcoDynBat project on the DLCA of the electricity flows Swiss buildings.

2. Introduction to chapter 1 (WP1)

The goal of the WP1 is a literature review on the international state-of-the-art methods and considered aspects, concerning the environmental assessment of the electricity uses in buildings within a dynamic life cycle assessment (DLCA) framework.

<u>The general strategy is, thus, to provide a comprehensive picture of DLCA for the building sector and then a focus on the concepts and aspects that could significantly affect the results of DLCA studies, concerning intra-annual electricity flows in any Swiss building.</u> These identified aspects then serve as a basis for the development of a DLCA framework (see WP3) that corresponds to the general goals of the project.

WP1 is divided into the following sub-tasks, which are presented in sections 3 to 7:

- Insure a good knowledge and information exchange of between Empa and HES-SO on the DLCA of buildings
- Review of existing DLCA frameworks for buildings that explicitly consider electricity management
- Review of existing methods and tools to carry out a DLCA for the electricity network
- Identification of methods to perform DLCA studies of decentralized energy production
- Analysis of current DLCA case studies in the building sector

Limitations and recommendations for the project are provided in all chapters.

3. Exchange of knowledge/information within the project

The exchange of knowledge between Empa and HES-SO has been facilitated by an Excel document that has been created by Empa to list important publications, with the key aspects of analysis. This Excel document has been distributed on the SharePoint website to give an overview of the important publications and reports to everyone who is involved in the project. This collaborative platform allowed the review and analysis to be performed at the different institutions with continuous updates.

The document has also been split into five sheets for the following types of publications:

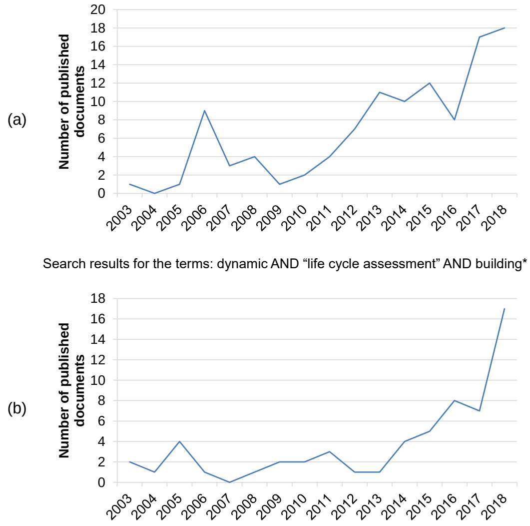
1. DLCA frameworks for buildings and energy management
2. DLCA methods and tools
3. Decentralizes energy production guidelines
4. Other relevant reviews
5. DLCA case studies of buildings

General information on the first author, date of publication, and title are provided for all documents. The other aspects of analysis depend on the type of document (i.e. differences between sheets). The references are listed in table 3 (on page 32) for the 5 previous categories to give a picture of how significantly each subject has been covered in the literature. Table 3 shows that there are more articles on DLCA of cases studies than articles on frameworks and methods for DLCA.

A comprehensive search for international publications on these subjects was performed with the help of the Scopus search tool. The statistics of identified publications from this tool provided some context into recent works on the DLCA method, when it is applied to the building sector. Indeed,

figure 9 shows an increase interest for the subject in the last 10 years and figure 10 identifies key contributors to the development with the regions, where they work. These statistics have helped to rank the relevance of the publications and clearly highlight the recent participation of Swiss researchers on the subject of DLCA. The same publications also show that the term “dynamic” is not always linked to the DLCA method for buildings, but often relates to models in the field of building energy simulation. The combined searches presented in

figure 9 and figure 10, provided more than 150 documents, but approximately 40 documents were kept for further analysis, since they were focused on the temporal variability of energy flows within buildings and they were thus, relevant to the EcoDynBat project.



Search results for the terms: dynamic AND “life cycle assessment” AND building*

Search results for the terms: tempo* AND “life cycle assessment” AND building*

Figure 9 : Histograms (2003-2019) for documents found on Scopus with the given search terms

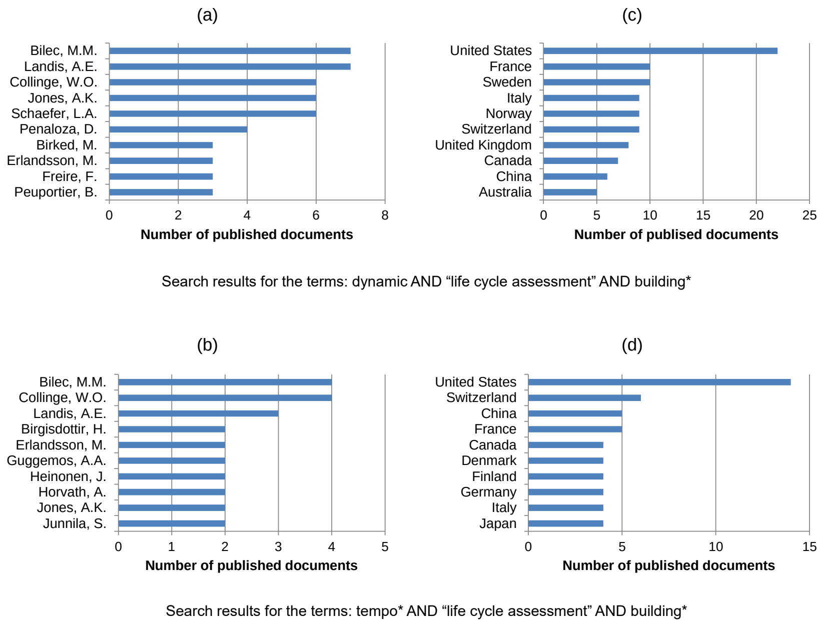


Figure 10 : Numbers of documents by authors (a) & (b) or by country (c) & (d) with given search terms

Table 3 : Classification of identified publications based on their main subjects

Main subjects	References	# of publications
DLCA frameworks for buildings and energy management	(Collinge, Landis et al. 2013, Su, Li et al. 2017, Wu, Li et al. 2017, Zhang 2017, Negishi, Tiruta-Barna et al. 2018)	5
DLCA methods and tools	(Heijungs and Suh 2002, Beloin-Saint-Pierre, Heijungs et al. 2014, Tiruta-Barna, Pigne et al. 2016, Cardellini, Mutel et al. 2018)	4
Decentralized energy production guidelines	(Frischknecht, Heath et al. 2016, Wernet, Bauer et al. 2016)	2
Other relevant reviews	(Zabalza Bribián, Aranda Usón et al. 2009, Rehberger and Hiete 2015, Anand and Amor 2017, Breton, Blanchet et al. 2018)	4
DLCA case studies of buildings	(Sandberg and Brattebø 2012, Collinge, Landis et al. 2013, Collinge, Landis et al. 2013, Roux and Peuportier 2013, Collinge, Landis et al. 2014, Messagie, Mertens et al. 2014, Fouquet, Levasseur et al. 2015, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2017, Sohn, Kalbar et al. 2017, Sohn, Kalbar et al. 2017, Zhang and Wang 2017, Collinge, Rickenbacker et al. 2018, Gimeno-Frontera, Mainar-Toledo et al. 2018, Hu 2018, Milovanoff, Dandres et al. 2018, Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018, Karl, Maslesa et al. 2019, Negishi, Lebert et al. 2019)	21

4. DLCA approaches

Within the 40 identified documents from a comprehensive search, three articles propose DLCA approaches for the environmental assessment of buildings. Section 4.1 presents the general analysis of these three publications, following a chronological order. The important aspects of these approaches are, then, presented in section 4.2, with a description of the current limitations and common choices that are relevant to the context of the EcoDynBat project.

4.1 Description of key concepts

The analysis of the three DLCA approaches focuses on finding aspects, within each publication, which are considered to be critical for more representative assessments of energy flows in buildings. Identified limitations are, also, presented, in order to define the scope of analysis that comes with the use of theses DLCA frameworks.

4.1.1 Publication 1: Collinge et al. 2013

Collinge, Landis et al. (2013) proposed a DLCA approach, which "*explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems*". The key aspects of this approach are presented with its implementation for "*historical and projected future environmental impacts of an existing institutional building*" in the USA.

Key aspects

The first choice of this approach is to keep the standard matrix-based computational method of the LCA methodology, while forming new matrixes and vectors for each time step (e.g. months). In other words, all flows of the building's model should be described by time series.

The authors also specify that their DLCA approach follows an attributional approach (Sonnemann, Vigon et al. 2011), which means that it "*attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle)*". This is considered different from the *"information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)*", which is called a consequential approach (Sonnemann, Vigon et al. 2011).

The potential existence of feedback loops within a temporally descriptive model of the life cycle of buildings is recognized in the description of the approach, but their effects are considered significant only for the foreground processes. For example, the electricity mix is an input for the building's operation and is used as an input for the production of construction materials. These two activities do not occur at the same time, but they are presented by the same electricity process in the "static" model of the supply chain. Such a misrepresentation should, therefore, be avoided with the DLCA approach, but only for foreground processes.

The difference in timing, between processes and their emissions (called lag time) at any level of the supply chain are explained in the documents with a potential strategy to consider them in the chosen computational structure, but they are not included because of data limitations.

The model considers four categories of time series in the calculation, which are: (1) building operations, (2) supply chain dynamics, (3) inventory dynamics, (4) environmental system dynamics.

Two different periods were used for the analysis: one for the full life cycle of the building, the other for the remaining life of the building (i.e. future impacts). The full lifetime was also separated in four distinct phases: initial construction, initial operations, renovation activities and future operations.

The scope of the building's model included: building materials, operating fuels/electricity and their upstream processes, but temporal differentiation of flows was not applied to upstream processes. Material transportation, on-site construction activities, routine maintenance and end-of-life disposition were excluded from the scope.

Rather detailed descriptions of the temporal differentiation for all flows in the building's life cycle have also been provided with their sources and temporal precisions (i.e. monthly or yearly). This information was then used to create temporally differentiated life cycle inventories (TD-LCIs).

Temporally specific characterization factors (TS-CFs) were used for some impact categories when dynamic life cycle impact assessment (DLCIA) methods were available. Static CFs were used for the other impact categories. This allows for the consideration of impact variations when emissions of pollutants occur at different moments over the life cycle.

Some future scenarios were defined to perform sensitivity analyses on specific flows and TS-CFs during the phase of future operations.

Limitations

The authors have highlighted the following four major limitations for their work:

1. Need for TS-CFs in most impact categories
2. Low data availability for temporal differentiation of flows in the model of a building's life cycle
3. No consideration of spatial variability (not linked to temporal variation)
4. Uncertainty of future scenarios

These are all, to some extent, related to the very common challenge of managing the lack of useful information for models of the LCA framework. Within these, the need to predict future scenarios for the relatively long life cycles of buildings is an especially difficult issue on which the LCA community has not found a consensus in implementation.

4.1.2 Publication 2: Su et al. 2017

Su, Li et al. (2017) proposed a "*dynamic assessment framework based on LCA principles after reviewing the research progress of DLCA*". The key aspects of this framework are presented mainly through a conceptual discussion with the avowed goal of being the "*base for developing a useful tool for conducting forecast evaluation and promoting sustainability*" in the building sector. This publication has the added benefit of also providing a humble review of publications on DLCA.

Key aspects

There is clear distinction between economic/social progresses and dynamic CFs in recently proposed developments for the DLCA framework. The economic/social progresses relate to time-variations for systems, energy properties, and evolution during different stages. The dynamic CFs relate to considerations of time horizons and time functions.

The DLCA framework applied to buildings is mainly relevant during the operation phase.

Two limitations are highlighted by the authors: (1) previously proposed DLCA frameworks have not been often applied to buildings, (2) there is a lack of consideration for dynamic occupancy behavior.

The authors proposed four different types of "time-dependency factors":

1. Technological progress, related to the evolution of any process in human activities
2. Variation in occupancy behavior during the building's life cycle since the occupants' condition changes
3. Dynamic characteristics, related to the previous concept of TS-CFs
4. Dynamic weighting factors that consider the economic changes and public concerns

Nonetheless, no propositions are made in the document for the factors of dynamic characteristics and dynamic weighting factors since they are not considered "building-specific" issues.

A proposition is made to use time functions to describe all LCI flows without any explanation on how they should be described or on what are their key characteristics.The authors mention the need for a time-varying LCA database to conduct DLCA studies while also stating that the most commonly used LCA database do not offer such information.Some options for predicting future trends are presented: general equilibrium models, energy demand and supply equilibrium models or adaptive system theory.

Two key classes of assessment for occupancy behavior are also defined: (1) profile identification and (2) quantification methods. The first class can be defined by sociological analysis or tracking surveys and describes changing trends in human behavior.Regression analysis, mathematical simulation and environmental simulation all are quantification methods to describe occupancy behavior.

Limitations

The description of this DLCA framework is only conceptual with specific examples for some aspects that need to be considered, mainly focusing on the occupancy behavior. Nevertheless, the following three aspects are identified for future developments of this proposed DLCA framework:

1. Carrying out some case studies while applying the main concepts of this DLCA framework
2. Development of better models for occupancy behavior within all types of building
3. Adding more information on the consideration of TS-CFs and dynamic weighting factors

Overall, these next steps in development show that the proposed framework is still under development and that implementation strategies have not yet been defined. The authors also mention the variation of inputs between regions in the list of other aspects to consider, therefore highlighting the need for regionalization in DLCA just like the publication of Collinge, Landis et al. (2013).

4.1.3 Publication 3: Negishi et al. 2018

Negishi, Tiruta-Barna et al. (2018) recently proposed a "*new LCA framework including the time dimension*" which has been based on a literature review that aimed at "*identifying the time-dependent characteristics of a building system at*" the levels of building technology, end-users and external systems. The proposed framework uses operational and reproducible tools to perform temporal evaluations, which consider dynamic LCI (DLCI) and DLCIA methods.

Key aspects

The article presents a variety of aspects that vary over time in building systems. They are:

- Energy consumption (linked to typology of inhabitants and thermal performance levels)
- Degradation of building materials (lower performance and replacement)
- Technical innovations during the long lifetime of a building (prospective aspects)
- Energy production and its evolution over the lifetime of a building (prospective aspects)

The literature review highlights the different ways that time was considered in the LCA studies of different buildings. Overall, system's dynamics and DLCIA methods are the main aspects that are analyzed. Energy consumption and production comes up often and in different ways as key aspects for the LCA studies on buildings. The variation of energy can be intra-annual or prospective.

The description of the proposed DLCA framework then starts with a description of the following key dynamic aspects to consider for buildings:

- Typology of occupancy and inhabitants' behavior (consider long-term evolution scenarios)
- Building components (consider degradation/increase of performance and replacements)
- Energy production equipment (i.e. variations in the source of energy)
- Energy mix (long-term scenario for its evolution)
- Biogenic carbon emissions and carbon uptake (carbon storage/sequestration)
- End of life technologies (prospective improvement scenarios with potential time lags)

A reference is made to a general DLCA tool named DyPLCA (see sub-section 5.1.3), which is proposed to calculate DLCI from a generic temporal database that works with version 3.2 of the ecoinvent database (Wernet, Bauer et al. 2016). Adapted DLCIA methods can then be applied to the DLCI.

The generic temporal information, which describes the flows in the building's model, can be applied to both foreground and background processes.

The DLCA methodology structure is also described with the following five steps:

1. Data collection and calculation (for component and energy use)
2. Conventional modelling of the building's lifecycle (static LCA)
3. Configuration of building's dynamics (adding the generic temporal information)
4. Calculation of DLCI
5. Calculation with DLCIA methods

This methodology allows for the identification of past, present and future environmental impacts, if results from the DLCIA methods are kept in a time-differentiated structure (i.e. temporal distribution).

Limitations

The authors suggest the four following limitations to their DLCA framework:

1. Missing DLCIA method to assess all the environmental categories of traditional LCA studies
2. Lacking data to describe the system's dynamics of buildings over their full life cycle
3. Limited knowledge on long-term evolutions of technology increasing the uncertainty on results
4. Method and tools cannot use environmental data from the building sector (e.g. EPD)

It should, also, be mentioned that no examples of implementation of this DLCA methodology have been published yet.

4.2 Recommendations for the EcoDynBat project

Many concepts and ideas have been described in the three previous publications and some can be useful for the EcoDynBat project, even if its general scope is limited to intra-annual electricity flows. Common aspects and current limitations that were identified in these frameworks are, thus, listed to check if critical assumptions must be made in the DLCA framework of the EcoDynBat project. The goal here is to spot specific assumptions that bring significant changes to dynamic assessments of electricity flows for buildings when compared with the more traditional "static" LCA framework.

4.2.1 Common aspects of the DLCA frameworks

The published DLCA frameworks for buildings are not described with similar vocabularies, often lack detailed descriptions of their implementation and discussions do not focus on the same modelling assumptions. Nevertheless, some common aspects have been identified and they relate to the aspects of a building's life cycle that need to be considered in DLCA studies. Indeed, all authors seem to agree on the importance of the three following considerations:

- The importance of considering the **behavior of occupants**

In the context of DLCA, the behaviors of occupant relate to variations of uses during the full lifetime of the building and the types of occupant (e.g. young family with children). Some authors advocate for measurements and others for models to describe such changes in consumption.

- The need to consider the **system's dynamics** during the life cycle of the building

In the context of buildings, system's dynamics should include the consumed energy (with production sources). Indeed, the importance of considering the temporal variations for energy flows during the full life cycle of a building is mentioned in the three publications.

- The relevance of **using DLCIA methods**

For all environmental assessments of buildings, DLCIA methods are models that consider the variations of impacts when extractions of natural resources and emissions of pollutants occur at different times (e.g. different hours, days, years).

4.2.2 Current limitations

Limitations in the descriptions of the proposed DLCA frameworks are apparent for many subjects with a clear lack of details for their implementation. The missing information mainly shows that there is no consensus on modelling choices and assumptions when DLCA are carried out. This means that it is currently impossible to choose general guidelines that could increase the chance for some comparability between the results of DLCA studies for different buildings. Still, the following paragraphs raise critical limitations for the accomplishment of the EcoDynBat project.

The previous publications highlight the current lack of availability for temporally differentiated data that can be used to offer a comprehensive model of processes and flows for the description of a building's life cycle. Only Negishi, Tiruta-Barna et al. (2018) claim to have access to temporally differentiated flows for the whole ecoinvent database (i.e. version 3.2), but this information is based on generic descriptions that are not easy to validate at the moment and that are not available for the most up-to-date version.

The discussions of the previous publications mainly focus on prospective modelling strategies when they talk about the consideration for energy production and flows. The intra-annual variations of energy production and of a building's consumption are not debated, which means that proposed DLCA frameworks will not provide insights on the key concepts behind the models of such variations.

While all authors agree on the relevance of considering variations of impacts in time with DLCIA methods, they also all reveal that there are only a few DLCIA methods and that it is currently impossible to cover a comprehensive range of impact categories with such models. The only constantly covered category is the global warming potential (GWP) that is based on dynamic functions or series of TS-CFs.

The proposed DLCA frameworks for buildings are not directly linked to LCA standards for the environmental assessment of buildings, such as the EN 15978, the ISO 21931 and the SIA 2040 for Switzerland even if Negishi et al. (Negishi, Tiruta-Barna et al. 2018) most of the EN 15978 rules. This missing link lowers the potential to compare, in a fair manner, results of DLCA studies with "static" LCA of buildings.

4.2.3 Aspects to consider in the EcoDynBat project

The common aspects and identified limitations in DLCA frameworks reveal that:

- Energy flow variations in DLCA of buildings are considered important by the three publications. This confirms, to some extent, the relevance of the chosen subject for the EcoDynBat project.
- The lack of verifiable and up-to-date descriptions for temporally differentiated flows is a limiting factor at least for the comprehensiveness of the temporal consideration in systems' dynamics.
- Modelling choices and assumptions to consider intra-annual variations of energy flows are not given in DLCA frameworks that have been created especially for the assessment of buildings. Guidelines for creating such models should therefore be found in other documents if they exist.
- It might be possible to consider the variations of impacts from greenhouse gas (GHG) emissions that are linked to varying levels of energy flows during the life cycle of buildings, but many other categories of environmental impacts will probably need to be assessed with "static" CFs.
- A clear link with LCA standards for the environmental assessment of buildings is not currently available, but might be necessary to assess the importance of carrying out DLCA studies of energy flows in buildings.

5. Calculation methods and tools

One book and three scientific publications were found to describe the available methods and tools to carry out a DLCA assessment of energy flows in buildings. The focus was mainly on DLCI calculations since DLCIA methods are still difficult to find for all impact categories and a strategy to link them has already been proposed by Beloin et al. (2017) when TS-CFs are available. The overview of methods and tools starts with the general computation structure of "static" LCA (see sub-section 0) and ends with very recent tools (see sub-sections 5.1.3 and 5.1.4).

5.1 Description of key aspects for the methods and tools

The analysis of the review of DLCI calculation methods and tools looks at different aspects to evaluate their usefulness in the framework of the EcoDynBat project. The analyzed benefits and limits all report on the usability of the calculation methods and tools. The critical aspects relate to:

- The ease of use with chosen LCA databases (i.e. latest versions of ecoinvent and KBOB)
- The flexibility in managing different levels of temporal precision to describe energy flows
- The existence of calculation tools to carry out a DLCI calculation

Similar computational strategies are also highlighted when they could be found in many documents.

5.1.1 Publication 1: Heijungs and Suh 2002

Heijungs and Suh (2002) have offered a comprehensive description of the computational structure that is used in "standard" LCA software. They also proposed a "simple" way of considering the systems' dynamics for the calculation of LCIs within section 9.3 (page 194) of their book. This strategy is presented to explain the complexity of DLCI calculations within the current LCA computational framework and serves as a basis of reference for the developments of the three following publications.

Key benefits

The basic concept behind the consideration of system dynamics in a matrix-based computation of LCIs is to differentiate processes and flows which happen in different periods (e.g. years). Figure 11 provides an example of how the technological matrix (**A**), the environmental matrix (**B**) and functional unit vector (*f*) are expanding when system dynamics are considered for the calculation of DLCIs.

Environmental matrix $\mathbf{B}_{n,m}$ | Identity matrix $\mathbf{I}_{m,m}$ | Technology matrix $\mathbf{A}_{m,m}$ | Functional unit vector f_m

$$LCI = \begin{bmatrix} b_{1,1} & \cdots & b_{1,m} \\ \vdots & \ddots & \vdots \\ b_{n,1} & \cdots & b_{n,m} \end{bmatrix} \times \left(\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} - \begin{bmatrix} a_{1,1} & \cdots & a_{1,m} \\ \vdots & \ddots & \vdots \\ a_{m,1} & \cdots & a_{m,m} \end{bmatrix} \right)^{-1} \times \begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix}$$

Temporal differentiation

n : types of elementary flows (e.g. pollutant emissions)
m : # of processes to describe the human activities
$b_{i,j}$: elementary flow i from process j
$a_{i,j}$: direct process flow i needed by process j (0 on diagonal)
f_i : direct process flow i needed in the functional unit

$$DLCI = \begin{bmatrix} b_{1,1} & \cdots & b_{1,m\times p} \\ \vdots & \ddots & \vdots \\ b_{n\times p,1} & \cdots & b_{n\times p,m\times p} \end{bmatrix} \times \left(\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} - \begin{bmatrix} a_{1,1} & \cdots & a_{1,m\times p} \\ \vdots & \ddots & \vdots \\ a_{m\times p,1} & \cdots & a_{m\times p,m\times p} \end{bmatrix} \right)^{-1} \times \begin{bmatrix} f_1 \\ \vdots \\ f_{m\times p} \end{bmatrix}$$

p : # of periods of time that are considered in the DLCA

Figure 11: Matrix-based structure of DLCI calculation with temporal differentiation of processes and flows

Such a computational structure can work with current LCA software or other calculation software (e.g. Excel, MATLAB) if processes and elementary flows are temporally differentiated. The obtained DLCI could then be linked to TS-CFs of chosen DLCIA methods to implement a full DLCA study.

Limitations

The chosen LCA databases for the EcoDynBat project (e.g. latest versions of ecoinvent and KBOB) do not provide such temporally differentiated descriptions, which means that a lot of effort would be required to create dynamic models (for ecoinvent: *m* >13,000 processes to temporally differentiate).

Moreover, the example of figure 11 clearly shows how the size of matrices and vector can increase dramatically with more temporal precision (e.g. *p* = 8760 hours per year), which can quickly become a computational problem for office computers, LCA software and other calculation software.

5.1.2 Publication 2: Beloin-Saint-Pierre et al. 2014

Beloin-Saint-Pierre et al. (2014) proposed a conceptual solution to the implementation challenge of temporal differentiation that has been revealed by Heijungs and Suh (2002). The idea is to replace the values in matrices and vectors by process-relative temporal distributions. This new description of flows can then be used to calculate study-relative DLCI if products of convolution are performed, instead of the regular multiplications that are in the "standard" LCA computational structure (see figure 11).

Key benefits

The key benefits of such a representation of flows are to enable the reuse of many process' descriptions for different studies or within the same life cycle while offering the possibility to increase temporal precision at any level without much more effort or higher numbers of process. In theory, this option should reduce the amount of work to model systems' dynamics in LCA, which is currently one of the main causes for the lack of comprehensive DLCA studies on any type of system.

This computational structure, which is called the ESPA method, can also be link to the "breadth-first" search strategy in the language of graph algorithms. It usually is linked to quick running time but high memory requirements that might not fit with the capacity of current office computers. It also requires a cut-off in the calculation, meaning that it will stop after a certain amount of processes is considered in the supply chain model. This is not necessarily a critical issue if enough calculation steps are carried out to consider most of the flows values (e.g. >95%) from the "standard" LCI.

Limitations

The ESPA method is currently only a conceptual proposition and no algorithms or computational tools have been developed for its implementation on LCA case studies. Such a development would require too much time, within the available resources of the EcoDynBat project.

Moreover, no LCA database has started to use this instance of process-relative temporal distributions to describe the flows. Too much work would therefore be necessary for comprehensive and consistent temporal differentiation of processes in energy models of EcoDynBat if they are based on ecoinvent and its >13,000 processes.

5.1.3 Publication 3: Tiruta-Barna et al. 2016

Tiruta-Barna et al. (2016) have recently made a computational tool to carry out full DLCA calculations. This web-based tool is named DyPLCA and can be accessed on the web[2]. It uses process-relative temporal distributions just like the ESPA method to describe flows, but it is based on a depth-first traversal search strategy. This traversal algorithm is often linked to longer running time with lower memory requirements that fit better with current memory capacity of office computers. The DyPLCA tool has the added benefit of being directly linked to the DLCA framework for buildings that was proposed by Negishi et al. (2018) (see sub-section 4.1.3). Very recently, some of these authors have also published a new article on the creation of a temporally differentiated version of ecoinvent (Pigné, Gutiérrez et al. 2019).

Key benefits

The usability of the DyPLCA tool has been proven for many system models and obtained DLCIs can be linked to DLCIA methods. Simple examples of DLCA applications are available on its website.

The use of generic process-relative distributions is stated in the description of the tool to define the temporal considerations for all processes in version 3.2 of the ecoinvent database. This offers a rather comprehensive description of background datasets for any DLCA study. It is also possible to provide new process-relative flows to describe the foreground processes.

[2] http://dyplca.univ-lehavre.fr/projects

The use of process-relative temporal distributions in DyPLCA supports a temporal precision up to the level of seconds for all flows. Still, most of the provided implementation examples use a yearly precision to describe the DLCIs and allow quick calculations (e.g. a few seconds).

Limitations

From a general perspective, the key aspects and functionalities of the DyPLCA tool clearly show a high potential for usability in the EcoDynBat project. Nevertheless, limitations in the use of DyPLCA come up with a deeper analysis of its inner workings.

The main drawback is the lack of transparent and detailed descriptions for the generic process-relative temporal distributions that are provided for the background information (i.e. v3.2 of ecoinvent). This means that complete thrust in their temporal representativeness would be required.

The second obstacle is more specific to the EcoDynBat project, since it has been stated that the most up-to-date version of ecoinvent would be used to describe the background processes of the systems' models. Using DyPLCA would therefore force the use of an older version of ecoinvent to guarantee consistency between modelling assumptions. DyPLCA also uses the rather complex "allocation at the point of substitution" (APOS) system model of ecoinvent that does not fit with the "cut-off" system model, which has been chosen for the EcoDynBat project.

5.1.4 Publication 4: Cardellini et al. 2018

Cardellini et al. (2018) also proposed a computational tool to perform DLCA calculations. The tool, which is named Temporalis, is an open-source package of Brightway 2 (Python-based LCA software) and its documentation can be found on the web[3]. The algorithms of Temporalis also use the process-relative temporal distributions as a structure to describe the flows in models of the assessed systems. Temporalis uses a best-first traversal search strategy that offers average running times and memory requirements when compared to the ESPA method and the DyPLCA tool. This search strategy rests on the principle that processes with higher shares of environmental impacts should be temporally defined first which is a concept that has been proposed by other researchers (Collet, Lardon et al. 2014). Moreover, Temporalis can combine "static" and temporally differentiated descriptions of processes for calculations. Until now, its implementation has, only, been applied to rather simple case studies that do not offer much insight for its use on more complex systems.

Key benefits

In theory, the use of process-relative temporal distributions in Temporalis can support any temporal precision level for all the flows of the model. Still, descriptions with more temporal precision are expected to bring higher computational times.

Limitations

Temporalis is a DLCA computational package that is not currently linked to any temporally defined LCA database, which means that it does not yet offer useful DLCI results if efforts are not made to provide temporally differentiated datasets. Its use is therefore afflicted with the common problem of lack of temporally differentiated modelling data. As stated in the documentation, it can however use any of the existing LCA databases as a frame of reference.

[3] https://temporalis.readthedocs.io/en/latest/

The other issue with Temporalis relates to usability since it is a package, which only works with the Python-based Brightway 2 LCA software. This means that LCA practitioners need to have a working knowledge of the Python language to carry out any DLCA assessment.

5.2 Recommendations for DLCA calculations

Many options for DLCA calculations have appeared in recent years, which should bring opportunities for more, simpler and faster implementations in the future. Nevertheless, in the EcoDynBat context, current limitations have a range of consequences when performing DLCI calculations. The review of methods and tools therefore provides some ideas on what is currently possible and the choices that must be made to obtain relevant results to assess the systems' dynamics of energy flows in buildings.

5.2.1 Key aspects of the methods and tools

Table 4 summarizes the key aspects for the two main types of computational structure that have been proposed to perform DLCI calculations. Different software tools are presented as possible options for the matrix-based structure. Both the DyPLCA and Temporalis options are then analyzed for the traversal search structure that uses process-relative temporal distributions. Some common aspects can be observed between the methods and tools in table 4 with a clear lack of easily accessible and understandable data that temporally differentiate the flows from model systems' dynamics.

Table 4: List of benefits and limits for DLCI computational methods and tools

Methods	Matrix-based (process/period)	Traversal search algorithms (process-relative temporal distributions)	
Tools	Excel, Python, R	DyPLCA	Temporalis
Benefits	· Simple concept for temporal differentiation	· Linked with a proposed DLCA framework for buildings · Temporal description in the required format is available for v3.2 of ecoinvent · Temporal precision for flows' descriptions up to the seconds	· Any temporal precision level for flows' descriptions · Is combined with Brightway 2 (LCA software)
Limits	· Temporal description in this format is not available in any LCA databases · High temporal precision is hard to reach with detailed LCA databases	· No transparent information on the defined generic process-relative temporal distributions	· Temporal descriptions in the required format is not available

5.2.2 Aspects to consider in the EcoDynBat project

The summary of key aspects for DLCI calculations that are presented in table 4 promotes some critical choices for computation in the EcoDynBat project. These key aspects are:

Temporally differentiated information is not available in both the KBOB and the most recent version of the ecoinvent LCA databases. This lack of useful description for flows in DLCI calculations applies to matrix-based and traversal search computational structures except for version 3.2 of ecoinvent where generic process-relative temporal distributions are defined for the latter. The lack of descriptions for these generic distributions and their link to an older version of the ecoinvent database sadly raise concerns for the EcoDynBat project. Then again, there is not enough time during the project to define consistently and comprehensively such distributions for all datasets of ecoinvent and KBOB.

The other option is to create different processes for each period and implement some matrix-based computational algorithms in some calculation software options. Such a choice will limit the combined temporal precision and the level of details in modelled systems. Indeed, an hourly description for one year of processes in ecoinvent would require the creation of roughly 110 million datasets, which does not fit with the available time resources of the EcoDynBat project. The general goal of the project is however to investigate the effect of temporal precision which thus forces an aggregation of processes to reach a manageable amount of information.

Such a simplification of the modelled systems has often been done in LCA studies, but it brings some issues in the temporal representativeness of the DLCIs. For example, the temporal description of the supply chain that models the life cycle of a hydro power plant can be aggregate over time, but it will then be impossible to show that pollutant emissions occur mainly during the construction phase, which can be a long time ago. This example of temporal discrepancy (i.e. time lag) can be concerning when most of the environmental impacts in the assessment are related to such a renewable source. “Luckily”, the key sources of the environmental impacts in the current Swiss electricity consumer mix are mostly linked to fossil fuels (Wernet, Bauer et al. 2016), which create more impacts during their use phases. This situation thus reduces the temporal discrepancy caused by aggregation over time since a significant share of the impacts occurs when electricity is consumed.

Within the context of the EcoDynBat project, the only viable choice is to take the option of temporal differentiation through process distinction, but it will be important to remember that such a choice comes with some temporal discrepancies. Here, temporal differentiation with process distinction means that a service (e.g. production of electricity) that is offered at different periods will be described with different processes for each period. The main discrepancy in such a model is that time lags between emissions and the service provided by the process are not considered. This is often not an issue for annual average processes, but the temporal representativeness is reduced when processes are describing production of electricity for every hour of the years. For example, there is a time discrepancy between when impacts occur for the manufacturing of renewable energy installation and when such energy is produced. This is an issue since processes that describe renewable installations will be linked to the time of electricity production and not the time when the installation was created.

Beyond this issue of representativeness, implementation of DLCI calculation should be straightforward since the matrix-based computational structure is rather simple and can be implemented in different software options.

6. Decentralized energy assessment

Documents that specifically focus on methods and tools to perform a DLCA of decentralized energy production at the intra-annual scale were not found on the web. It then made sense to look specifically for recent documents that propose relevant information on the LCA of photovoltaic (PV) installations since such installations are the most common decentralized production option for Swiss buildings. Guidelines and a tool were thus identified to provide a basic evaluation framework and some benchmark values that could be used to lay the foundation for a DLCA of decentralized energy in the Swiss context. This information is here combined with the key findings of chapters 0 and 5 to insure that recommendations for the DLCA of decentralized energy production fit with the identified methodological and implementation limits.

6.1 Important aspects to consider for decentralized production

The analysis of guidelines and a tool to model respectively the environmental impacts of PV electricity and electricity production of building-integrated PV installations in Switzerland was deemed relevant to identify the most appropriate modelling choices for the EcoDynBat project. The applicability of such modelling choices will then be discussed for a more general application to other types of decentralized energy sources.

6.1.1 Guidelines: Frischknecht et al. 2016

In 2016, a group of LCA experts, working within a task force of the international energy agency, published methodological guidelines to perform the LCA of PV electricity (Frischknecht, Heath et al. 2016). This document offers a consensus among the authors on the critical modelling assumptions that can be used to obtain benchmark values for the environmental impacts of PV electricity. Some of the key assumptions that can be transferred to the Swiss context are thus listed in the following sub-sections.

Key modelling choices

Many PV-specific parameters must be used as inputs of the LCA models to assess the environmental impacts of its produced electricity (e.g. kWh). The following sections present the modelling choices and key input values that are recommended by the international guidelines.

The basic strategy for the calculation of impacts per kWh of produced electricity is to aggregate the environmental impact over the full life cycle for a PV installation and divide this value by an estimate of the produced electricity during the use phase. The estimation of the electricity production considers the following aspects with some benchmarks:

- Life expectancy of the PV installation and its components: 30 years
    - PV panels: 30 years
    - Inverters: 15 years
    - Transformers: 30 years
    - Structure: 30 years
    - Cabling: 30 years

- Irradiation received by the PV installation: no benchmark for the EcoDynBat project
- Performance ratio of the PV installation: 0.75 (default value if no site-specific information)
- Degradation of module efficiency: 0.7% reduction/year

Any system model can be used (e.g. attributional) and electricity inputs for manufacturing of the different components should be based on relevant electricity grid mix (i.e. producing countries for PV panels that are sold in Switzerland with proportions based on market shares).

The models of PV electricity production that are provided in the ecoinvent LCA database respect the proposed benchmark values with an average irradiation level for the country-specific datasets. It is therefore rather straightforward to adjust the datasets with site-specific irradiation levels.

Limitations

While environmental impacts of a kWh produced by a PV installation in Switzerland are rather simple to obtain from existing databases (i.e. ecoinvent and KBOB), such values conceal that most of the impacts occur, during the short period of the manufacturing. Indeed, it is not temporally representative to link impacts at every period of electricity production (i.e. neglect time lag), but more relevant to show impacts during manufacturing and end-of-life with potentially significant use of water during the lifetime for cleaning. The effects of the inverter's replacement, after 15 years, should also be presented in the temporal description of pollutant flows and their impacts. Conversely, considering the variation of pollutant emissions, during the life cycle of a PV installation will be relevant, only if DLCIA methods are used since results from normal LCIA methods will not be affected by the timing of emission.

The methodological guidelines also state that site-specific information should always be preferred to generic values if it is available. Such a remark highlights the importance of obtaining technical details on the analyzed PV installation to perform a more representative LCA or DLCA of all case studies.

Overcoming these modelling simplifications for specific PV installations of a building can be managed for each case study of EcoDynBat, but the lack of temporal details on the Swiss PV production raise concerns for the temporal representativeness of impacts from the electricity mix. For example, a yearly installed capacity of PV installations in different regions of Switzerland would be necessary to identify precisely the moment of impacts from PV installations that provide electricity on the grid at a later time (sometimes years later). This modelling challenge for background data has already been exposed in sub-section 5.2.2 and will probably need to be a modelling simplification in the EcoDynBat models.

6.1.2 Dynamic modelling of PV electricity production

As mentioned above, estimations of site-specific electricity production are important to obtain more representative impact assessments of electricity production from PV installations, mainly when they are significant sources of energy in buildings. A model of dynamics for electricity production is therefore a relevant addition to the assessment of buildings, but DLCA studies of PV installations are difficult to find in the literature. It thus seems relevant to identify the key modelling assumptions that need to be considered in the EcoDynBat project. The search for a tool that enables such dynamic calculations will then be left to the efforts of WP2, which focus on data sources.

Key aspects of sources

In the context of the EcoDynBat project, the model of electricity production from PV installations needs to provide information on when PV electricity is available for the building and the levels of production at different periods for all sites within Switzerland. This information will be sufficient to evaluate the environmental impacts that can be linked to PV electricity over the assessment period.

Databases like HelioClim-3 (Espinar, Blanc et al. 2012) describe the dynamics of solar irradiation for the past based on satellite observations almost everywhere in the world. These sources of information can reach a temporal resolution of 1 minute and a spatial resolution of less than 5 km, which should be sufficient for the EcoDynBat project.

Subsequently, this type of data on irradiation levels can be translated into quantities of electricity production for different periods over the years (e.g. hour, day, and month). These calculations use many of the aspects that are also used in "static" LCA of solar electricity (see 0). The only difference is that they are applied to short periods instead of the full operational time.

Challenge

The basic challenge, in the search for a relevant source to model the dynamics of decentralized solar electricity production, is about finding the most representative tools to evaluate production since irradiation data is clearly available with sufficient details for the EcoDynBat project.

6.2 Recommendations for the EcoDynBat project

The lack of specific documentation on carrying DLCA of decentralized energy sources reduced the usefulness of this part of the review for identifying key aspects of calculations. Documents that offered general discussions on the environmental assessment of decentralized energy sources were also not identified, which forced a focus on PV models for more broad inspiration on the subject. Overall, the analyzed guidelines gave some relevant information, which was combined with the knowledge of the project partners to list some key aspects and propose recommendations to perform a DLCA of such systems for Swiss buildings.

6.2.1 Key aspects for the estimations of decentralized production

The information provided in the methodological guidelines for the LCA of PV electricity clearly shows that the <u>ecoinvent and KBOB databases can offer useful descriptions</u> to model the potential life cycle impacts of PV installations without many modifications. The <u>main expected change relates to the temporal differentiation of flows</u>, which has already been identified and discussed in chapters 0 and 5. Moreover, it is important to use specific data mainly for the following aspects:

- Site of the installation (to consider the site-specific and temporal variations of irradiation levels)
- The type of technology for panels and their sites of manufacturing
- The total energy conversion efficiency of the installation
- Lifetime of the installation's components
- Reduction in efficiency over time

Some benchmarks are available for these aspects when site-specific information is not available.

Additionally, <u>methodological guidelines (Frischknecht, Heath et al. 2016) provide a general equation to estimate the total electricity production of the PV installation</u> over its full life cycle. This equation is useful but <u>not sufficient to carry out a DLCA of the annual electricity use buildings</u> since hourly production of PV electricity needs to be estimated to identify the periods when electricity from the grid is used and in what quantities.

6.2.2 Aspects to consider in the EcoDynBat project

The key concepts from the previous sub-sections of chapter 6 offer many insights on how to perform a DLCA of a building-integrated PV installation. These concepts are here translated into key aspects that need to be considered for the more general DLCA of decentralized energy production.

Some <u>relevant descriptions of decentralized energy sources are already available in LCA databases</u>, mainly for PV installations. These datasets are, however, not sufficient to evaluate the temporal distributions of their energy productions and related pollutant emissions. Gathering further information will therefore be necessary, at least, for the installations on buildings, which are foreground processes in the system models of the EcoDynBat project.

<u>Relevant site-specific characteristics should be identified for considered energy sources</u>. Examples of key aspects for PV installations will be useful for this identification mainly for impacts of renewable energy, which is highly dependent on energy resource availability at the building's site.

The <u>hourly distribution of self-consumed energy is also important information to obtain</u> for the DLCA of buildings with decentralized sources. Indeed, short-term variability (during a year) cannot be predicted within the scope of the project so a <u>generic distribution for a year should be used</u>. Acquiring such data will require further work since analyzed tools do not offer this detailed information and measures from specific building might not offer this information. It will also be <u>important to remember that there is a significant temporal mismatch between pollutant emissions and energy production when renewable energy sources are considered</u> if DLCIA methods can be used in the EcoDynBat project.

7. Review of case studies

Twenty-one studies were found in the search for publications on DLCA of buildings. Most of these assessments have not explicitly followed a specific approach (e.g. in chapter 0) nor focused on the intra-annual variations of electricity uses in buildings, but they presented key modelling choices for the DLCA of the buildings sector. <u>The review of some of these studies can thus help in the identification of aspects that should be considered in the EcoDynBat project.</u> This review also offers some aspects of comparison for the expected changes in impacts when dynamics of systems are considered. The following sub-sections therefore highlight the key aspects for the EcoDynBat project and for a fair comparison with results from some of the previous studies.

7.1 Modeling assumptions in DLCA of energy used in buildings

The analysis of case studies helped in the identifications of common modelling choices that can have significant effects on the results of DLCA studies for buildings. All of these choices are presented in the following sub-sections (7.1.1 to 7.1.8) and their expected effects are discussed.

7.1.1 Focus on energy flows during the operational phase

Eight of the 21 DLCA studies on buildings focus on the dynamics of energy flows during the operational phase (Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2017, Sohn, Kalbar et al. 2017, Sohn, Kalbar et al. 2017, Collinge, Rickenbacker et al. 2018, Milovanoff, Dandres et al. 2018, Vuarnoz and Jusselme 2018, Karl, Maslesa et al. 2019). This focus can be explained by the significant proportion of life cycle impacts that can be linked to the operational phase of buildings and because energy use is the main contributor during that phase. Indeed, reviews on this aspect for LCA of buildings around the world show that between 71% and 96% of total impacts for existing building can be linked to energy use (Sartori and Hestnes 2007, Ramesh, Prakash et al. 2010). This observed trend validates the focus of the EcoDynBat project since more details on key sources of impacts often warrants more representative assessments of environmental impacts. It also links back to the key aspects that have been mentioned in the approaches proposed by Collinge et al. (Collinge, Landis et al. 2013) and Negishi et al (Negishi, Tiruta-Barna et al. 2018). Conversely, it is worth considering that DLCA studies with different scopes might prohibit a fair comparison of environmental hotspots.

7.1.2 Short- vs long-term dynamics of energy flows

The considered scope of temporal variability in the 21 DLCA studies for buildings is split between short-term (11 studies on intra-annual variations (Collinge, Landis et al. 2013, Roux and Peuportier 2013, Collinge, Landis et al. 2014, Messagie, Mertens et al. 2014, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2017, Collinge, Rickenbacker et al. 2018, Milovanoff, Dandres et al. 2018, Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018, Karl, Maslesa et al. 2019)) and long-term (10 studies on prospective evolutions (Sandberg and Brattebø 2012, Collinge, Landis et al. 2013, Fouquet, Levasseur et al. 2015, Roux, Schalbart et al. 2016, Sohn, Kalbar et al. 2017, Sohn, Kalbar et al. 2017, Zhang and Wang 2017, Gimeno-Frontera, Mainar-Toledo et al. 2018, Hu 2018, Negishi, Lebert et al. 2019)). <u>Here, studies on short-term variations are thus clearly linked to the targeted temporal scope of the EcoDynBat project.</u>

The DLCA studies that focus on short-term changes mainly account for the variations of environmental impacts between different periods (e.g. hour and month) for the produced electricity in a region. Such variations can be linked to the availability of different energy carriers at each hour over a year. They are then combined with the measured electric load profiles[4] in buildings to calculate the hourly impacts of the electricity (from the grid), which is used in buildings. Logically, the short-term studies require empirical data on the hourly electricity supply for a given country or region. They are thus often retrospective. An interesting aspect of such studies is that they consider the match of environmental impact from the kWh supplied to the building with the load profile (if measured data are used) for the same hourly time step (Collinge, Landis et al. 2013, Collinge, Rickenbacker et al. 2018). Such studies are falling within the scope of this project, so it will be possible to compare them with results that will be produced in the EcoDynBat project.

The DLCA studies, with a focus on long-term changes, are instead looking on the evolution of the infrastructure that produces energy in a region (e.g. electricity mix). Such studies use prospective models, scenarios and regulations to define a changing mix of options for energy production over the typical life cycle of a building (e.g. 50-60 years). The combination of intra-annual and prospective models is still rare with only three explicit examples (Collinge, Landis et al. 2013, Roux, Schalbart et al. 2016, Sohn, Kalbar et al. 2017), suggesting some methodological or implementation challenges. One of these challenges is the need to predict the future, which brings inherent uncertainties on the results of studies. For now, some long-term DLCA studies have tried to offer some evaluation of this source of uncertainty by presenting results for different possible future scenarios. The importance of considering this evolution of mix will depend on the timescale and the site of the building since transformation of the electricity grid is not expected to be the same in all countries and will require more or less time depending on regulations and policies. Nevertheless, any LCA study that claims to cover the full life cycle of buildings (e.g. 60 years) should consider using scenario analysis to carry out the assessment.

7.1.3 National case studies

DLCA studies have been carried out for buildings in eight different countries or smaller regions (i.e. Belgium (Messagie, Mertens et al. 2014), China (Zhang and Wang 2017), Denmark (Sohn, Kalbar et al. 2017, Sohn, Kalbar et al. 2017, Karl, Maslesa et al. 2019), France (Roux and Peuportier 2013, Fouquet, Levasseur et al. 2015, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2017, Milovanoff, Dandres et al. 2018, Negishi, Lebert et al. 2019), Norway (Sandberg and Brattebø 2012), Spain (Gimeno-Frontera, Mainar-Toledo et al. 2018), Switzerland (Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018), and United States (Collinge, Landis et al. 2013, Collinge, Landis et al. 2013, Collinge, Landis et al. 2014, Collinge, Rickenbacker et al. 2018, Hu 2018)). The energy production options, the energy needs of buildings and available technology options are different for these regions and are all aspects that can significantly affect the results of studies. Moreover, the short- and long-term variations of these aspects are also expected to be different between these countries. This comment is warranted by the diverse trends that are observed between DLCA studies that are made in different countries. It is therefore <u>not recommendable to infer some general conclusions on key contributors and benchmarks from DLCA studies of buildings by looking at results from one specific country</u>. This observation rationalizes the need for the Swiss specific investigation of the EcoDynBat project. It also limits the relevance of comparing quantitative results between countries.

[4] Or to conventional default scenarios of occupancy and electricity patterns (see e.g. the SIA 2024)

7.1.4 Sources of data

Sources of LCA data

LCA databases and dynamics of energy flows are key issues of the input data in DLCA studies of buildings. The options for input data on the dynamics of flows for electricity production or use in buildings have their advantages and drawbacks depending on the goals of the study. Variations of results from different LCA databases (or different versions) have been known for a while (Takano, Winter et al. 2014), but similar trends and ranking should be kept if the system model is the same (e.g. attributional). It is therefore important to mention such differences in the chosen LCA database when results of studies are compared, but environmental hotspots for similar buildings in the same region should be similar when key modeling assumptions are equivalent. The DLCA studies that have been found mainly use the ecoinvent database for the description of background processes, but versions and system models vary. This diversity is expected because annual updates are provided by the ecoinvent association since the start of version 3 in 2013. Moreover, the use of different system models raises an issue for the comparison of results since these models are not made to provide similar results. In addition, the KBOB database, with its modeling assumptions, has been used for some DLCA studies (Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018).

Sources of data for energy flows in electricity production

The diversity of the data sources to describe the dynamics of energy flows for production is much broader. Many of these publications use the national statistics to describe the dynamics of the energy production for their case study. These statistics are provided either by institutes (e.g. EPA) or by grid or transmission system operators (e.g. RTE). They can be used to model both short-term variations and long-term evolutions. The ENTSO-E statistics[5]have been used more recently to provide input data that describe the dynamics of electricity production in all European countries (Vuarnoz and Jusselme 2018). This source of information provides a wealth of data for every hour of the day since 2015.

The description of energy use in DLCA studies of building is based on three different types of data inputs. The first type is related to measurements (e.g. electricity load profiles) in the assessed buildings (Collinge, Landis et al. 2013, Collinge, Landis et al. 2013, Sohn, Kalbar et al. 2017, Sohn, Kalbar et al. 2017, Collinge, Rickenbacker et al. 2018, Karl, Maslesa et al. 2019). This type of information is precise and representative, but it never covers the entire use phase of the building mainly because studies are carried out before the end of life or they only address part of the life cycle. Other publications model the energy use with estimations from different software options that provide short- and/or long-term heat budgets (Roux and Peuportier 2013, Fouquet, Levasseur et al. 2015, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2017, Gimeno-Frontera, Mainar-Toledo et al. 2018, Vuarnoz and Jusselme 2018, Negishi, Lebert et al. 2019). These modelled values are specific for the site of the building and some key thermal properties, but offer theoretical values that are not necessarily confirmed by observations. The third type used by LCA practitioners is to take buildings' consumption curves from national standards to carry out an assessment that fits with the current regulations of the building sector in a chosen country (Sandberg and Brattebø 2012, Zhang and Wang 2017, Vuarnoz, Cozza et al. 2018). Such inputs are average values that are not representative of any "real-world" building, but can be used to offer an equivalent frame of reference for the comparison of assessment frameworks. This specificity of the national standard consumption curves makes them particularly interesting in EcoDynBat together with the use of electricity load profiles from real buildings.

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[5] https://www.entsoe.eu/

7.1.5 Temporal resolution of flows

The dynamics of flows in models of buildings in DLCA studies are provided with four different levels of resolution, in the identified publications. The most precise level for the temporal differentiation of flows is the hour, which is applied mainly for studies focusing on short-term variations with the exception of two prospective studies (Roux, Schalbart et al. 2016, Sohn, Kalbar et al. 2017). Daily and monthly differentiations are intermediate levels of resolution, which are often chosen when hourly data is not available for studies focusing on short- or long-term aspects. Yearly differentiation of flows is the least precise level that is used in DLCA studies and is employed mainly for long-term prospective assessments. The effect of applying different resolutions for the description of energy dynamics has been evaluated in one publication (Karl, Maslesa et al. 2019) for Danish buildings. The results of this study show that no significant variations can be observed between hourly, daily, and monthly resolutions for the analyzed office buildings. The only significant change is between yearly and monthly resolutions. This observation will need to be compared with results from the EcoDynBat project to check if conclusions are the same for two different countries.

7.1.6 Allocation rules for the building on-site electricity production

Some studies have also analyzed the influence of allocation rules for the electricity production from PV panels in a DLCA framework (Fouquet 2014) when buildings are considered multifunctional systems, because they produce energy and provide living spaces. According to ISO 14044 (ISO14044 2006) and ILCD Handbook (Joint Research Center 2010), in attributional LCA, two approaches can be used to deal with this aspect: the system expansion, also called avoided burden approach or the co-products allocation. The approach of avoided burden considers the 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 installation are thus 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 on-site production is calculated according to the self-consumption ratio (dividing the PV electricity used on-site and the total production). In addition, the EN 15978 (Standardization 2009) suggests communicating the amount of produced energy and allocating all impacts of the decentralized installation to the building.

7.1.7 Types of building

Different types of buildings are expected to show different trends in DCLA studies. Indeed, differences in “typical” dynamics of energy use for residential, office, industrial and institutional buildings could show diverse environmental hotspots, since energy should be consumed at different periods of the day. For example, the main consumption of energy from office buildings is expected between 8:00 and 18:00 in most countries, while residential buildings normally use more energy during the periods between 6:00 to 8:00 and 17:00 to 23:00 for weekdays. When these periods of higher energy use are linked to variations in the availability of energy sources during days, weeks and months, the expected disparities become clear. Nevertheless, such a comparison between building types in DLCA studies has not been found in the literature and new assessments will be needed to confirm this hypothesis. Most of the published DLCA studies have focused on residential buildings (Roux and Peuportier 2013, Fouquet, Levasseur et al. 2015, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2016, Roux, Schalbart et al. 2017, Sohn, Kalbar et al. 2017, Sohn, Kalbar et al. 2017, Zhang and Wang 2017, Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018, Negishi, Lebert et al. 2019) with some insights on offices (Collinge, Rickenbacker et al. 2018, Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018, Karl, Maslesa et al. 2019) and academic institutes (Collinge, Landis et al. 2013, Collinge, Landis et al. 2013, Collinge, Landis et al. 2014, Collinge, Rickenbacker et al. 2018, Hu 2018). Strikingly, all DLCA studies on residential buildings are conducted in Europe and institutes are only assessed in the US, suggesting that the choice of a building type is decided mainly by the access to data.

7.1.8 Considered impact categories

The published DLCA studies have used about nine different LCIA methods to assess the impacts of buildings. More than half use methods that provide multi-criteria assessment (e.g. ReCiPe and TRACI) and most of them assess the GWP. Some of these studies use DLCIA methods that consider variations of impacts, based on the moment of emissions, but only for GWP (Collinge, Landis et al. 2013, Fouquet, Levasseur et al. 2015, Negishi, Lebert et al. 2019) and POCP (i.e. photochemical ozone creation potential) (Collinge, Landis et al. 2013, Collinge, Rickenbacker et al. 2018). This means that all differences, in impacts between dynamic and static LCA, for all other studies only depend on the dynamics of energy flows and not the moment of pollutant emissions. The rare use of DLCIA methods also hints at the demanding task of using such method with current software options.

Two studies suggest that impacts for all categories will increase (Karl, Maslesa et al. 2019) or decrease (Hu 2018) when dynamics of systems are considered, but most of them show both rises and reductions , depending on the chosen categories. These different trends are expectable because of the diverse scopes and types of building system that are analyzed. Moreover, the current lack of consistency, in used LCIA methods hinders the fair comparisons between studies for all impact categories. To some extent, comparisons between results for the GWP category are possible, but different publications have used different versions and temporal horizons, which limits the fairness of this comparison.

7.2 General observations within DLCA studies

Finding general observations and common trends in the analyzed DLCA studies is challenging because the goals and scopes are so diverse. It then becomes relevant to concentrate our analysis on the case studies that offer relevant information for the context of the EcoDynBat project. All DLCA studies with a focus on prospective assessments of long-term evolutions are therefore discarded since they rarely look into the environmental effects of short-term variations. This leaves 11 studies that can be check to see if common outcomes can be found when intra-annual variations are considered, thus probably guiding some important modelling choices for the next steps of the EcoDynBat project.

It then becomes clear that a comparison of quantitative impacts from these 11 DLCA studies is not reasonable, because the input data (e.g. LCA databases) and LCIA methods are not consistent. Additionally, the different scopes of analyzed system (e.g. full life cycle vs operation phase) prevents from a hotspot analysis in the relative results. This leaves only one option for general comparison, which is to check for common trends in the variations of impacts between dynamic and static LCA.

Table 5 thus provides an overview of eight DLCA studies where all modelling choices are informed and it clearly shows that considering intra-annual variations of energy flows bring different changes in impacts depending on other aspects of the studies' context. This lack of common trends clearly shows that the chosen country, considered life cycle phases, building types, and temporal resolution bring different variations impacts when energy dynamics are considered, which justifies further exploration. Table 5 also shows that buildings with different energy sources might bring different results when system dynamics are considered. Indeed, two publications from France (Roux and Peuportier 2013, Fouquet 2014) show that the changes in impacts will be different when DLCA are carried out if the building is linked to different decentralized installations for energy production. These changes can come directly from the types of installation or because of the computational rules from standards (e.g. EN15978) where annual averages are supposed to be used for considering self-consumption.

It is also important to mention that results from the EcoDynBat project will have a rather similar basis of comparison , as two studies from Switzerland that have recently been carried out, which have many equivalent modelling choices (Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018). The main differences between these studies and the work of the EcoDynBat project reside in how EcoDynBat considers diverse temporal resolutions and the higher level of details of the modeling of the electricity production in neighboring countries.

Table 5 : Key modelling choices of DLCA studies and changes in impacts when dynamic models are used

Studies	Country	Focus	Building type	Resolution	Effect from dynamic model when compared to static results
Karl et al. 2019	Denmark	Operation	Office	Hourly Daily Monthly Yearly	↑ all impacts ↑ all impacts ↑ all impacts ↑ all impacts
Collinge et al. 2018	USA	Operation	Institute Office	Hourly Monthly Hourly Monthly	↑ GWP,↓ all other impacts ↑ all impacts ↓ all impacts ↓ all impacts
Vuarnoz & Jusselme 2018	Switzerland	Electricity	Residential + Offices	Hourly	↓ all impacts
Vuarnoz et al. 2018	Switzerland	Operation	Residential + Offices	Hourly	↓ GWP, ↑ all other impacts
Fouquet et al. 2014	France	Full life cycle incl. the analysis of three allocation rules for the exported PV electricity (operational energy use calculated using hourly dynamic simulation in the 2 resolutions)	Residential Residential + Solar PV (near zero energy building) Residential + PV + Solar thermal (Plus energy building)	Hourly Yearly Hourly Yearly Hourly Yearly	↑ CED, GWP, radioactive waste ↑ CED ↓ or ↑ for GWP, radioactive waste depending on the type of allocation rule ↑ CED ↓ or ↑ for GWP, radioactive waste depending on the type of allocation rule (only the 3 most sensitive indicators to the switch between hourly and yearly resolution are reported here)
Roux et al. 2017	France	Operation	Residential	Hourly	↓ CED, Water use, RW ↑ all other impacts
Roux et al. 2016	France	Operation	Residential	Hourly	↑ Human health = Eutrophication ↓ all other impacts
Roux & Peuportier 2013	France	Full life cycle	Residential Residential + Solar thermal Residential + Cogeneration Residential + Solar PV	Hourly	↑ Non-radioactive waste = Eutrophication ↓ all other impacts ↓ CED, Water use, RW ↑ all other impacts ↑ Human health = Eutrophication ↓ all other impacts ↑ Non-radioactive waste = Eutrophication ↓ all other impacts

8. Conclusions

Many key modelling assumptions and methods were identified in this comprehensive literature review. Some of these observations can be used to structure a useful assessment framework, appropriate for the objective of the EcoDynBat project on intra-annual variations of electricity flows in Swiss buildings. These findings can be classified in three categories, which are related to: (1) modelling of the energy flows in buildings, (2) methods for computation of DLCIs, and (3) functions of buildings. The following list presents these recommendations and the reasons why they are retained.

8.1 Recommended system modelling choices

The relevance of the EcoDynBat objective on intra-annual variations of energy flows is first validated by the limited number of studies on systems' dynamics for the environmental assessment of buildings. The recent Swiss publications on the subject (Vuarnoz, Cozza et al. 2018, Vuarnoz and Jusselme 2018) provide interesting ideas, but some simplifications are still made on the temporal variability of imports and exports of the electricity flows. For example, the authors use annual average for the import/exports between Switzerland and Germany and the effect of such a simplification has not been assessed in their work. Moreover, the existing DLCA frameworks for buildings (Collinge, Landis et al. 2013, Su, Li et al. 2017, Negishi, Tiruta-Barna et al. 2018) do not propose a clear strategy to consider such variations. The literature review thus confirms the relevance of carrying out further DLCA studies on intra-annual energy flows for Swiss buildings, at different levels of temporal and regional precision, to evaluate the level of variability from such assessment.

Results from the EcoDynBat project will be more useful if they can be compared with previous Swiss benchmarks for energy flows in buildings (e.g. KBOB). It is therefore important to choose modelling assumptions to ensure some consistency where it can be found. That is why the use of an attributional perspective is recommended for the assessment. This consistency goal also justifies the use of "standardized" values to describe some aspects of the systems as, for example, the PV installations (see sub-section 6.1.1 for details) when case specific information is not available. The use of the latest version of ecoinvent and KBOB and their system models should also help in respecting consistency in background data. However, site-specific aspects should be prioritized over consistency in order to increase the overall representativeness of the comparison between previous benchmarks and new results that consider the systems' dynamics.

The focus on energy flows within buildings will also necessitate a transparent and detailed description of the data sources that will be used to describe the systems' dynamics with their corresponding assumptions and limits. Some scientific publications offer insights on the key information and choices that need to be considered in such studies, but they are not very detailed probably because of the usual synthesis format of such publications. For now, useful ideas have been provided to consider temporal variations for energy flows in buildings with decentralized production, but more details will be necessary to describe the use of Swiss electricity mix at different periods (e.g. day, week).

Some modelling simplifications will probably be necessary for the DLCA studies in the EcoDynBat project, mainly because there is still an important lack of temporally differentiated LCA data. Indeed, all temporally differentiated flows that will be considered will need to be defined by the project partners to ensure transparency in the assessment. The temporal simplifications should be kept at a minimum for foreground processes while finding a balance between increased precision and the time needed for system modelling and computation of DLCIs (see also sub-section 8.2). For background processes, it seems necessary to neglect the lag times between emissions timing and use of energy since considering such an element would force a temporal description of all flows in the chosen databases.

8.2 Recommended computational structure

Traversal graph computational methods and tools show great promise for the future of DLCA studies, but their use in the EcoDynBat project is impeded by the lack of temporally differentiated data in LCA databases. Indeed, such methods and tools rely on descriptions of flows by process-relative temporal distributions, which are not provided in the latest version of the ecoinvent and KBOB databases. The use of the matrix-based computational structure is therefore recommended for this project.

The use of the matrix-based computational structure has been demonstrated by Collinge et al. (2013) and in some LCA software options with a limitation that is linked to the complexity of creating the required processes for detailed models with high temporal precision (e.g. hourly differentiation). Computational time can also become a limit that depends on the chosen software tools. Some investigation and tests with different tools is therefore recommended before the creation of calculation algorithms.

8.3 Recommended description of a building's functions

A well-defined description of the main function is a key concept in LCA. Two of the DLCA frameworks for buildings (Su, Li et al. 2017, Negishi, Tiruta-Barna et al. 2018) offer convincing arguments for considering that buildings should not only be described by their surface and use, but also by the amount of users. Indeed, the number of users (e.g. habitants, workers) is expected to have a significant effect on the energy flows and such an aspect should not be neglected to offer a relevant comparison of different buildings. For examples, an apartment of 90 m^2 that provide shelter for four habitants should not be directly compared with a house of 90 m^2 for two habitants. It is therefore recommended to consider the building's occupancy in the definition of its functional unit for any of the assessed systems in the EcoDynBat project.

8.4 Summary of recommendations

Table 6 summarizes the main recommendations for modelling choices in the EcoDynBat project.

Table 6 : List of key aspects to consider for the DLCA of energy use in buildings

For modelling energy

- Focus on intra-annual variations (short-term)
- Consider the detailed production of neighboring countries to model Swiss imports
- Ensure consistency with other assessment methods in the model's structure of:
  o Electricity mixes
  o Decentralized production
- Employ site specific data when available
- Offer transparent and detailed descriptions of data sources
- Minimize the amount of temporal simplifications
- Neglect lag-times in:
  o Background databases
  o Decentralized renewable energy production

For the computational structure
- Use matrix-based calculations to obtain DLCIs   o Can also be applied on processes instead of emissions
For the description of a building's function
- Use the type of building, the area and the number of users to define the FU

9. References

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ECODYNBAT Project

Dynamic Life Cycle Assessment of Buildings

Chapter 2: Data collection and Management (WP 2)

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Summary

The EcoDynBat project aims at studying the influence of time step choice on the environmental impact of the electricity demand of buildings in Switzerland. To achieve this objective, all sources of variability that influence this environmental balance have been identified and are presented in this document. Itis necessary to obtain the following detailed information, in order to characterize the electricity consumed in Switzerland and therefore its environmental impact:

- Means of production used in Switzerland,
- Means of production used in neighbouring countries,
- Cross-border electricity flows,
- Loss of distributions.

The aforementionned information was collected from various sources, both national (Switzerland, France, Germany, Austria, Italy) and European (via the platform set up by the European electricity grid operators ENTSO-E). For this purpose, a data collection platform has been set up. The collected data were then characterized and compared with each other. It appeared that most of the national data do not have the adequate temporal resolution (i.e. no hourly time) for the environmental analyses planned in the project. Conversely, European data (ENTSO-E) are available in hourly resolutions but do not present the accuracy of national data and statistics. Based on this assessment, it was decided to propose a methodological framework to harmonise European data (ENTSO-E) using the information available from national statistics. Using this information, a series of data called "EcoDynBat dataset" has been developed for the years 2017 and 2018. This data will be used as a basis for the project's environmental analyses.

The building's electricity consumption profile has also been identified as a key element that can influence the environmental balance sheet. To consider this aspect, different real building load curves will be considered in the project. In addition, the presence of decentralized electricity production facilities (photovoltaic or micro-cogeneration) will also modify the environmental impacts of buildings by limiting the use of the electricity grid. Finally, the use of a heat pump to meet heating demand is also identified as a key point since it induces a high seasonality of electricity demand. To be able to consider these different elements, models for calculating the energy performance of these systems have been proposed and are presented in this document.

All the data and models presented in this report will then be used in the case studies of the project.

Résumé

Le projet EcoDynBat a pour objectif d'étudier l'influence du choix de pas de temps sur l'impact environnemental de la demande d'électricité des bâtiments en Suisse. Pour réaliser cet objectif, l'ensemble des sources de variabilité pouvant influencer ce bilan environnemental ont été identifiées et sont présentées dans le présent document. Ainsi, pour caractériser l'électricité consommée en Suisse et donc son impact environnemental, il est nécessaire d'obtenir des informations détaillées suivantes :

- Moyens de production utilisés en Suisse,
- Moyens de production utilisés dans les pays voisins,
- Flux d'échanges transfrontaliers,
- Pertes de distributions.

Ces informations ont été collecté à partir de différentes sources aussi bien nationales (Suisse, France, Allemagne, Autriche, Italie) qu'européennes (via la plateforme mise en place par les opérateurs de réseaux électrique européen ENTSO-E). Pour ce faire, une plateforme de collecte de données a été mis en place. Les données ainsi collectées, ont ensuite été caractérisées et comparées entre elles. Il est apparu que les données nationales ne possèdent pas, pour la plupart, la résolution temporelle adéquate (i.e pas de temps horaire) pour les analyses environnementales prévues dans le projet. A l'inverse, les données Européennes sont disponibles en résolutions horaires mais ne présentent pas la précision des données et statistiques nationales. De fait, il a été décidé de proposer un cadre méthodologique permettant d'harmoniser les données Européennes à l'aide des informations disponibles par les statistiques nationales. A l'aide de ces informations, une série de données appelée « EcoDynBat dataset » a été développé pour les années 2017 et 2018. Ces données serviront de bases aux analyses environnementales du projet.

Le profil de consommation électrique du bâtiment a également été identifié comme un élément clef pouvant influencer le bilan environnemental. Pour considérer cet aspect, différentes courbes de charge réelles de bâtiments vont ainsi être considérés dans le projet. Par ailleurs, la présence de moyens de production d'électricité décentralisé (photovoltaïque ou micro-cogénération) va également modifier les impacts environnementaux des bâtiments en limitant le recours au réseau électrique. Finalement, l'utilisation d'une pompe à chaleur pour répondre à la demande de chauffage est également identifié comme un point clef puisqu'induisant une forte saisonalité de la demande électrique. Pour pouvoir considérer ces différents éléments, des modèles de calcul des performances énergétiques de ces systèmes ont été proposés et sont présentés dans ce document.

L'ensemble des données et modèles présentés dans ce rapport seront ensuite utilisés dans les cas d'études du projet.

Zusammenfassung

Das Projekt EcoDynBat untersucht den Einfluss der Zeitschrittwahl auf die Umweltauswirkungen des Strombedarfs von Gebäuden in der Schweiz. Um dieses Ziel zu erreichen, wurden alle Variabeln, die diese Umweltbilanz beeinflussen könnten, identifiziert und in diesem Dokument dargestellt. Um den in der Schweiz verbrauchten Strom und damit seine Umweltauswirkungen zu charakterisieren, ist es daher notwendig, detaillierte Informationen zu folgenden Aspekten zu erhalten:

- In der Schweiz verwendete Produktionsmittel
- Produktionsmittel, die in den Nachbarländern eingesetzt werden
- Grenzüberschreitende Handelsströme
- Verlust von Ausschüttungen.

Diese Informationen wurden aus verschiedenen nationalen (Schweiz, Frankreich, Deutschland, Österreich, Italien) als auch europäischen (über die vom europäischen Stromnetzbetreiber ENTSO-E eingerichtete Plattform) Quellen zusammengetragen. Zu diesem Zweck wurde eine Datenerfassungsplattform eingerichtet. Die so erhobenen Daten wurden anschließend charakterisiert und miteinander verglichen. Es zeigte sich, dass die meisten nationalen Daten nicht über die angemessene zeitliche Auflösung (d.h. keine Stundenzeit) für die im Projekt geplanten Umweltanalysen verfügen. Umgekehrt liegen europäische Daten über Stundenauflösungen vor, allerdings weisen sie nicht die gleiche Genauigkeit wie die nationalen Daten und Statistiken auf. Deshalb wurde beschlossen, einen methodischen Rahmen zur Harmonisierung der europäischen Daten unter Verwendung der aus den nationalen Statistiken verfügbaren Informationen vorzuschlagen. Ausgehend von diesen Informationen wurde für die Jahre 2017 und 2018 eine Datenreihe namens "EcoDynBat Datensatz" entwickelt. Diese Daten werden als Grundlage für die Umweltanalysen des Projekts verwendet.

Das Stromverbrauchsprofil des Gebäudes wurde ebenfalls als ein Schlüsselelement identifiziert, das die Umweltbilanz beeinflussen kann. Um diesen Aspekt zu berücksichtigen, werden im Projekt verschiedene reale Gebäudelastkurven berücksichtigt. Darüber hinaus verändert das Vorhandensein dezentraler Stromerzeugungsanlagen (Photovoltaik oder Mikro-KWK) ebenso die Umweltauswirkungen von Gebäuden, indem es die Nutzung des Stromnetzes einschränkt. Schließlich wird auch der Einsatz einer Wärmepumpe zur Deckung des Wärmebedarfs als wichtiger Punkt genannt, da sie eine hohe Saisonalität des Strombedarfs induziert. Um diese verschiedenen Elemente berücksichtigen zu können, wurden Modelle zur Berechnung der Energieeffizienz dieser Systeme vorgeschlagen und in diesem Dokument vorgestellt.

Alle in diesem Bericht vorgestellten Daten und Modelle werden dann in den Fallstudien des Projekts verwendet.

Table of content

Acronyms

AT : Austria

CH : Switzerland

CHP : Combined Heat and Power

DE : Germany

ENTSO-E : European Network Transmission System Operator

FR : France

GW: GigaWatt

GWh: Gigawatt hour

IT : Italy

LHV: Lower Heating Value

MW : MegaWatt

MWh : Megawatt hour

PV : Photovoltaic

RTE : Reseau de transport d’électricité (French TSO)

SFOE. Swiss Federal Officie of Energy (Office Fédéral de l’Energie)

SFTP: Secure Shell File Transfer Protocol

TP : Transparent Platform

TSO : Transmission System Operator

WP: Work Package

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1. Objectives

The objectives of this report are to:

- Identify the data needs and availability for the EcoDynBat environmental impact calculation for which the method will be defined in the chapter 3;
- Characterize the data and their quality for the identified relevant sources;
- Propose a framework to use the data sources in order to obtain an “EcoDynBat” dataset containing all the necessary inputs and models;
- Propose models in order to overcome the possible lack of data;
- Present the EcoDynBat dataset for environmental impact calculations.

In order to fulfil these objectives, this report first presents generalities about the Swiss electricity market and situation as a background information. Then, the data needs are characterized, according to the EcoDynBat project objectives by identifying the sources of variability to be considered for the environmental impacts calculations. Based on this identification, the relevant data sources are identified and their characteristics are presented. This assessment serves as a basis to develop the EcoDynBat dataset by proposing a framework to adapt, aggregate and manipulate the identified data. In addition, regarding possible missing elements for the environmental impact calculation, models are defined. Finally, the EcoDynBat dataset is thereby obtained.

2. Background

2.1 Electricity balance in Switzerland

By its location, at the centre of Western Europe, Switzerland is deeply involved in the continental electricity market. The country has several interconnections with its neighbouring countries (mostly France, Germany, Italy, and Austria). Switzerland is producing but also importing and exporting significantly with its neighbours to cover its own need or to contribute to the continental grid stability. At the national level, Switzerland has a very specific electricity market structure due to the 900 different electricity providers (Swissgrid, 2018).

The Swiss grid structure can be decomposed in three elements:

1. The Swiss national production mix,
2. The imports,
3. The exports.

According to the Swiss electricity statistics, in 2018 (OFEN, 2018), the national electricity production was about 67.5TWh, 55.4% produced by hydroelectric power plants (25% run off river, 30% reservoir), 36.1% by nuclear power plants and the remaining 8.5% was produced by the other production means (classical thermal plants or renewables). However, beyond these annual numbers, different points have to be highlighted:

- There are inter and intra-annual variation regarding the electricity national production and international exchanges. Depending on the climatic conditions and the power plants availability, the mix will vary over time, with short time step,
- The share of the 8.5% national production meansmeans that iscalled “classic thermal and others” within the classification of the Swiss Federal Office of Energy (SFOE) has increased by 33.5% since 2013. This increase is mainly due to a high growth of photovoltaic installations (+236.3%) and thermal power plants (27.3%).

Figure 1 shows the evolution of the Swiss production mix as well as the annual variability of hydro-electricity production in Switzerland. This production source is clearly dependent on the climatic and hydrologic conditions and their variability (rain, snow amount in winter, temperature, etc.).

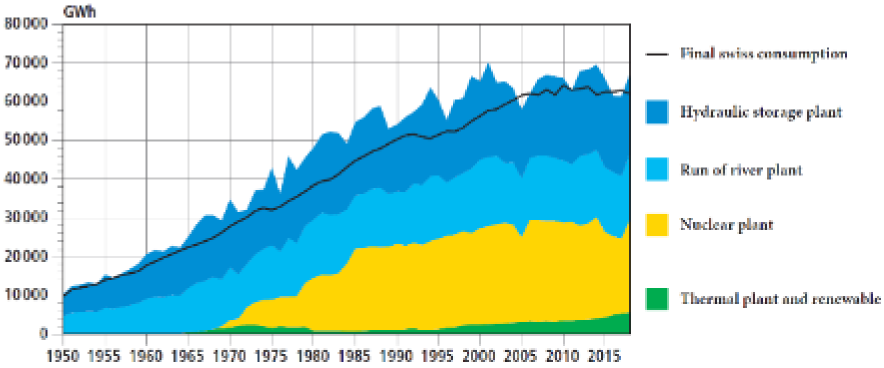

Figure 1. Historic evolution of the Swiss electricity production means (OFEN, 2018)

On a yearly basis, by comparing the annual net Swiss electricity production6 with the national consumption in Figure 2, it appears that the indigenous production is sometimes not sufficient to cover the national needs. This situation occurred for the first time in 2005 and again in 2017. While in the past Switzerland was a net exporting country, over the last years this trend has changed due to two factors. First, the national electricity demand has increased (especially in winter), and second, the hydroelectricity production has slightly decreased.

The annual balance between net production and consumption can be seen in Figure 2, while an intra-annual variability is observed in Figure 3. The monthly balance is depicted for two distinct time periods, between 1989-2004 and 2005-2018. This choice is done because 2005 corresponds at the first year with a yearly negative balance between net Swiss production and Swiss consumption.

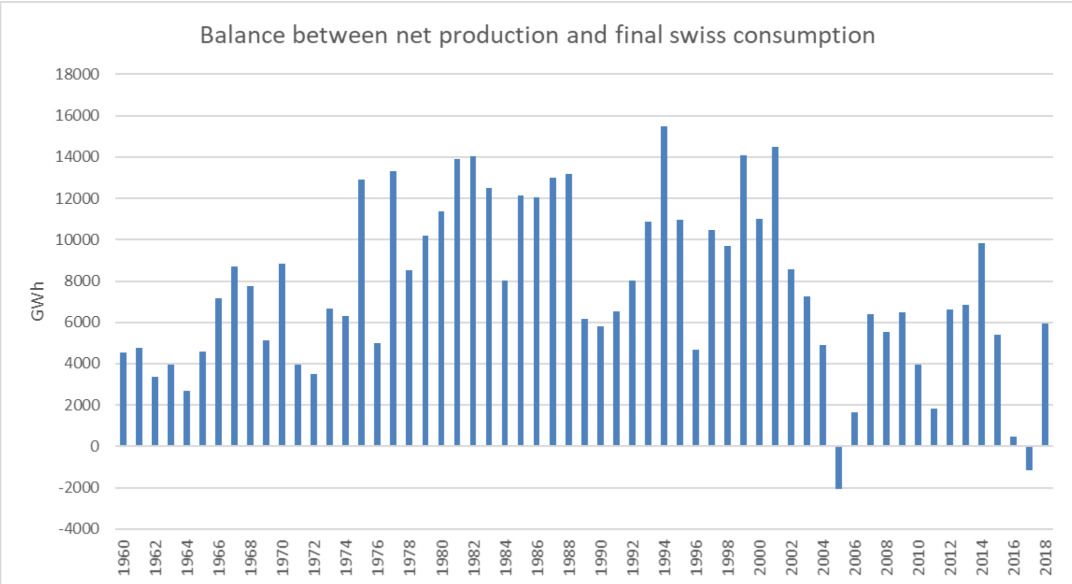

Figure 2. Balance between net production and final consumption in Switzerland (OFEN, 2018)

[6] The net annual electricity production is the annual production minored by the electricity consumption necessary to pump the water for the pumping storage hydropower plants.

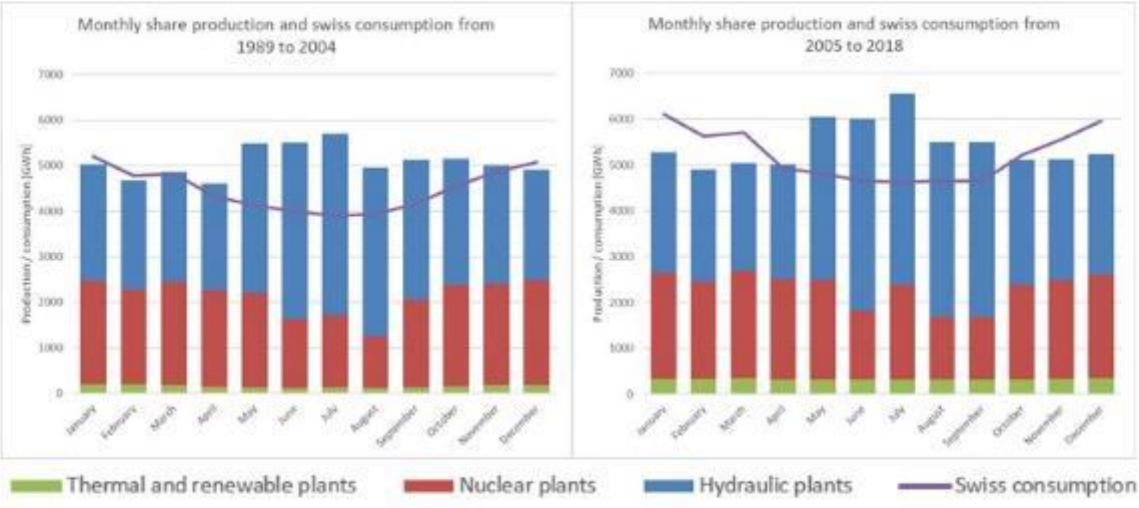

Figure 3. Average monthly Swiss average electricity production by energy carriers versus the electricity demand, left : period from 1989 to 2004, right : period from 2005 to 2018 (OFEN, 2018)

From these figures, it appears that:

I. Between the two averaging periods, the gross production and the final consumption has increased. On a monthly basis, the consumption has increased between 12% and 19%, while the production has increased by 7% on average. The production between April and September has increased between 7% to 19%, while for the other months the production variation is ranging between -1% to 7% confirming a high monthly variability.

II. The interval during which the production does not cover the consumption has increased. During the period of 1989-2004 the production deficit occurred between December and February, while from 2005 to 2018 the deficit occurs from October to March.

III. The share of the production means is quite constant over the two averaging periods, with only a slight increase of the production source called “thermal means and other including photovoltaic”.

The electricity deficit between production and consumption has been mitigated by increasing imports. Annually, the national production has constantly increased from 1960 to 2004 (Figure 4, left) and has stabilized since. The imports and exports tends to follow the same trend but in a lower trend than the production. Finally, the annual balance between imports and exports has decreased in magnitude and has even inversed in nature. Thus, since 2005 Switzerland imports more than its exports (Figure 4 right).

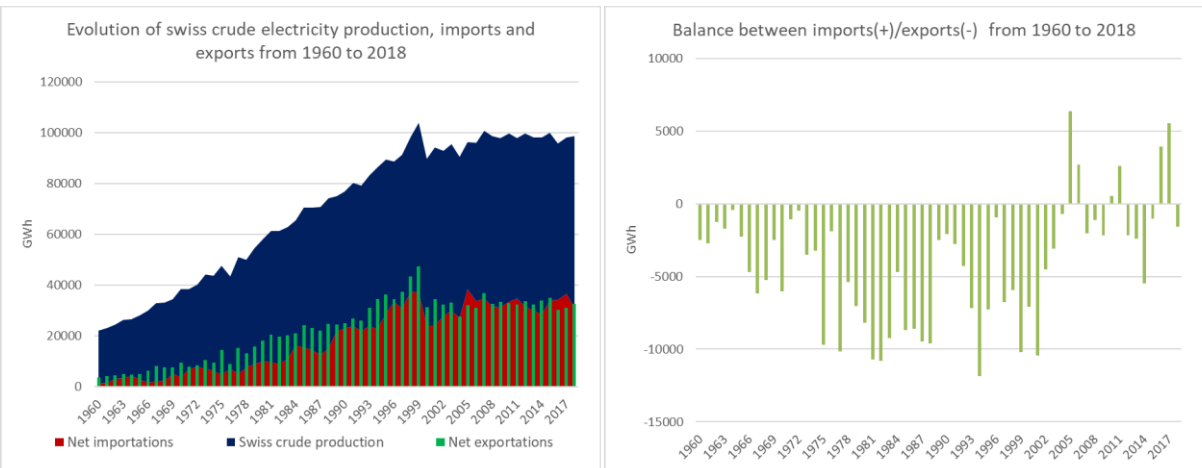

Figure 4. Annual Swiss production, imports and exports evolution over the time (left). Imports/Exports balance (right) (OFEN, 2018)

On a monthly basis, the imports/exports balance has also changed. Such as for the national production, two periods are considered, between 1989 and 2004 and from 2005 and 2018, Figure 5[7].

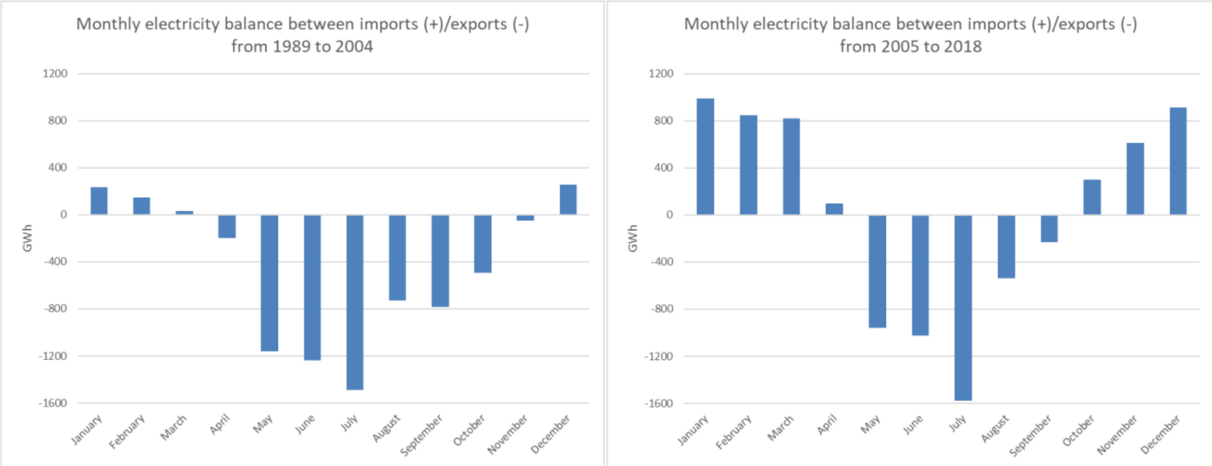

Figure 5. Monthly imports/exports balance in Switzerland between 1989 and 2004 (left) and between 2005 and 2018 (right) (OFEN, 2018)

Figure 5 shows that:

I. The monthly imbalance amplitude of the imports/exports has increased while the annual profile remained similar.

II. The time interval during which the exports exceeds the imports has decreased. Between 1989 and 2004, this period was ranging from March to November, while between 2005 and 2018 it occurs from Mai to September.

Thus over the years, the dependence of electricity's imports has increased in volume and in timeframe.

2.2 Origins of the electricity imports

To assess the environmental impact of the Swiss electricity, it is necessary to identify the production supply and volume of foreign electricity imports. While the national production is generally low carbon intensive and relies on a significant share of renewable energies, it is not the case for the neighbouring countries. Therefore, it is likely that imports play a significant role in the environmental impacts of the Swiss electricity supply mix.

The left part of Figure 6 shows the share by country of the electricity imported in Switzerland, while the right part shows the production mixes of these countries.

[7] When the balance is positive, the imports are higher than the exports and vice-versa

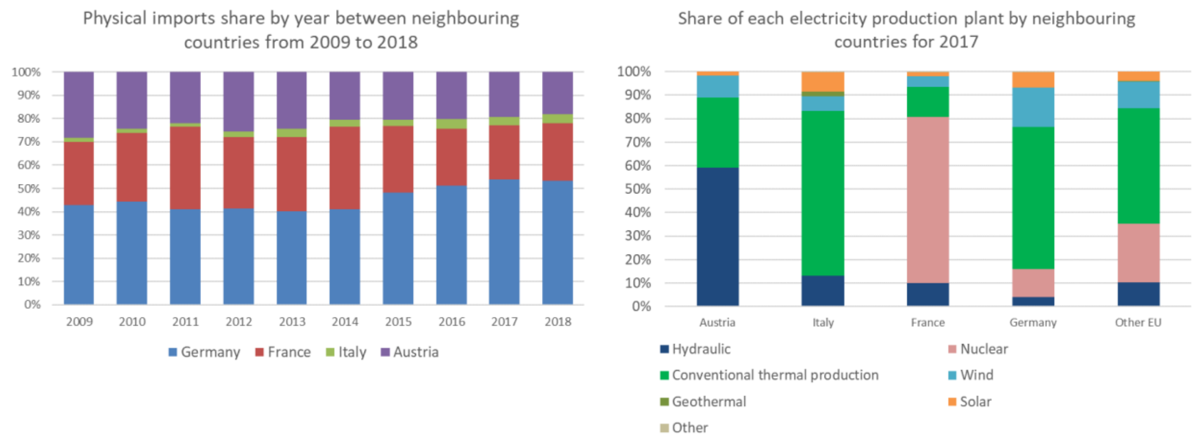

Figure 6. Share of imports in Switzerland per countries over the years (left), production mix of the countries from which Switzerland is importing, (OFEN, 2018)

Thus, on an annual basis, Switzerland is mostly importing electricity from Germany (DE) followed by France (FR) and Austria (AT). The corresponding country mix mostly relies on fossil fuels (DE), Nuclear (FR) and Hydro-electricity (AT).

In Figure 7 is presented the relative production mix fluctuation for Germany, as a illustrative example, on a monthly, daily and hourly basis for 2017. The daily data are provided for the third Wednesday of each month8. The hourly data are provided for three specific hours, 6am, 12am and 5pm, which correspond to peak electricity demands.

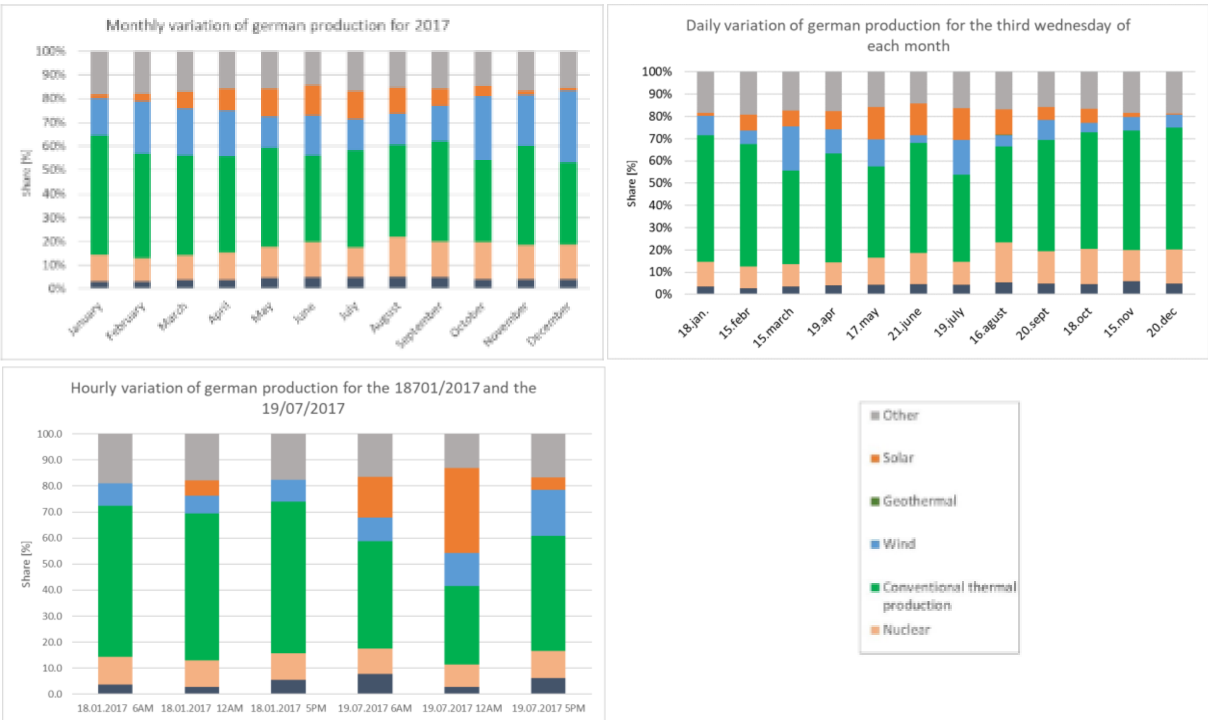

Figure 7. Monthly, daily and hourly variation of electricity production for Germany in 2017 (ENTSO-E, 2019)

Figure 7 shows that the German production mix greatly varies for each considered time step. According to Figure 6, on an annual basis, the share of conventional thermal plant is 60.7% and the share of

[8] This choice has been made according to the SFOE statistics on electricity which use the third Wednesday of each month to provide information about the daily Swiss production mix.

photovoltaic electricity is 6.4%. This repartition is different with ENTSO-E data when considering different time steps. The following shares are obtained:

- On a monthly basis, the electricity production from thermal plant is ranging from 34% to 50%. The share of PV electricity is ranging from 1% to 12.6%;
- On a daily basis, the share of electricity production from thermal plant is ranging from 39% to 57% while the photovoltaic electricity is ranging from 0.6% to 14.4%;
- On an hourly basis, the share of electricity production from thermal plant is ranging from 30% to 58%. The minimum daily value occurs in summer at midday, while there is more variability in term of share in Winter (range between 30% to 44%). The daily photovoltaic electricity is ranging between 0% and 32.7% depending of the time of the day and the season, with the maximum share occurring in summer at 12:00.

For each country, these time variations of the production mix relies significantly on the available national electricity production possibilities and the electricity suppliers' business models. Thus, the daily variation in the imported electricity sources result in a variability of the electricity environmental impacts for the imported flows and thus for the electricity consumed in Switzerland. Therefore, it is necessary to consider the fluctuation of the Swiss production but also the international imports/exports according to the smaller possible time step, to have a correct assessment of the environmental impacts of the Swiss electricity.

Since Switzerland significantly relies on imports from countries, which present very different electricity mix profiles, it is essential to address the question of the time variability on the environmental impact of the imported electricity. Thus, within the EcoDynBat project, this aspect will be addressed by considering the fluctuation of the imports as well as the fluctuation in the quality (type of energy) imported from the neighbouring countries.

3. Problematic and method

Based on the context and observations described in section 1, the EcoDynBat project will study the dynamic environmental impacts of the electricity demand at the buildings' level. The six different aspects that will be considered, includes national production mix, international electricity exchange, grid distribution and conversion losses, electricity consumers' profile and decentralised electricity production, Figure 8.

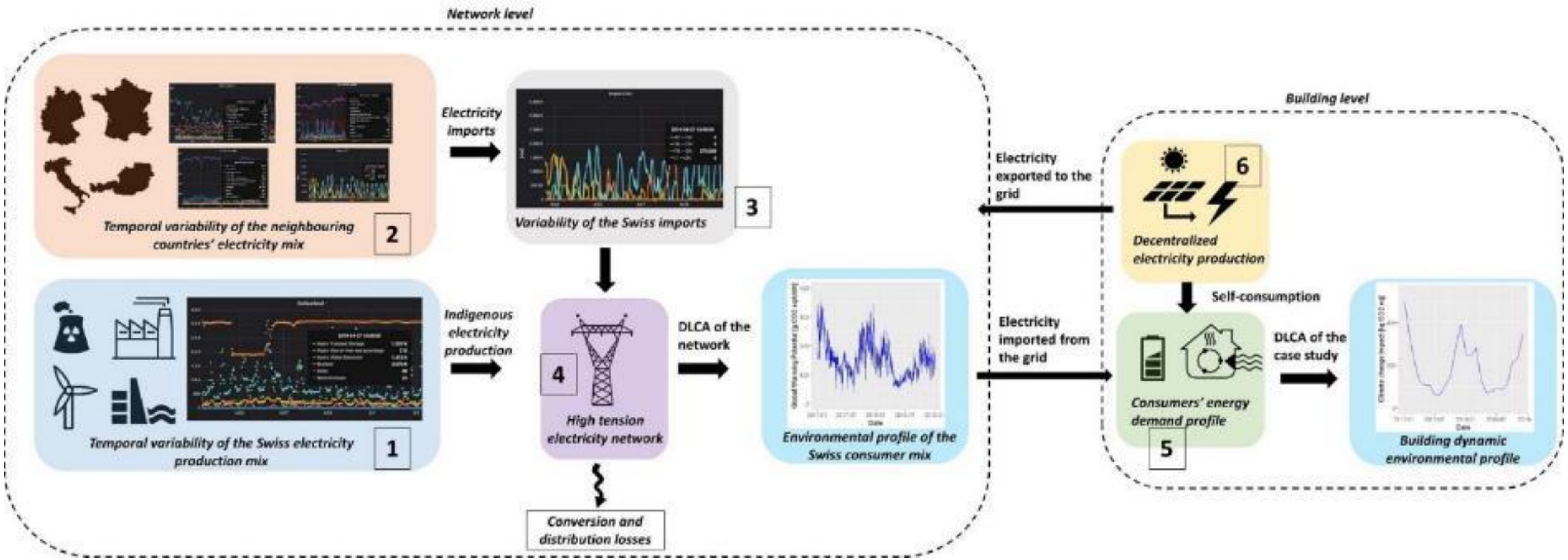

Figure 8. EcoDynBat Project framework

In order to calculate the environmental impacts of the building's electricity demand, it is first necessary to characterize the electricity consumed at the building electric sockets such as introduced in chapter 1. To do so, the production mix of Switzerland and each foreign country will be defined on an hourly basis (number 1 and 2 in Figure 8), allowing for aggregation over various time-steps (aggregation procedure presented in the chapter 6).

Moreover, since Switzerland continuously exchanges electricity with its neighbouring countries, the imports and exports to and from Switzerland have to be modelled (number 3 in Figure 8). In addition, the grid incurs losses, which are varying depending on factors such, as outdoor ambient temperature, and these losses need to be considered (number 4 in Figure 8). Finally, the building electricity demand profile has to be considered. Thus, in order to assess the environmental impacts of the electricity at the Swiss plug, it is necessary to know:

- The quantity (the amount) and quality (type of sources used to produce) of electricity produced in Switzerland by the different energy carriers;
- The quantity and quality of electricity imported and exported with the neighbouring countries;
- The grid losses;
- The building electricity demand profile;
- The presence of a decentralized electricity production system and its amount of self-consumed electricity;

At the building level, such as introduced in the EcoDynBat chapter 1, it is necessary to model the electricity consumption profile (number 5 in Figure 8). This profile depends on several factors such as the building typology (residential, offices, etc.) and the quantity and profile consumption of the electric equipment used (for example, heat pumps, driers, etc.). It can show large electricity consumption fluctuations over the time, especially when heat is produced with an electrical technology.

At the building level, the availability of a decentralized electricity production system (6 in the Figure 8 such as photovoltaic or micro-CHP could have a significant influence on the environmental impact of the building electricity demand. Indeed, in such cases a portion of the produced electricity will be used for self-consumption in the building itself, leading to a reduction of the electricity drawn from the grid. Additionally, this self-consumed electricity will have environmental impacts, which need to be considered in the environmental assessment.

Finally, it will be necessary to characterize the environmental impact of each of the production sources used in Switzerland and abroad, as well as of the decentralized electricity production systems, in order to assess the overall environmental impact of the building electricity consumption.

Therefore, a proper environmental assessment of electricity consumption from a building requires collecting a large amount of data from various sources, which need to be harmonized in order to be coherent, as schematised in Figure 9. The aim of the EcoDynBat Work Package 2 is thus to explain how such data sets have been gathered and modified to carry out the DLCA for the operation phase of buildings. This framework of data gathering and modifications is schemed in the Figure 9 .

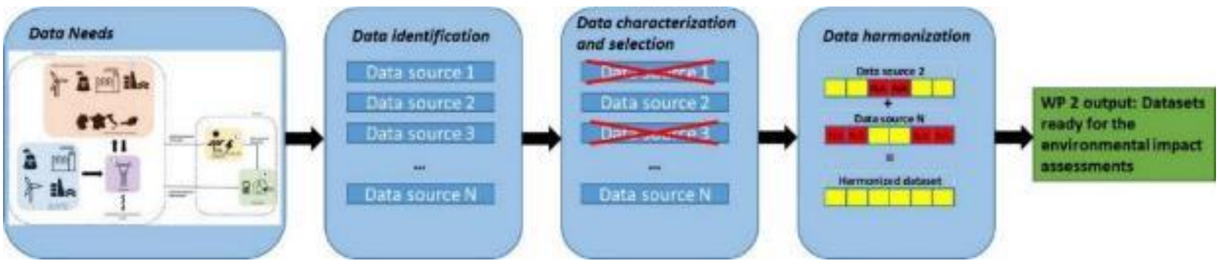

Figure 9. Work Package 2 framework

The required data have been identified and presented in the present chapter 3. Based on these data, a thorough review will identify, characterize, and select sources that describe the electricity grid data sources in the chapter 4.1. Then, their relevance and reliability will be assessed in the chapter 4.3. When necessary, harmonization procedures will be set in place in order to merge various data sources together and obtain the dataset required for the environmental impact assessment of the building electricity consumption, see the chapter 5. The EcoDynBat electricity grid data set will then be presented in the chapter 6.

Finally, at the building level, the data collection procedure and the models used to overcome some lack of information will be presented, in the chapter 7.

4. Electricity grid: Existing data sources review

This chapter identifies the existing data sources that provide the necessary information on the electric mixes in Switzerland and abroad as well as the cross-border exchange flows, section 4.1. Then, because of the large amount of data to be collected, the EcoDynBat collecting framework is presented in order to handle the information in a usable format, section 4.2. Once collected and formatted, the data are then characterized, and finally compared among the various data source to identify their reliability and robustness, section 4.3.

4.1 Review of existing data sources

There are various sources of information providing data on electricity mixes. At the Swiss level, two of them have been identified, namely data from Swissgrid (Swissgrid, 2019) and data from the Swiss Federal Office of Energy (OFEN, 2018). At the European level, there are several data sources mostly provided by the Transmission System Operators (TSO), for example in France (RTE, 2019), in Austria (e-Control, 2019), Germany and Italy (Terna, 2019) which provide similar information. At the European level, the European Network of Transmission System Operators for Electricity (ENTSO-E, 2019), which is an association regrouping 43 TSOs, also provides information about electricity mixes and exchanges. These data sources are presented here after in this following section.

4.1.1 Swissgrid data

Swissgrid is the national TSO provides reports and data, among which the Swiss electricity statistics that provides information with a 15 minutes time step on the grid operation parameters described in Table 1.

Data available within Swissgrid
Total energy consumed by end users in the Swiss control block
Total energy production Swiss control block
Total energy consumption Swiss control block
Net outflow of the Swiss transmission grid
Grid feed-in Swiss transmission grid
Cross boarder exchange (imports and exports) with Austria, Germany, France and Italy
Transit, total import, total export
Secondary and tertiary control energy prices
Consumption and production for all the Cantons
Production across Cantons
Consumption across Cantons
Production control area CH - foreign territories
Consumption control area CH - foreign territories

Table 1. Data available from Swissgrid

Thus, Swissgrid provides also information regarding the network operation characteristics and flows, both between Switzerland and the neighbouring countries. In addition, as seen in Figure 10, the exchanges with the neighbouring countries are given at each time step (15 minutes) in the two directions (gross exchanges).

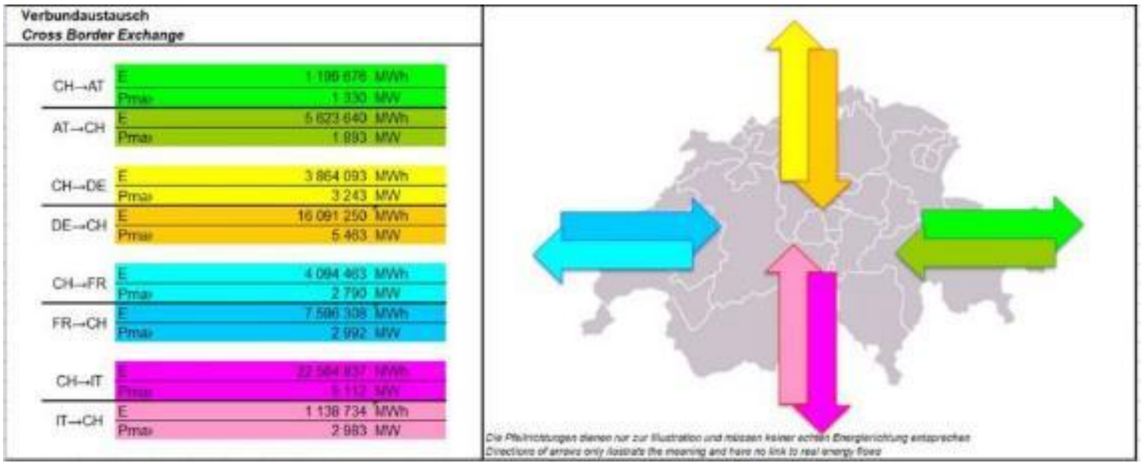

Figure 10. Example of available data from Swissgrid, gross exchange with the neighbouring countries (Swissgrid, 2019)

The Swissgrid data are of high interest, as it provides information about the quantity of electricity produced and gross exchanges at the boarders. However, it does not provide any information regarding the production mix of the electricity on the grid at each time step, i.e., the production sources. Therefore, this data source cannot be used alone, since the information on the production mix is not provided.

4.1.2 Swiss Federal Office of Energy (SFOE)

The SFOE provides a large set of data and information regarding the Swiss electricity mix. This data relies on information provided by Swissgrid and on other sources of information, which fully characterize the Swiss electricity consumption (for example, electricity consumption per industrial sector, etc.).

The most complete, annual based, data source is the “Annual Swiss electricity statistics report” (OFEN, 2019). In these annual reports can be found the monthly production mix energy, (Table 2), as shown in Table 2, as well as for some selected days of the year (as shown in Table 3).

Jahr Année	Landeserzeugung – Production nationale Wasserkraftwerke Centrales hydrauliques	Kernkraftwerke Centrales nucléaires	Konv.-therm. und erneuerbare Kraftwerke Centrales thermiques classiques et renouvelables	Total	Verbrauch der Speicherpumpen (–) Pompage d'accumulation (–)	Netto-erzeugung Production nette	Einfuhr physikalisch Importation physique	Ausfuhr physikalisch Exportation physique	Landes-verbrauch Consommation du pays	Verluste Pertes	End-verbrauch Consommation finale	Ausfuhr-überschuss (–) Einfuhr-überschuss (+) Solde exportateur (–) Solde importateur (+)
	GWh											
	Januar – Janvier											
2009	2 675	2 426	284	5 385	117	5 268	3 622	2 640	6 250	394	5 856	+ 982
2010	2 805	2 423	326	5 554	137	5 417	3 394	2 567	6 244	394	5 850	+ 827
2011	2 652	2 435	321	5 408	144	5 264	3 682	2 733	6 213	392	5 821	+ 949
2012	2 796	2 437	310	5 543	133	5 410	3 616	2 900	6 126	386	5 740	+ 716
2013	3 112	2 421	343	5 876	101	5 775	3 240	2 834	6 181	389	5 792	+ 406
2014	2 509	2 469	326	5 304	154	5 150	3 525	2 636	6 039	380	5 659	+ 889
2015	3 110	2 430	367	5 907	79	5 828	3 799	3 437	6 190	390	5 800	+ 362
2016	2 236	2 200	431	4 867	214	4 653	4 110	2 728	6 035	380	5 655	+1 382
2017	3 199	1 293	437	4 929	199	4 730	3 832	2 002	6 560	413	6 147	+1 830
2018	2 713	2 060	447	5 220	261	4 959	3 734	2 782	5 911	372	5 539	+ 952

Table 2. Monthly statistics available from SFOE (OFEN, 2018)

2018 Monat	Januar – Janvier Mittwoch Mercredi 17.1.2018	Samstag Samedi 20.1.2018	Sonntag Dimanche 21.1.2018	Februar – Février Mittwoch Mercredi 21.2.2018	Samstag Samedi 24.2.2018	Sonntag Dimanche 25.2.2018	März – Mars Mittwoch Mercredi 21.3.2018	Samstag Samedi 24.3.2018	Sonntag Dimanche 25.3.2018	April – Avril Mittwoch Mercredi 18.4.2018	Samstag Samedi 21.4.2018	Sonntag Dimanche 22.4.2018	2018 Mois
+ Laufkraftwerke	39,2	37,6	38,1	35,7	29,3	27,8	29,7	24,5	22,0	52,1	61,7	62,2	+ Centrales au fil de l'eau
+ Speicherkraftwerke	62,4	40,0	28,1	66,6	58,3	48,3	40,3	18,5	15,5	34,0	33,1	28,4	+ Centrales à accumulation
+ Kernkraftwerke	66,6	66,7	66,8	66,7	66,6	66,5	74,5	74,8	72,0	74,6	74,4	74,3	+ Centrales nucléaires
+ Konv.-therm. und erneuerbare Kraftwerke	15,2	14,0	13,9	16,6	16,5	16,3	13,9	13,9	13,6	16,1	16,1	16,1	+ Centrales therm. classiques et renouvelables
+ Einfuhrüberschuss	33,1	32,8	43,0	33,6	27,1	35,7	61,7	54,9	48,1	–	–	–	+ Excédent d'importation
= Gesamtabgabe	216,5	191,1	189,9	219,2	197,8	194,6	220,1	186,6	171,2	176,8	185,3	181,0	= Fourniture totale
– Ausfuhrüberschuss	–	–	–	–	–	–	–	–	–	6,3	28,8	27,0	– Excédent d'exportation
= Landesverbrauch mit Speicherpumpen	216,5	191,1	189,9	219,2	197,8	194,6	220,1	186,6	171,2	170,5	156,5	154,0	= Consommation du pays avec pompage
– Speicherpumpen	5,8	–	–	3,3	–	–	10,1	–	–	8,6	–	–	– Pompage d'accumulation
= Landesverbrauch ohne Speicherpumpen	210,7	–	–	215,9	–	–	210,0	–	–	161,9	–	–	= Consommation du pays sans pompage

Table 3. Daily statistics available from SFOE (OFEN, 2018)

The SFOE data provides useful information regarding the grid losses, the imports, and the exports. In addition, it also gives the necessary information regarding the electricity production mix in Switzerland. However, this information is available only with monthly time resolution and on hourly basis for 3 days each month, on a daily time resolution. This data are thus not sufficient to reach the EcoDynBat objectives.

4.1.3 Data at the European level

In Europe, the national TSOs provide data on electricity quality and quantity on their grids as well as imports and exports. Figure 11, Figure 12, Figure 13 and Figure 14, give an example of data available on the webpage of, respectively, the French (RTE, 2019) and Austrian TSO regulators (E-Control. 2019), German production mix (Fraunhofer, 2019) and Italian TSO (Terna, 2019).

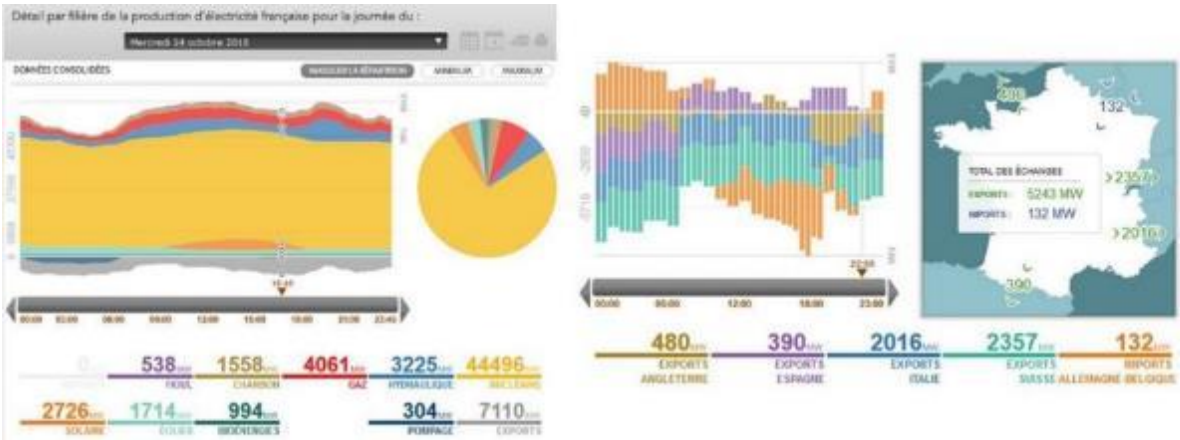

Figure 11. Available data from the French TSO: electricity mix (left), imports/exports (right), (RTE, 2019)

Date	Einspeisung Laufkraftwerke (>25 MW)	Einspeisung Speicherkraftwerke (>25 MW)	Einspeisung Kalorische Kraftwerke (> 25 MW)	Einspeisung Windkraftanlagen	Sonstige Erzeugung	Physikalische Importe	Abgabe an Endverbraucher	Netzverluste	Verbrauch für Pumpspeicherung	Physikalische Exporte	"Netzabgabe" Abgabe an Endverbraucher + Netzverluste (ohne PSP)
01.01.2016 00:00	955.16	476.92	949.80	220.48	728.33	5 211.49	5 764.49	340.44	606.38	1 830.88	6 104.93
01.01.2016 01:00	963.65	444.98	893.32	145.35	717.86	5 356.32	5 502.15	326.03	1 070.69	1 622.59	5 828.19
01.01.2016 02:00	959.45	286.76	870.20	103.57	730.27	5 630.07	5 263.52	321.15	1 395.64	1 600.01	5 584.67
01.01.2016 03:00	960.32	312.36	827.45	49.40	728.39	5 704.94	4 965.87	309.22	1 519.48	1 788.30	5 275.09
01.01.2016 04:00	972.64	255.85	786.18	36.38	732.11	5 703.69	4 879.44	307.37	1 710.50	1 589.73	5 186.81
01.01.2016 05:00	973.35	293.86	777.20	29.03	730.96	5 625.81	4 963.19	309.95	1 650.06	1 507.01	5 273.13
01.01.2016 06:00	975.04	343.68	799.93	28.76	743.00	5 571.71	4 977.38	306.48	1 629.34	1 548.92	5 283.85
01.01.2016 07:00	970.27	309.20	815.94	32.89	823.58	5 783.40	5 298.14	321.86	1 537.75	1 577.53	5 620.00
01.01.2016 08:00	964.64	289.90	827.54	28.80	784.23	5 982.39	5 464.52	335.15	1 617.62	1 460.20	5 799.66
01.01.2016 09:00	1 012.77	316.98	925.92	37.46	827.90	5 985.86	5 845.50	353.39	1 728.84	1 179.15	6 198.90
01.01.2016 10:00	1 005.75	265.45	968.11	42.99	849.66	5 353.40	6 177.40	363.22	582.98	1 361.75	6 540.63
01.01.2016 11:00	1 079.89	395.82	1 004.71	45.04	876.39	4 844.54	6 336.90	373.83	206.78	1 328.89	6 710.73
01.01.2016 12:00	1 130.01	746.99	1 008.36	48.91	889.12	4 416.56	6 278.75	360.58	172.27	1 428.34	6 639.33

Figure 12. Available data from the Austria TSO (E-Control, 2019)

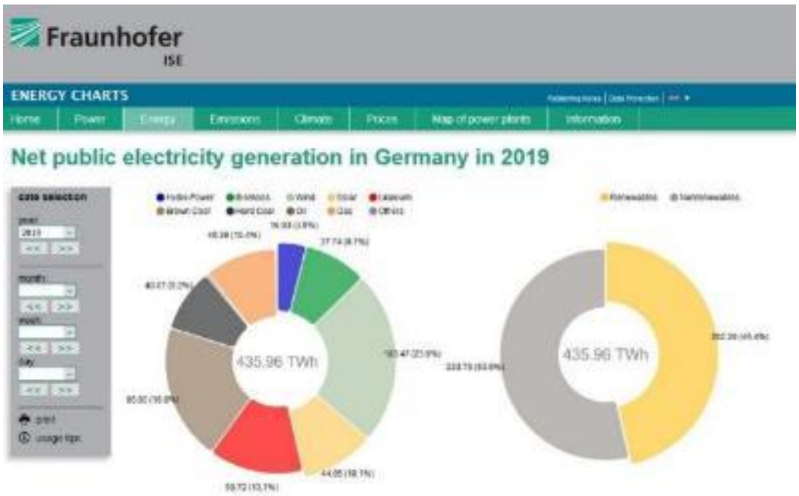

Figure 13 German national production data (Fraunhofer, 2019)

Monthly Energy Balance Sheet

[GWh]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Hydro	2.804	2.249	2.648	2.759	3.896	4.718	4.434	3.860	3.485	2.226	2.101	2.350	37.530
Thermal	21.089	16.850	14.618	13.803	14.186	16.333	17.292	16.079	15.243	17.081	19.032	17.894	199.500
Geothermal	504	454	501	479	488	473	492	478	462	480	476	498	5.785
Wind	1.797	1.536	1.935	1.369	1.251	915	1.255	1.079	1.353	1.265	1.509	2.228	17.492
Photovoltaic	1.081	1.193	2.322	2.492	2.816	2.845	3.023	2.920	2.195	1.918	1.074	932	24.811
Net Total Production	**27.275**	**22.282**	**22.024**	**20.902**	**22.637**	**25.284**	**26.496**	**24.416**	**22.738**	**22.970**	24.192	**23.902**	**285.118**
Import	2.073	3.568	5.155	3.613	3.701	3.290	4.161	3.013	3.886	3.782	2.991	3.659	42.892
Export	803	383	404	537	498	461	508	373	346	203	308	308	5.132
Net Foreign Exchange	**1.270**	**3.185**	**4.751**	**3.076**	**3.203**	**2.829**	**3.653**	**2.640**	**3.540**	**3.579**	2.683	**3.351**	**37.760**
Pumping	265	211	190	248	204	172	130	144	140	172	250	315	2.441
Electricity demand[(1)]	**28.280**	**25.256**	**26.585**	**23.730**	**25.636**	**27.941**	**30.019**	**26.912**	**26.138**	**26.377**	26.625	**26.938**	**320.437**

Figure 14 Italian production mix data (Terna, 2019)

The data sources reflect what the TSOs, public regulator or research institutes can provide as information. For the sake of transparency, they regularly publish the information regarding their production mixes, as well as their imports/exports. The French TSO and German research institute offer a live and online tool while the Austrian and Italian TSOs rely on a downloadable Excel or PDF files. In any cases, they provide the necessary hourly data of the national electricity market.

Moreover, at the European level, the legal directive (CE) n°543/2013 (European Commission, 2013) required the creation of a transparency platform for the electricity production in Europe to "create the fair conditions for all stakeholders". Since January 2015, ENTSO-E provides a transparent platform (TP), available at transparency.entsoe.eu (ENTSO-E, 2019). Its main objective is the collection of data about generation, load, transmission and import/export balance from TSOs, power exchanges or other qualified third parties. Currently, the TP includes 104 different dataset types, freely published and updated daily.

The production data as well as the import/export information are available for 32 countries across Europe, as shown in Figure 15.

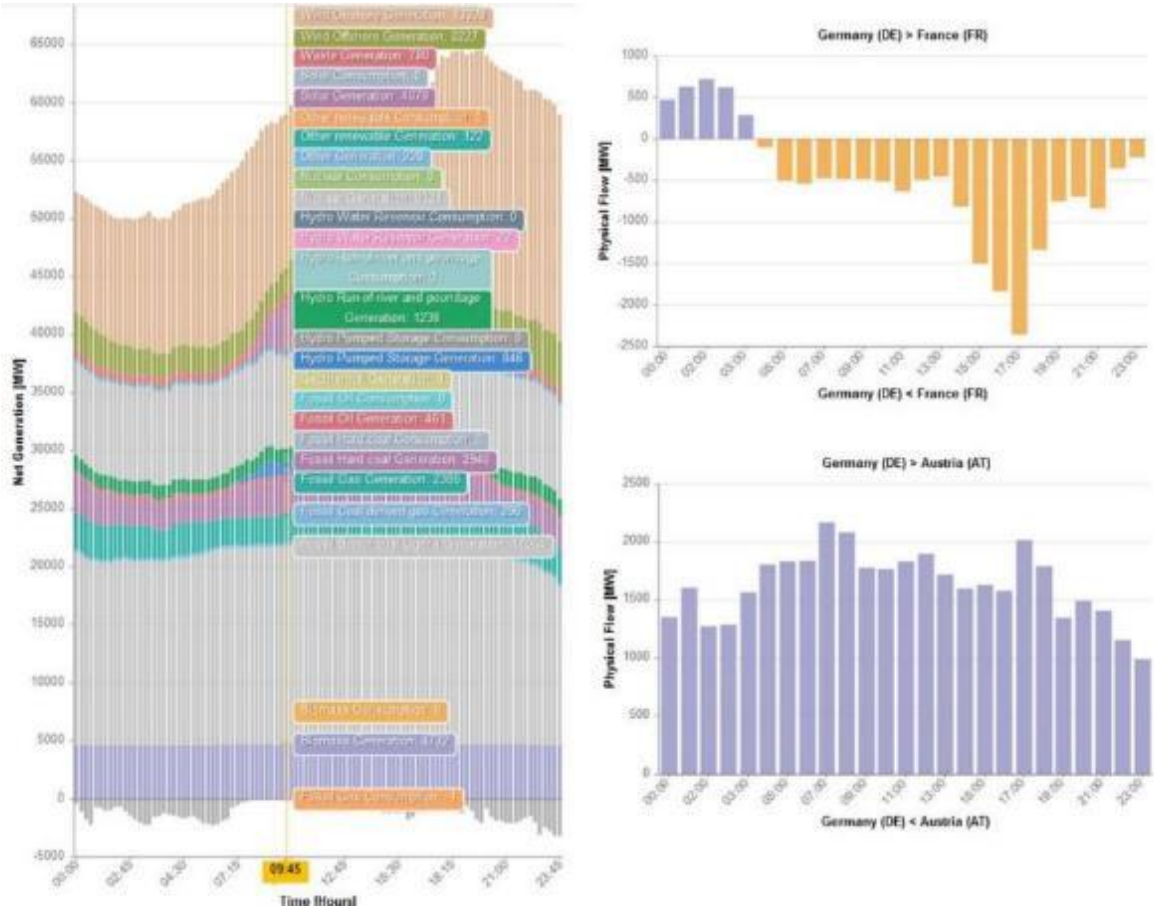

Figure 15. Available data from ENTSO-E, example for German data per energy carrier (left), and cross boarder exchanges (right) (ENTSO-E, 2019)

The available information on ENTSO-E shows some differences between the countries. The time step varies from one country to another (from 15 minutes to 1 hour). It also appears that the collected information mostly relies on electricity production sources injected at the high voltage level. However, for some of the countries, it appears that the entire production mix is provided (for example, France).

The electricity production sources provided by ENTSO-E are listed in Table 4. They have been divided into three categories, fossil base sources, renewable sources and others.

Fossil source	**Renewable source**	**Other**
Lignite	Biogas	Nuclear
Coal	Waste	Hydro Pumped storage
Oil	Marine energy	
Natural Gas	Geothermal	
Gas from coal	Photovoltaic	
Fossil oil shale	Onshore wind	
Fossil Peat	Offshore wind	
Other fossill fuel (unidentified)	Hydro reservoir	
	Hydro run of	
	Other renewable source (unidentified)	

Table 4. list of ENTSO-E production source

This data source is of high interest for the present project since it provides much of the needed information for the LCA of the Swiss supply mix. Indeed, it provides information about the electricity production mix of each country and the energy of the imports/exports. The Swiss data are also available on the ENTSO-E platform and the value from this source compared to the national sources will be discussed below.

4.1.4 Summary of the data review

Table 5 summarizes the data review introduced above and characterizes the main aspects to take into account in the EcoDynBat project.

From the review of the different sources, it appears that the ENTSO-E source is the most appropriate since it provides the information on the quantity of electricity produced in each country, as well as the import and export energy between all the countries. Indeed, no other data sources provide sufficient information regarding the production mix of countries with a high resolution (at least hourly). Nevertheless, the ENTSO-E data will be compared to the national datasets (Swiss and abroad) to check for consistency. If discrepancies are found, solutions will be proposed in order to adjust the data to obtain consistent values for the environmental impacts calculations.

	Swissgrid	SFOE	RTE	E-Control	Fraunhofer Institute	Terna	ENTSO-E
Geographical scope	Switzerland	Switzerland	France	Austria	Germany	Italy	Europe (32 countries, including Switzerland)
Time scope	2015 -> today	2015 -> 2018	2012->2019	2017->2019	2010->2011	2017->2019	2015 -> 2018
Time step	15 minutes	Year, months, and 3 days per month	15 minutes	Month	15 minutes	Month	15 minutes to 1 hour
Overall Electricity consumption	Not Available	Available	Available	Available	Available	Available	Available for all the countries
Overall Electricity production	Available	Available	Available	Available	Available	Available	Available for all the countries
Electricity production mix	Not provided	Provided for three days per month	Provided per 15 min	Provided on monthly basis	Provided per 15 min	Provided on monthly basis	Available for all the countries
Import	Available with each of the neighbouring countries, gross value	Available with each of the neighbouring countries, gross value	Provided per 15 min	Provided on monthly basis	Provided on monthly basis	Provided on monthly basis	Available for all of the countries, net value (i.e., net balance between import and export)
Export	Available with each of the neighbouring countries, gross value	Available with each of the neighbouring countries, gross value	Provided per 15 min	Provided on monthly basis	Provided on monthly basis	Provided on monthly basis	Available for all of the countries, net value (i.e., net balance between import and export)
Grid losses	Not available	Available on a monthly basis	Not available	Not available	Not available	Not available	Not available

Table 5. Summary of the data used in the present project

4.2 Data acquisition

The data is a critical issue of the project. Indeed, it is necessary to obtain values regarding the production mix, imports, and exports amongst the European countries as well as the information regarding the grid losses. A large quantity of data have to be collected, stored and formatted in order to be first characterized and compared among the different data sources and then further manipulated for the environmental impacts' calculation. This section describes how the datasets are collected and stored for the project purpose.

4.2.1 National datasets

The two identified Swiss datasets are from Swissgrid and SFOE. The Swissgrid data can be collected in .csv format. They can be used for data mining programs such as the open source software R or Spyder (Python).

The SFOE data are partially available in excel format. Some of the necessary information is available only in PDF within the annual report about the Swiss electricity statistics. In this case, they have been extracted manually and stored in a .csv format in order to be used with the appropriate software.

The RTE data information are easily accessible and have been extracted in a .csv file format to be used in the datamining software. The Austrian and Italian data were available on PDF format and have been manually extracted. The German data were available online and were extracted manually too.

4.2.2 ENTSO-E datasets

The ENTSO-E datasets present the advantage of being exhaustive for each European country. As a drawback, they represent an enormous amount of data to be collected, stored and manipulated within the project. The ENTSO-E Transparent Platform (TP) is a very useful framework for data retrieving, however, yet, the visualization is not sufficiently satisfactory. For that reason, it was decided to use the TP only for collecting ENTSO-E datasets. A separate EcoDynBat framework is then set up to store and visualize the data, as shown in Figure 16. Within this framework, the data of the production mix and the import/export of each country member of ENTSO-E are continuously imported and stored to be used later for the environmental impact calculation.

In the following sections, the most significant elements of the data flow, reported in Figure 16, are described in details. The data are first retrieved from the TP (purple arrows) and subsequently made available for visualization and download (blue arrows).

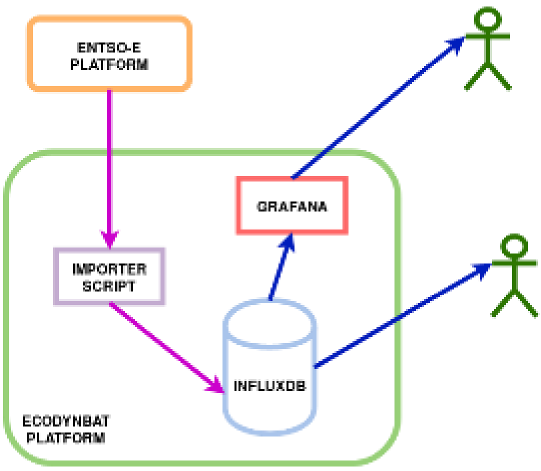

Figure 16. EcoDynBat platform schema and data flows

A Secure Shell (SSH) File Transfer Protocol (SFTP) protocol is used for the EcoDynBat platform in order to ensure a simple and secure access. Among the 104 datasets types of ENTSO-E, the following time-series are gathered for useEcoDynBat platform:

- The production of each energy carrier

- The imports/exports from each country to its neighbouring countries

Each time-series contains data of ENTSO-E countries from January 2015.

Importer script

In order to ensure a daily automatic download of the aforementioned datasets, a Python script was developed and deployed on a server. All the code is released under MIT license and accessible at gitlab.com/supsi-dacd-isaac/entsoe-data-getter (SUPSI, 2019). The script runs once a day to update the time-series. Mainly, it downloads raw data files from TP via SFTP, analyses them and inserts the new values in the EcoDynBat database.

Data storage

All the data acquired from TP are stored in an InfluxDB server (InfluxDB, 2019). It is a time-series database, projected and developed to be extremely performant in the management of this specific dataset type.

According to DB-engines (DB-engines, 2019), a website that collects data about the databases usage trends, InfluxDB is currently the most used time-series database. For these reasons, it was decided to use this database server for storage.

Fundamentally, an InfluxDB database is constituted by a set of measurements. A measurement is a data container where multiple time-series can be stored without limitations. Each time-series is identified using a set of tags, which are metadata able to label the datasets.

Regarding the interaction with external users, a simple and efficient REST interface is provided.

EcoDynBat database

The EcoDynBat database is maintained by an InfluxDB instance running on a server. Currently the database uses 380 Mo of disk space and is composed of the following data:

- *generation*, where generation datasets are stored
- *cross_border_flow*, where imports/exports datasets are stored

Each measurement has its own tags set, comprehensive of metadata required to identify the time-series, e.g. main tags of generation are reported as follows:

- *type* (Solar, Nuclear, etc.)
- *map_code_desc* (CH, IT, etc.)

Data access

In order to provide a user-friendly graphical user interface (GUI) for the data visualization, Grafana (Grafana, 2019) was installed on a server. Grafana is a tool for displaying time-series data. It is extremely powerfull, free and open-source. Its main features are the capability to get data from many different databases, including InfluxDB, and the providing of a smart GUI, very helpful for the data visualization. Fundamentally, a Grafana server comprises a set of dashboards. A dashboard is a container of different plots (e.g. scatters, graphs, carpet plots, etc.).

To make easier the Grafana usage for the project partners, the following three Grafana dashboards were created:

- *ENTSO-E Generation*, to visualize generation time-series as graphs versus time
- *ENTSO-E CrossBorderFlow*, to visualize imports/exports time-series as graphs versus time
- *ENTSO-E CarpetsPlot*, to visualize generation time-series as carpet plots

In Figure 17 and Figure 18 are shown the screenshots of ENTSO-E Generation and ENTSO-E CarpetsPlot dashboards as used in the present project

Figure 17. ENTSO-E Generation dashboard

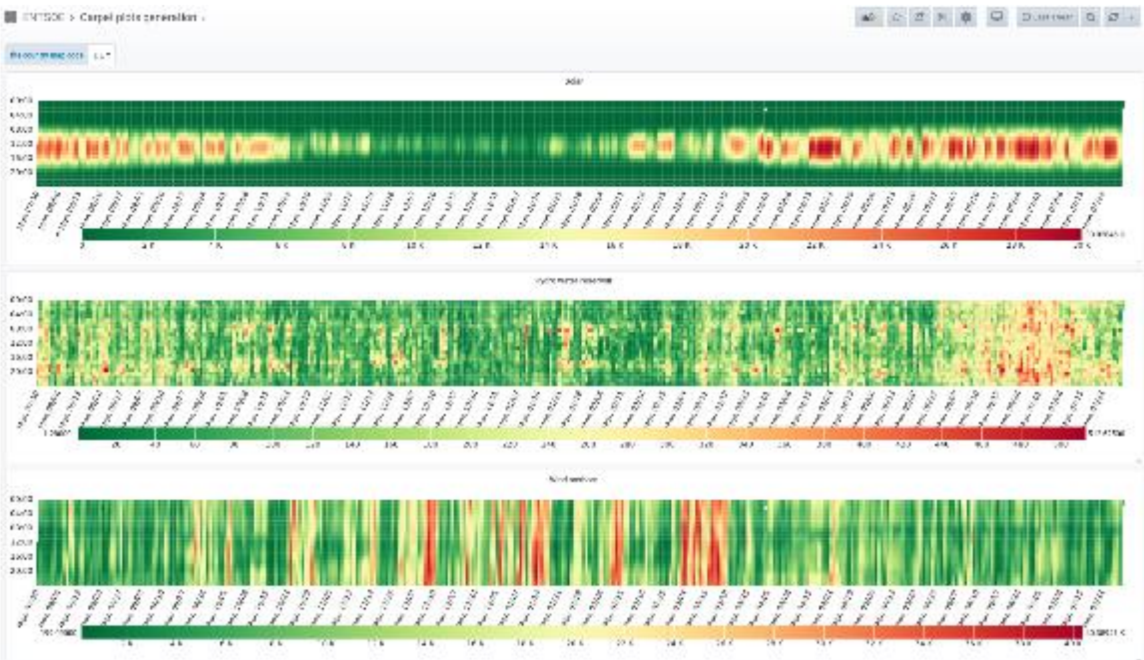

Figure 18. ENTSO-E CarpetsPlot dashboard

RESTful API via InfluxDB

In addition to Grafana, it is possible to download the EcoDynBat time-series in JSON format using the InfluxDB REST API. Following the download, it is possible to perform detailed and specific analysis not provided by Grafana (contribution assessment, data quality assessment. Etc.).

Currently, an example Python script was developed in order to help the project partners to download the data. The code is maintained on a SUPSI server and can be accessed upon request. In Figure 19 is depicted the script execution using PyCharm program.

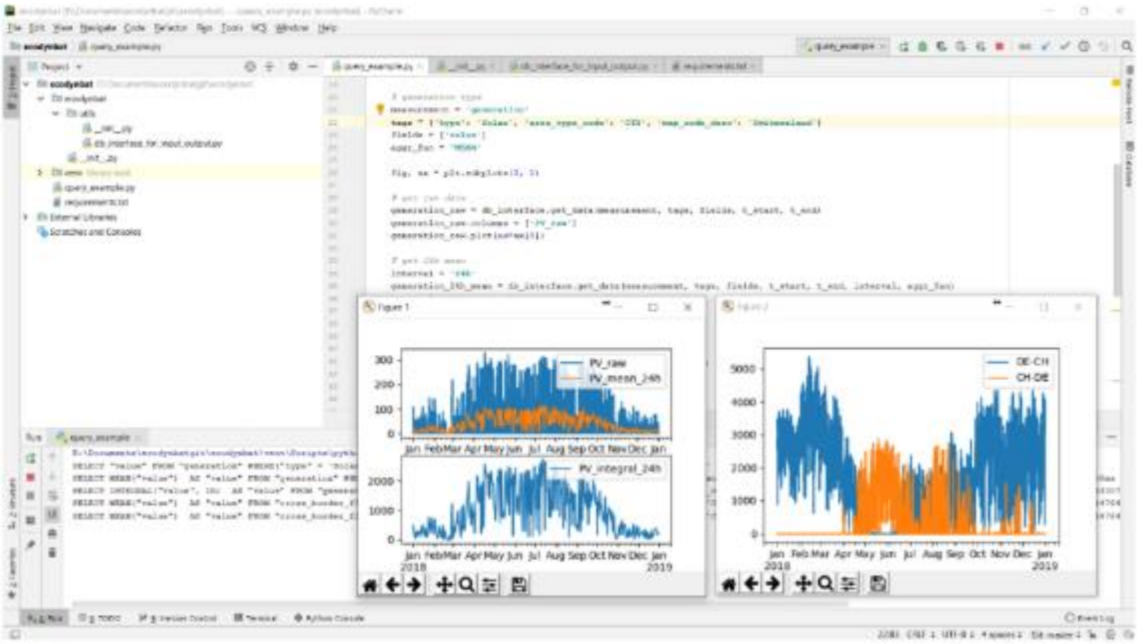

Figure 19. Plots of time-series downloaded from InfluxDB via REST interface

National production mix description and import/export flows characterization

In this chapter, datasets of the data for Switzerland and its neighbour are shown and briefly described. For the sake of the visualization in this report, only data related to 2018 and daily aggregated are presented. The aim of this section is to present the raw structure of the collected data as well as the main general trends regarding the electricity mix for Switzerland and its neighbouring countries.

Energy production

The following pictures report the production profiles of Switzerland, Italy, Germany, Austria, and France. In order to facilitate the data visualization, only the most significant energy carriers are reported. However, to ease the reading of the figures, less meaningful cases are reported in the legends as opaque font. For example, in Figure 20 the datasets related to solar and onshore wind productions are not shown.

Figure 20 presents the production means for Switzerland according to ENTSO-E:

Figure 20. Energy production in Switzerland during 2018

As shown in Figure 20 the nuclear plants production appears to be the most important in the Swiss production mix, nevertheless the combined contribution of all hydro production source is higher. The nuclear production decreases significantly in June and between October and November, due to reactor maintenance operation probably. Nevertheless, the Swiss nuclear electricity production is important and found to be relatively constant over the year.

Regarding the hydro reservoir electricity and pumping storage plants, the production is more fluctuating over the year. Over a short time period (intra-day) fluctuations are observed and correspond to the consumption peaks which are as much as possible covered by flexible hydropower sources with a short-term response.

Finally, hydro-electricity from run-of-river is found to have a small contribution, which is relatively constant over the year, with a slight increase in summer. Other energy carrier contributions based on renewables are very small, and not displayed for the sake of figure clarity.

Key sources for German production are presented in Figure 21.

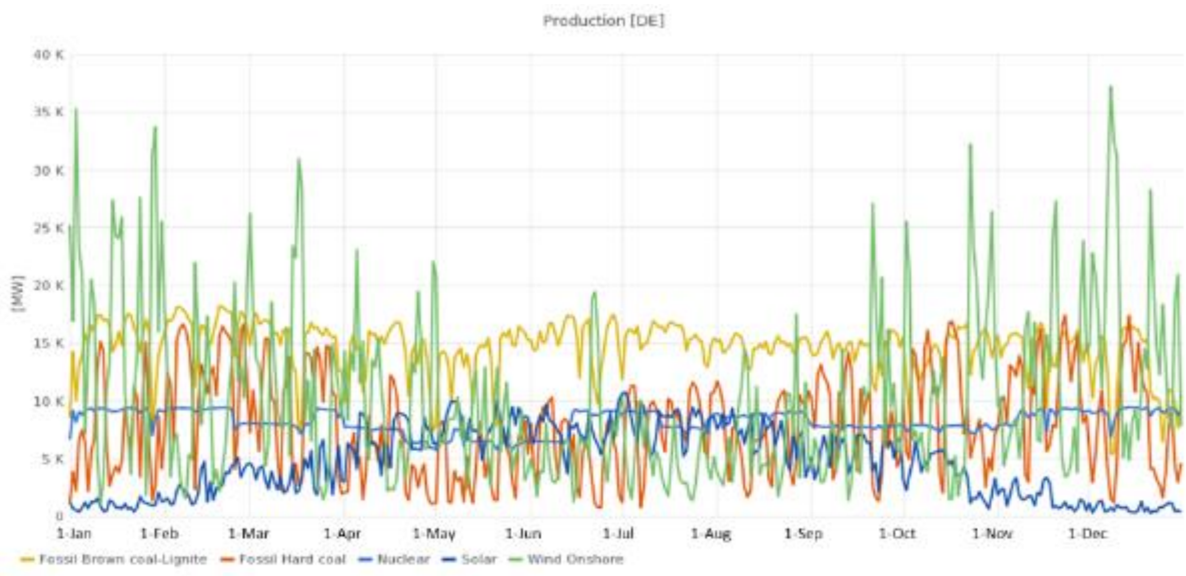

Figure 21. Energy production in Germany during 2018

For Germany, many different energy carriers are significant over the year, related both to renewable resources, such as wind and solar plants, and fossil ones. The most constant and significant electricity production source is found to be coal (fossil brown coal lignite or hard coal). This fossil fuel based production is thus providing most of the German electricity (slightly more than 50%). The wind electricity production is also important and presents large variations during the year. In spring and summer, wind electricity decreases significantly as compared to fall and winter. Conversely, the photovoltaic electricity increases during this period, which tends to compensate partially the overall renewable electricity production.

In contrast, Figure 22 presents key sources for the French electricity production;

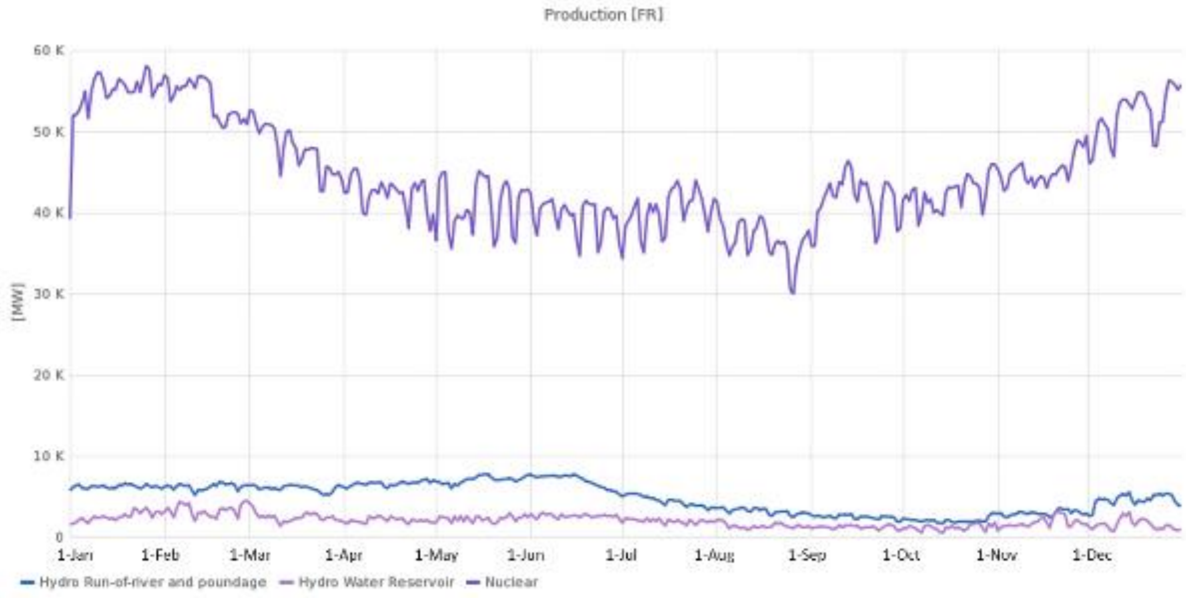

Figure 22. Energy production in France during 2018

The French electricity production clearly shows the importance of the nuclear power plants. This electricity is found to be fluctuating over the year because of: the power plants management, and: the maintenance rolling of the numerous plants. The other electricity production sources are found to be small in comparison and hydropower is completing the French mix. Only a very small amount of electricity is fossil based in the national production in France and since it is too small it has not been presented here above.

Key sources of the Italian production are shown in Figure 23.

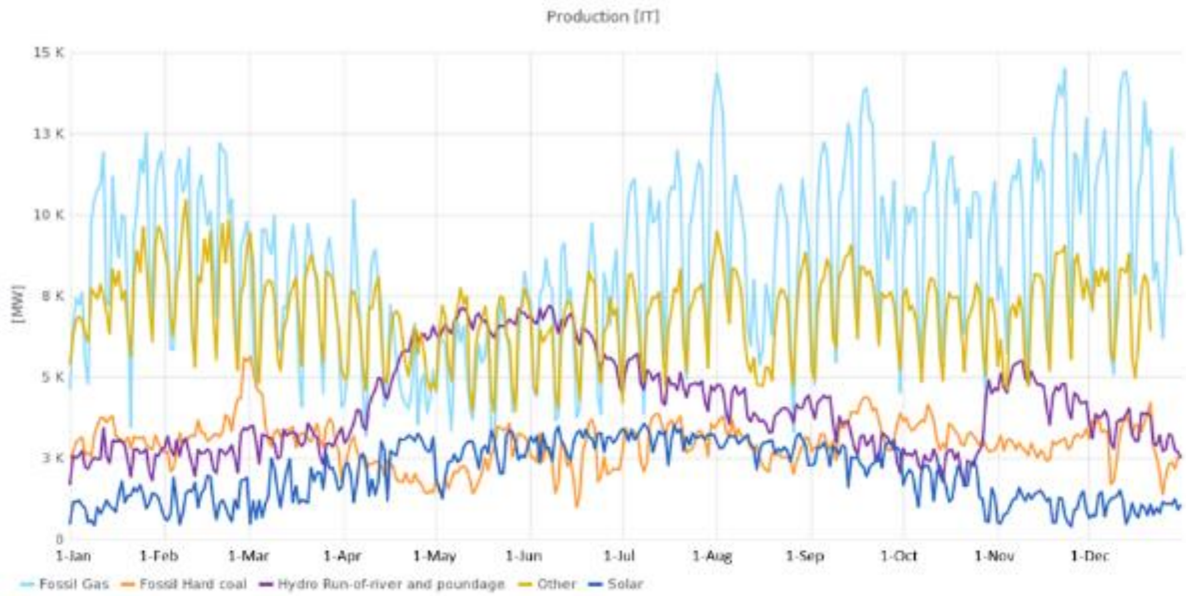

Figure 23. Energy production in Italy during 2018

The Italian electricity production is mostly relying on gas. Unfortunately, in ENTSO-E the Italian production data contains a significant amount of un-undefined energy carriers (i.e. other with the yellow line in Figure 23). Hydro run-of-river is a significant player on the Italian mix, especially in spring and summer. Fossil hard coal is also found to be an important source. Finally, the solar renewables complete the main energy carriers.

Key sources of the Austrian production is shown in Figure 24.

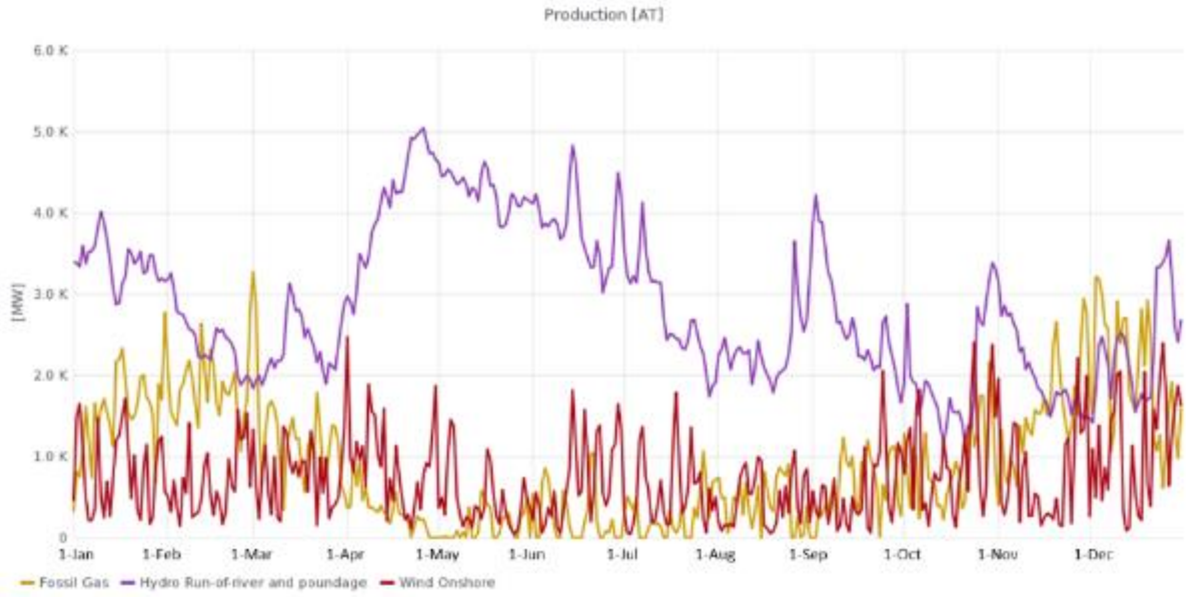

Figure 24. Energy production in Austrian during 2018

The Austrian national production is mostly driven by hydro run-of-river plants. The gas power plants are mostly used in winter and in a less extend in summer to balance the wind electricity intermittency. The wind electricity also plays a significant role in the Austrian mix, with important fluctuation, seasonally and daily. In Winter, the hydro-electricity tends to compensate the wind electricity production reduction.

Energy import/export

The following figures report the import/export profiles of Switzerland, Germany, France, Italy and Austria. The imports and exports provided in ENTSO-E are nets, i.e., it is equal to the difference between the imports minus the export. If the value is positive, the country is importing electricity from the bordering country. If the difference is negative, the value is set to zero in the following figures, and it means the country is exporting electricity from a bordering country. And vice-et-versa for the Export figures.

Figure 25 shows the Switzerland's imports and exports in 2018.

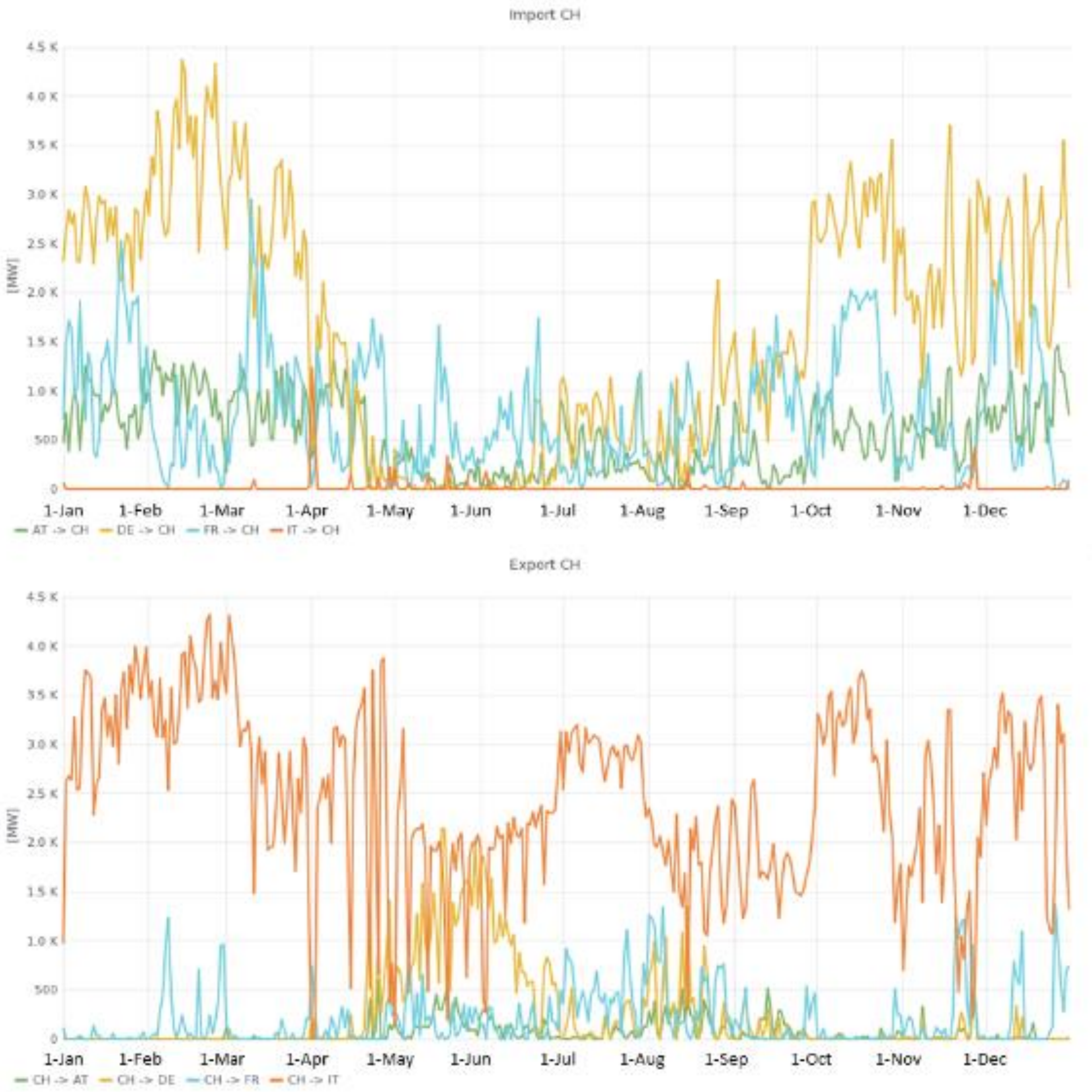

Figure 25. Energy import/export in Switzerland during 2018

Switzerland imports electricity from Germany during winter and autumn (Figure 25 – top) and exports the most to Italy during the entire year (Figure 25 - bottom). In comparison, France and Austria have significantly less influence with no seasonal influence (for 2018 at least.).

The Figure 26 shows Germany's imports and exports.

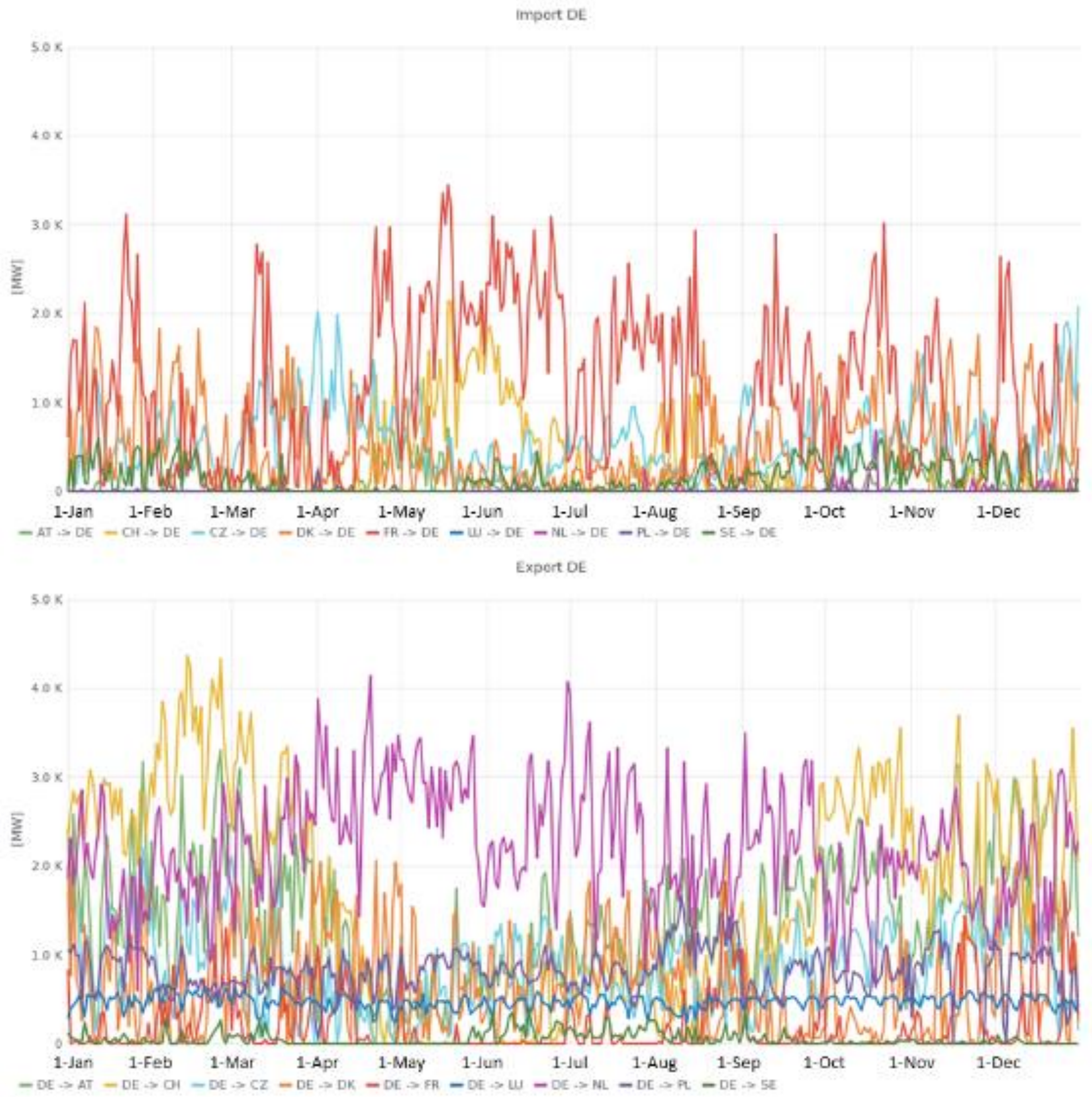

Figure 26. Energy import/export in Germany during 2018

In terms of net values, Germany has a large production capacity and is central in Europe. Thus, the country has several exchanges with its neighbours. The country mostly imports from France and, in a much smaller extent from, Switzerland and Czech Republic. Regarding the exports, Germany exchanges mostly with the Netherlands over the whole year and mainly during the cold periods with Switzerland and Austria.

The Figure 27 shows France’s imports and exports.

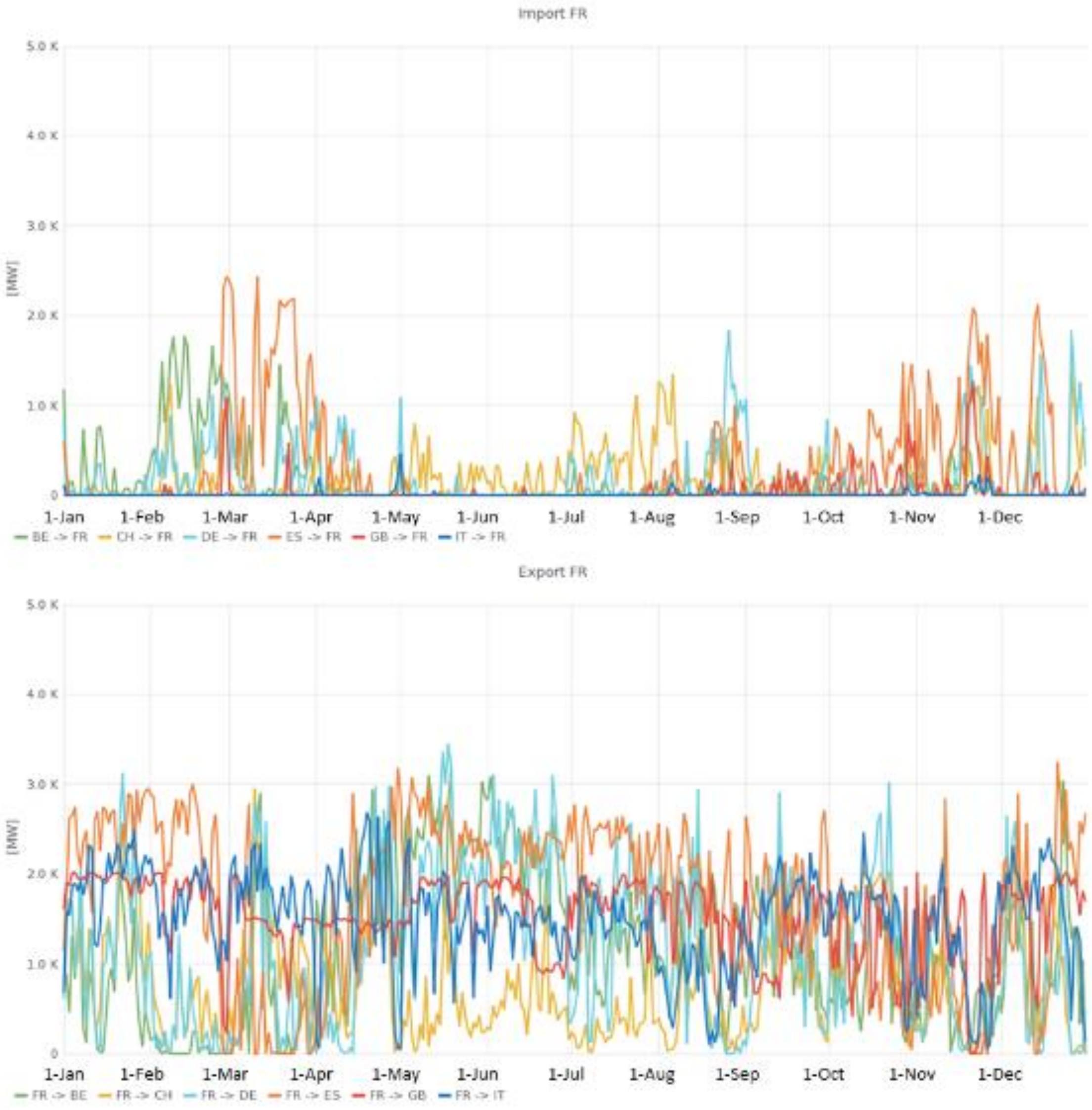

Figure 27. Energy import/export in France during 2018

In terms of net values, France does not import a lot over the year because of its large installed capacity of nuclear power. However, since many of the heat production in the French buildings relies on direct electricity radiators or heat pumps, a peak demand occurs during the winter. This explains why France mostly imports at this period of the year from all of its neighbours.neighbors. Regarding the exports, the country is largely exporting all over the year, to all of its neighbours to its large production capacity.

The Figure 28 shows Italy's imports and exports.

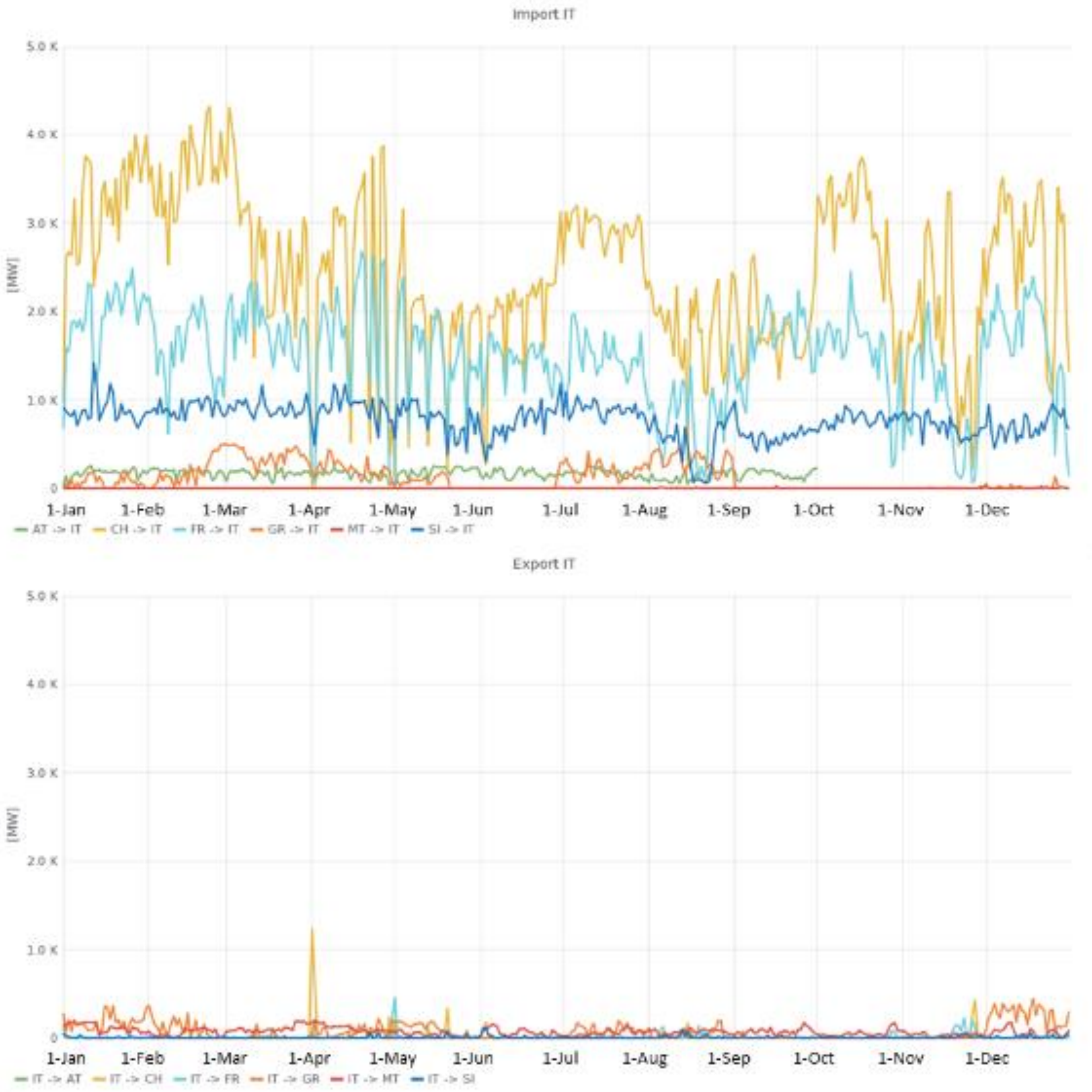

Figure 28. Energy import/export in Italy during 2018

In terms of net values, Italy is heavily relying on imports from its neighbouring countries, mostly Switzerland and France. The imports are relatively constant over the year, which shows that the country has a constant lack of production capacity. This point is confirmed by the country's exports, which are found to be very low.

The Figure 29 shows Austria's imports and exports.

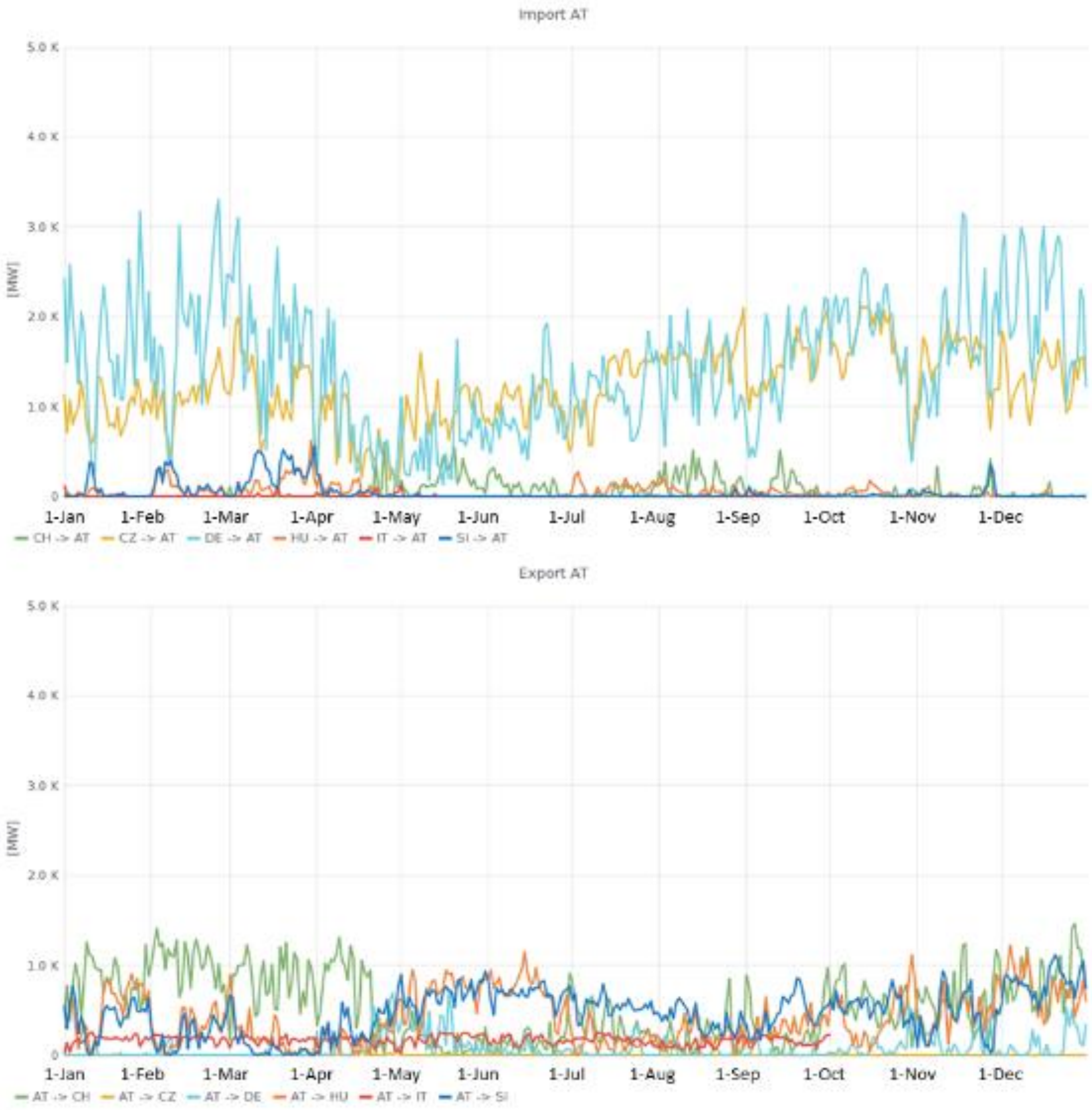

Figure 29. Energy import/export in Austria during 2018

Austria substantially imports electricity from Germany and Czech Republic and exports to Switzerland, Hungary, and Slovenia. Imports from Germany are lower in spring and summer because Austria has a strong hydropower-production (leading to higher production during these seasons). The exports to Switzerland mostly occur in winter and fall when there are peak demands in this country, as part of the Hydro (dam) are empty. Finally, a significant part of the summer exports is sent to Slovenia.

4.2.3 Summary of the data acquisition

Regarding the national data, the data have been easily collected from the various sources (Swissgrid, SFOE, ENTSO-E, E-Control, etc.). However, because of the lack of a common framework, it has been necessary to format them in order to make them usable for any calculation.

Regarding the ENTSO-E data, a new framework for exchanging data related to energy at a national level was developed in the present project, in order to visualize and download time-series about the energy productions and exchanges in Western Europe starting since 2015. The database is currently updated every day and is growing in terms of temporal representativeness with up to date data from 2015 to 2019. The project consortium will continue to maintain InfluxDB and Grafana services developed in present project after its end.

4.3 Comparison of data sources & summary

The EcoDynBat platform using ENTSO-E data is a strong base, with the production mixes of the European countries as well as the information related to the exports/imports between the countries. Nevertheless, it has been decided to compare these data with national data sources to check consistency for the project. If needed, different data may be combined to have a consistent dataset for the environmental impact calculation of the electricity consumed by buildings in Switzerland.

Three comparisons have been performed:

1- For France, ENTSO-E data are compared with the national data provided by RTE, the French TSO (cf. Figure 11);

2- For Austria, ENSTO-E data are compared with the data from the E-Control regulator;

3- For Italy, ENTSO-E data are compared with the data from Terna (TSO;)

4- For Germany, ENTSO-E data are compared with the data from the grid operators;

5- For Switzerland, ENSTO-E data are compared with Swissgrid and SFOE data.

These comparaisons are detailed in annex of chapter 2.

Summary of the comparison

After a deep analysis of the available national and international data, ENTSO-E is the only source of information that provides a sufficient level of details for all European countries regarding their national production mixes and cross-border flows.

The data comparisons between ENTSO-E and the national data sources have identified the following regarding the ENTSO-E source for Switzerland and its neighbouring countries:

- The data perfectly match for France,
- The data mostly match for Austria with some light divergences for exports which are deemed acceptable for the present project,
- For Italy, the data are matching with some partial divergence for the thermal production sources (12%) and the solar source (24%). Regarding imports, the results are reliable for the year 2017 and 2018,
- For Germany, the data are considered as acceptable despite a slight difference for the hydro and solar energy sources,
- As for Switzerland, the datasets have the same trends (except for 2016) but they present significant differences in absolute value for two reasons:
    - the electricity market structure with many electricity providers,
    - the availability of data in ENTSO-E TP is limited to the high-voltage grid while, according to Swissgrid a high share of electricity is produced at lower voltage in Switzerland, in particular for electricity from run-of-river.

Unfortunately, it is not possible to get access to more detailed data regarding this share of electricity produced at lower voltage. The only source of information with a daily time resolution is given by the SFOE and has been introduced in Figure 81. It presents coherent information compared to the Swissgrid data. Since no other sources related to the Swiss production mix is available, adjustment procedures have to be set in order to develop an EcoDynBat dataset enabling to perform the environmental impact calculation (see chapter 5).

The Swiss neighbouring countries will rely on the ENTSO-E data since they have been found to be sufficiently accurate, when compared with their national TSOs. Regarding the Swiss data, Table 6 describes the three data sources considered and compared, and the resulting choice for the EcoDynBat dataset.

	Swissgrid	SFOE	ENTSO-E	EcoDynBat dataset
Geographical scope	Switzerland	Switzerland	Europe (32 countries, including Switzerland)	Europe (32 countries, including Switzerland)
Time scope	2015 -> today	2015 -> today	2015 -> today	2017 -> today* * Since the informatics routine has been set to collect and process the data, the dataset is continuously increasing. However, for the environmental assessment performed within EcoDynBat, only complete and reliable years will be considered, namely 2017 and 2018.
Time step	15 minutes	Year, months, and 3 days per month	15 minutes to 1 hour	1 hour (least common denominator for the ENTSO-E datasets)
Overall Electricity consumption	Available	Available	Available	Not necessary
Overall Electricity production	Available	Available	Available	Adjustment of the ENTSO-E data with the Swissgrid data regarding the overall Swiss production Data regarding the production mix of the other European countries is assumed to be valid
Electricity production per energy carriers	Not provided	Provided for three days per month	Available	Data from ENTSO-E The difference between Swissgrid and ENTSO-E overall production (called "residue") is filled with a mix of energy sources based on the typical days provided by SFOE (see chapter related to harmonization rules)
Import	Available with each of the neighbouring countries, gross value	Available with each of the neighbouring countries, gross value	Available for all of the countries, net value (i.e net balance between import and export)	Gross balance from Swissgrid
Export	Available with each of the neighbouring countries, gross value	Available with each of the neighbouring countries, gross value	Available for all of the countries, net value (i.e net balance between import and export)	Gross balance from Swissgrid
Grid losses	Not available	Available on a monthly basis	Not available	Grid losses from SFOE on a monthly basis

Table 6. Summary of the EcoDynBat dataset choice, in green the chosen assumption from the literature sources (Swissgrid, SFOE, ENTSO-E)

The EcoDynBat dataset for Switzerland relies on the ENTSO-E source as a backbone. However, a first step requires removing the year 2016 from the assessment since the difference between the various sources was found to be too important. Thereby only 2017 and 2018 data will be considered.

The time resolution is chosen to be one hour, since it is a common denominator between all the national sources and ENTSO-E source for each country.

Regarding the Swiss production mix, the ENTSO-E data will be adjusted by adding a so-called "residue" being the difference between the ENTSO-E overall production and the daily production mix provided by SFOE for 108 days (see Figure 81 and Figure 82). The description of this adjustment procedure is given in the next chapter.

The Swiss imports and exports will be also adjusted by using the gross values provided by the SFOE instead of the net value provided by the ENTSO-E data. The description of this adjustment procedure is given in the next chapter.

Finally, ENTSO-E does not provide any information regarding the grid losses. In order to consider them, the grid losses provided by SFOE on a monthly basis will be considered. The description of this adjustment procedure is given in the next chapter.

Altogether, the EcoDynBat dataset is defined in order to provide the most complete information considering the current data sources. In a near future, if the data completeness is increased, it will be possible to update the dataset via the procedure defined into the project.

5. Electricity grid: Data adjustments and harmonization methods

The objective of this chapter is to provide harmonization rules in order to obtain the EcoDynBat dataset to be used regarding the Swiss consumption mix. Indeed, from the data need identification, the source identification and comparisons, it has been decided to rely as a back bone on the ENTSO-E data. Nevertheless, from the chapter 4, the Swiss data within ENTSO-E have been identified as requiring some harmonization with other data sources.

Table 6 summarized how the data from the various sources have to be merged to obtain the EcoDynBat dataset. Four adjustment rules are considered within this chapter in order to obtain a representative datase:

- Rule 0 : Missing data:
  - This rule will be used as a preliminary step in order to avoid any missing data using regression approach to fill the identified gaps
- Rule 1 : Swiss electricity residue
  - This rule will be used to complete the ENTSO-E production mix based on the SFOE/ENTSO-E data comparison presented in the 0
- Rule 2 : Gross cross border exchanges
  - This rule will be used in order to consider the gross cross boarder exchange from Swissgrid instead of the net exchanges of the ENTSO-E data
- Rule 3 : Grid losses
  - This rule will be used in order to encompasses the conversion losses from the production sites to the end consumer at low voltage.

These rules are detailed in the following sections.

5.1 Rule 0 : Missing data

During the data quality assessment, presented in the chapter 4.3, were identified hourly and daily gaps of missing data within the three years of hourly data for the production mixes, imports and exports. Unfortunately, the missing data is not identified in the datasets by a “N/A” but, by a “0” value.

It is thus necessary to develop algorithms to identify when the 0 values refer to missing information or a real no production or export/import. Since the overall dataset is composed of 17’520 hours for the European countries production mixes and imports/exports information, it is not possible to identify the missing data manually. To do so, different algorithms have been applied. The first one consists in identifying, if and when, a specific country had no production on its entire production mix during one or several hours.

It is also possible that only data about one production mean is missing for one specific country. This partial lack of data for a country is considered by adding a second algorithm of fault detection. Identifying the missing data only for a production mean in one country is complex since it is necessary to identify if the 0 value is related to a non-production or to a missing data

To identify the possible missing data, it was decided to choose specific production means (nuclear and the sum of all the fossil fuels energies) and to verify if these macro-categories were falling to zero. It is indeed unlikely to get a 0 production suddenly for the nuclear energy. Based on this algorithm additional missing hours were found.

To fill the missing information, two approaches are used:

- When only one hour is missing, a linear interpolation is made (see Figure 30 (left), between the existing data one hour before and later.))
- When more than one hour is missing, a typical day is built considering the 7 days before and after the missing period. Then, the missing values are filled by the typical value of the given missing hours (Figure 30 (right)).

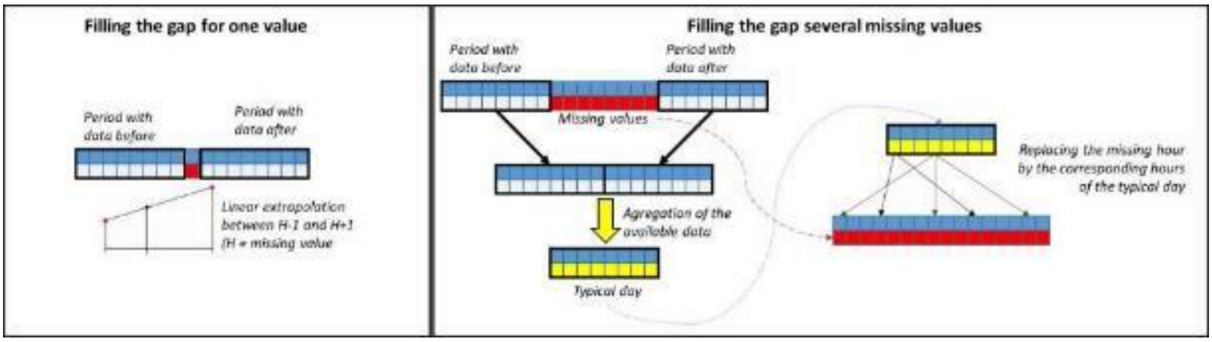

Figure 30. Methods used to fill the missing identified values in the ENTSO-E dataset

An example of replacement of a one day (24hours) missing production of coal power plants in Germany is given in the Figure 31.

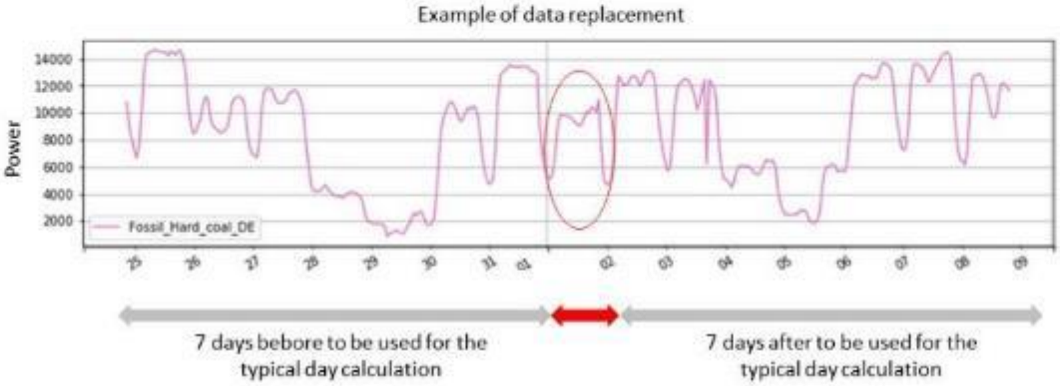

Figure 31. Examle of a resulting replacement of missing data during more than one hour (red).

Based on this approach the dataset is assumed to have complete values over the two years considered for the EcoDynBat dataset (2017, 2018). It should be noted that for this period, there were no missing values for Switzerland, only for the foreign countries.

5.2 Rule 1: Swiss “residue” production

As presented in Figure 79, the Swiss electricity production shows a deviation between the national datasets (from Swissgrid or SFOE) and the ENTSO-E source.

Following discussions with Swissgrid, it was identified that the difference is due to electricity produced and fed at lower voltage level than the high voltage grid, which is considered within ENTSO-E. Most of the differences between the two data sources are identified to be related to electricity produced by hydro run-of-river plants and a category named by SFOE “other” grouping small energy production, such as thermal plants and renewable sources (photovoltaic mostly). Unfortunately, it was not possible to access more detailed information from Swissgrid regarding the hourly Swiss production mix. To overcome this lack of data and to obtain a representative production mix, it has been decided to adjust the ENTSO-E data with the information provided by SFOE regarding the daily production mixes. To do so, for each hours of the datasets (2017 and 2018) the difference between the Swissgrid overall Swiss production and the ENTSO-E overall production has been calculated.

This difference is called “residue” for this study. For a given hour, the residue is quantified by comparing ENTSO-E and Swissgrid hourly data. Then, depending of the day and month of the given hour, the gap is filled by the share of production means identified in Figure 82 via the SFOE data. The schematic representation of Rule 1 is given in Figure 32:

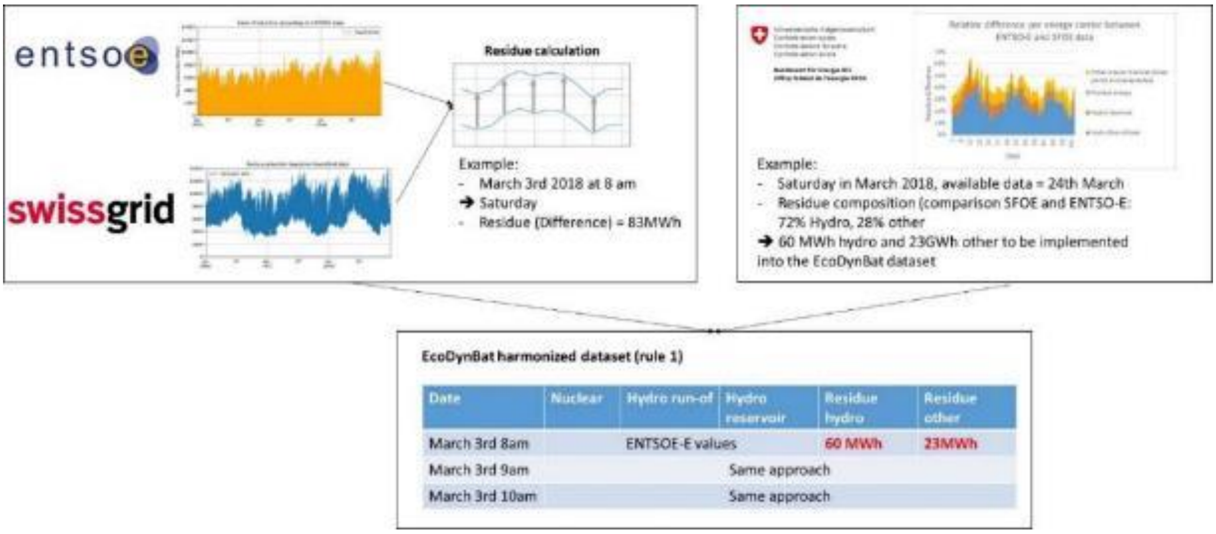

Figure 32. Description of Rule 1: Swiss "residue" production

For example, for the 3rd of March 2018 (a Saturday) the residue is 83 MWh. The closest SFOE daily production mix to this day is the Saturday 24th of March. The difference between the SFOE and ENTSO-E data is explained by the 72% difference in hydro production and the 28% difference in other production means (conventional + renewable, mostly PV). Thus, 60MWh of "residue hydro" and 23MWh of "residue other" are added to the ENTSO-E production mix. The production mix has thus two "additional production means" being "residue hydro" and "residue other". The same approach is used for all the hours of the two considered years.

This rule is applied in order to consider the overall electricity production as stated by Swissgrid and SFOE. It is also used to encompass the reality of the Swiss electricity network, which has a significant part of its production occurring at the medium voltage level. Based on this adjustment rule, the Swiss production mix is obtained.

5.3 Rule 2: Cross border exchanges

The assessment of the Swiss cross border exchanges (see annexes of chapter 2) showed some differences between the ENTSO-E data and the Swissgrid information. This difference was in particular explained by the fact that ENTSO-E is considering net exchanges while Swissgrid is considering gross exchange, i.e. its provides imports and exports separately. For energy accounting, the net exchange might be sufficient especially if the time resolution is low (year or month), it does not appear to be relevant for the LCA of electricity using a high time resolution. Indeed, for each hour, it is necessary to get the information about the production means used in order to calculate the associated environmental impacts.

The adjustment Rule 2 thus consists in using the gross cross-border exchanges provided by Swissgrid instead of the net exchanges provided by ENTSO-E. To do so, based on the ENTSO-E data, the information related to the imports and exports of Switzerland are replaced by Swissgrid information. The difference of Swiss supply mix between net and gross exchanges is given in Table 7.

	Swiss supply mix with ENTSO-E data + residue, **net** cross border exchanges	Swiss supply mix with ENTSO-E data + residue, **gross** cross border exchanges (after rule 2 application)
Swiss production	68.7%	64.6%
Imports from Austria	6.8%	6.9%
Imports from Germany	18.2%	18.6%
Imports from France	6.0%	8.6%
Imports from Italy	0.3%	1.3%

Table 7 Swiss supply mix with net exchanges and gross exchanges (using the adjustement rule 2) – Average shares for the two years aggregated

As a results, it shows that the Swiss supply mix has about one third of its electricity coming from the neighbouring countries, since there are many exchanges at each time step between the countries. The share of production and imports between the two approaches presents relatively similar percentage values.

5.4 Rule 3: Grid losses

Considering the adjustments Rules 0 to 2, the Swiss supply mix is now characterized for the EcoDynBat project. It is however, necessary to include grid losses in order to get the environmental impacts of the electricity at low voltage, which is the type of electricity, that is consumed in Swiss buildings at plug.

ENTSO-E provides only information on the production mixes and cross boarder exchanges since it relies on the European grid. Fortunately, the SFOE data provides also information about the grid losses with a monthly time resolution as shown in Figure 33:

Figure 33. SFOE monthly grid losses

The SFOE data on grid losses are thus used for the EcoDynBat dataset. For all hours of a given month, the grid losses obtained via SFOE are taken into account.

5.5 Summary of the adjustment procedure

The adjustment procedure aims at providing the necessary dataset for the environmental impact calculations. The four steps of the EcoDynBat dataset creation, based on the adjustments procedures, are summarized in Figure 34.

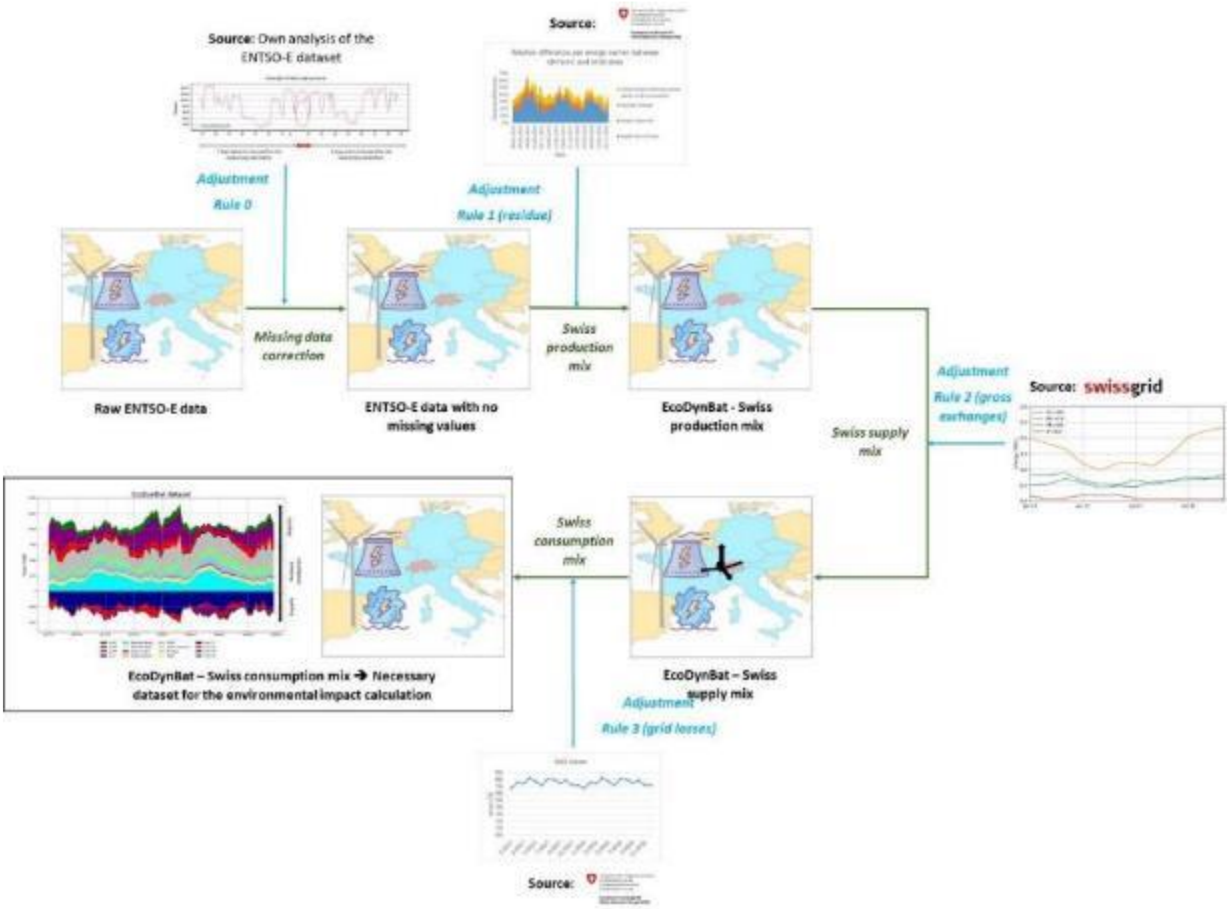

Figure 34. EcoDynBat dataset creation

The initial step (Rule 0) aims at obtaining the ENTSO-E dataset with not missing values. Then, step 1 (Rule 1) defines the Swiss production mix representative of the electricity panorama, i.e., including medium voltage electricity production means. Then, Rule 2 (step 2) provides the Swiss supply mix considering the gross cross-border exchanges. Finally, step 3 (Rule 3) provides the Swiss consumption mix by adding the grid losses.

Based on this sequential procedure, the EcoDynBat Swiss consumption mix is obtained. This dataset is ready to be used for the LCA calculations. The current EcoDynBat dataset, although already processed, is sin essence still a raw dataset. The method to be defined in WP3 will provide the calculation procedure and the assumptions to make to handle this dataset for the computation of the environmental impacts of the building electricity demand.

6. Electricity grid: EcoDynBat full dataset

Considering the datasets and the adjustments rules detailed previously, the EcoDynBat dataset is graphically represented in Figure 35 and encompasses, production, imports and exports for the two years 2017 and 2018. The numerical values can be found in annex of chapter 2.

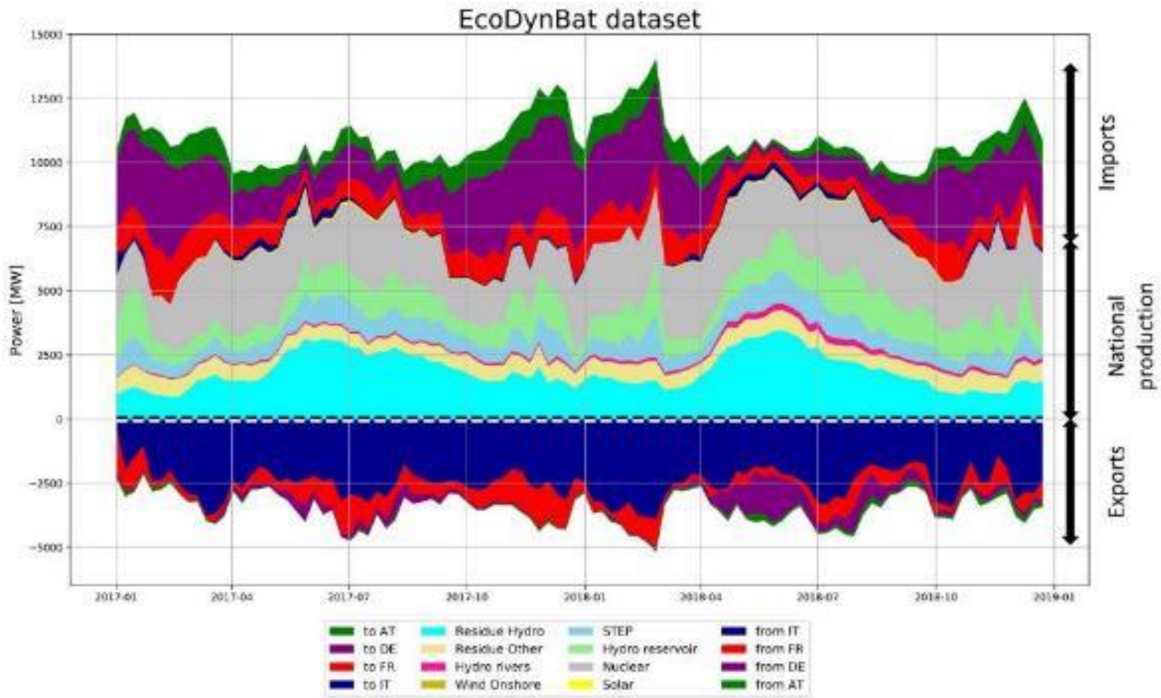

Figure 35. Example of the EcoDynBat dataset for the period 2017-2018

<u>Notes :</u>

- Negative values corresponds to the exports **to** Austria (AT, green), Germany (DE, purple), France (FR, red) and Italy (IT, blue)
- Positive values correspond to Swiss production mix, including the residue part as described in Rule 1, on top of which are added the imports **from** AT, DE, FR and IT. The colours are the same as for the exports (see right axis).

The share of production sources, imports and exports are summarized annually, over the 2 years below:

		2017	2018
Production mix	Hydro (including residue)	44.9%	43.5%
	Other	9.3%	9.0%
	Wind	0.1%	0.1%
	Pumping storage (STEP)	11.3%	10.6%
	Nuclear	33.6%	36.3%
	Solar	0.7%	0.5%
Imports	from AT	19.5%	18.5%
	from DE	53.5%	52.9%
	from FR	23.4%	24.9%
	from IT	3.5%	3.7%
Exports	to AT	1.5%	3.8%
	to DE	5.2%	12.1%
	to FR	21.1%	13.0%
	to IT	72.1%	71.1%

Table 8 Shares of production mixes, imports and exports, based on the EcoDynBat dataset

Details for the exports are presented in the Figure 36. It appears that Switzerland is mostly exporting electricity to Italy throughout the years. The exports to France tend to be slightly higher in winter because the French electricity consumption is more heat-sensitive (high share of electric heaters). Until spring 2018, Switzerland was not exporting much to Germany. However, from May to August 2018, the Swiss export to Germany have increased but then became again small after October.

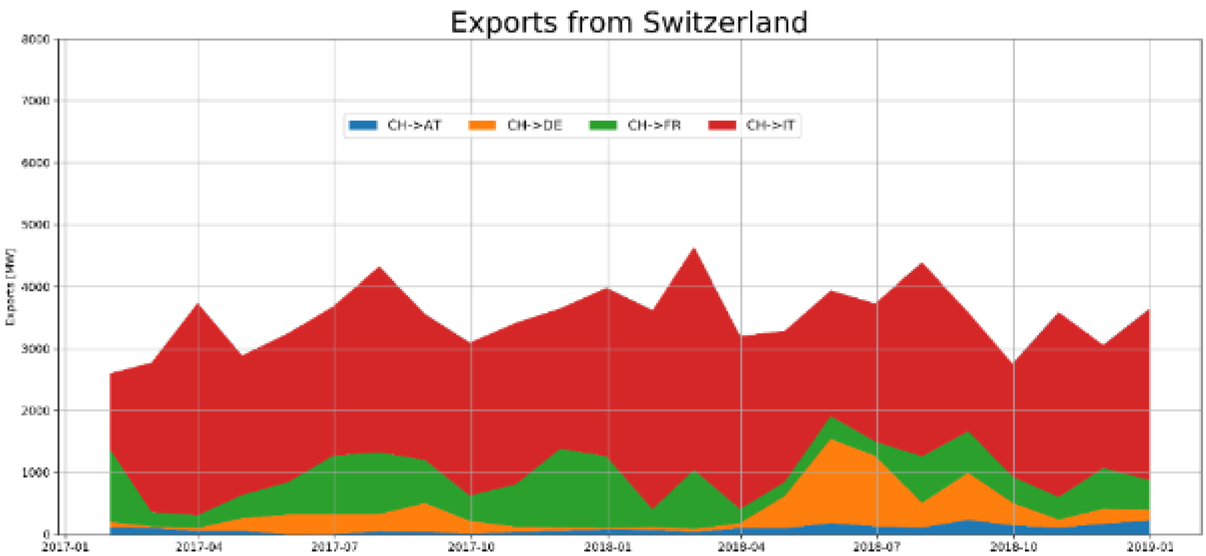

Figure 36 Swiss exports for 2017 and 2018

Globally, because of the electricity sent to Italy, the Swiss exports show less variability than the imports. The imports from the neighbouring countries to Switzerland are presented in the Figure 37. The imports are varying more and are low in spring (Figure 37), when Switzerland has an important amount of self-production from the hydro-power plants due to the melting snow from the mountains, see Figure 38. However, in fall and winter, Switzerland is importing largely from Germany because the country has a lack of production capacity at that time. The imports from France a relatively constant over the two years with only limited increases in Winter. The same trend is observed for the Austrian imports. Finally, Switzerland has almost no imports from Italy. From the imports figure, it clearly appears that German connection is used for the modulation.

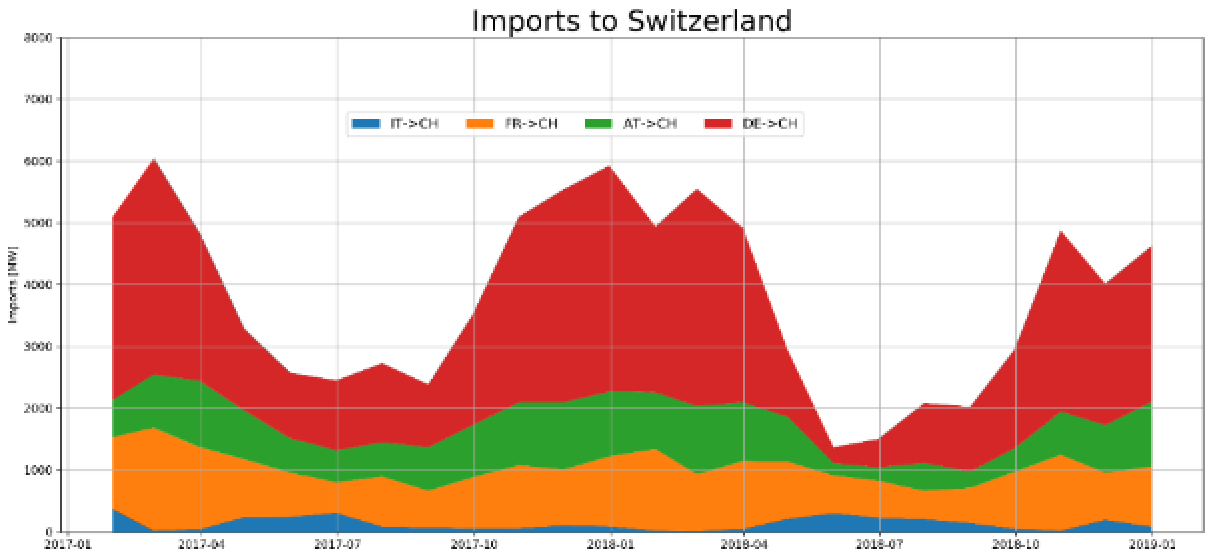

Figure 37 Swiss imports for 2017 and 2018

Regarding the Swiss national production, the mix is mostly driven by nuclear and hydroelectric production means (Figure 38). The pumping storage (STEP) and hydro plants show more electricity production in summer until the end of fall. The nuclear electricity only shows variation when a reactor appears to have been switched-off for maintenance or control. Altogether, over the two considered years, the Swiss electricity production tends to be similar while the equilibrium is maintained by the imports.

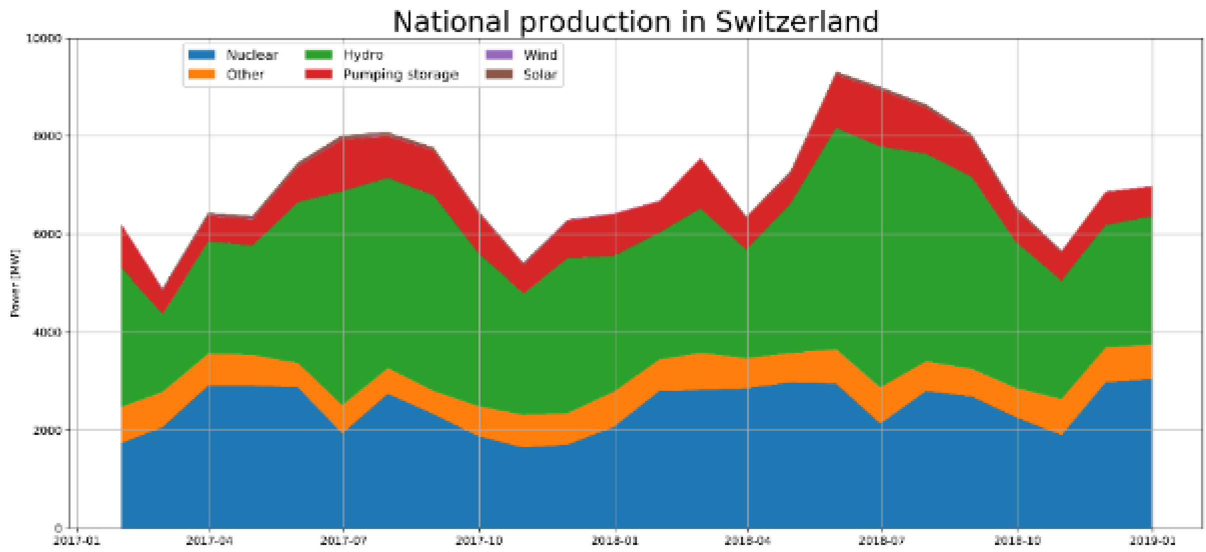

Figure 38 Swiss national production for 2017 and 2018

<u>Note:</u>

- For a sake of clarity, the hydro-electric residue, reservoir and run-of-river sources have been aggregated into a single "Hydro" category

The dataset presented in Figure 35 will serve as the foundation for the LCA calculations. The data are available on an hourly basis on a weekly basis in annex of chapter 2 for the sake of conciseness.

The EcoDynBat dataset is available on an hourly basis and for each element, the date and time index is indexed. The project aims at assessing the time step influence on the environmental impact performance of the electricity consumed in the Swiss buildings. It is thereby necessary to aggregate the hourly values with different time steps, for example, days, weeks, months, etc.

To do so, based on a Python code, the EcoDynBat dataset will basically be aggregated. The power over the time step considered will be simply averaged. Regarding the imports and exports, the same approach is used.

7. Building energy demand: data collection and models

In the previous sections, the EcoDynBat dataset regarding the electricity mix has been provided. Another important aspect to be covered in the present project is related to the building electricity demand. Indeed, as stated in chapter 3, the variability in term of electricity demand of the buildings, but also electricity production from the decentralized electricity production will play a significant role on the building's environmental impact.

In order to use real data for the electricity consumption of buildings. different agreements have been signed with partners (Losinger, Amstein+Walthert, Soleol, Viteos) to obtain load curves of buildings. In addition, from other studies, the academic partners also collected data on buildings that will also be considered. Nevertheless, the collected data was relying in real building with specifics installation. Some of them were equipped with heat pump and photovoltaic installation, but other did not have such systems. In order to be able testing several variant for the building, it was thus necessary to develop models to simulate the presence of heat pumps and photovoltaic systems in non-equipped buildings. In addition, micro-cogeneration (CHP) is not installed in any of the considered buildings. It has been thus necessary to develop a specific model to assess this technology. This chapter aims thus at introducing such models to be used for the case studies.

7.1 Photovoltaic production

To generate production curves of typical PV rooftop installations in Switzerland with a detailed resolution (i.e. hourly time resolution, steps), a PV plant design tool and a simulation script have been used. The design tool aims at characterizing the installation (surface, technologies, orientation, etc.) while the script aims at estimatin the electricity production.

Thus, as a first step in the generation of a PV production curve after the choice of the building, a PV plant design tool that, for a given location and roof shape, generates realistic configurations of module placement and orientation, has been used. For the design of the PV plants, the online tool Insun was used (Insun, 2019).

Insun is not yet commercially available, but since SUPSI partially developed it in the framework of an Innosuisse project, it was allowed to use it in the context of the present project. Insun contains tools that ease the design of the PV plant. In particular, it features a tool for the automatic module placement and an instrument for the analysis of shading.

Since Insun is not yet publicly available, it was used only for the generation of the PV plant configuration. While for the simulation of power production, SUPSI developed a python script based on the open-source python library pvlib (Holmgren et al. 2018). The simulation module takes plane-of-array (POA) irradiance, air temperature and wind speed, as external inputs and outputs the PV power profile, and allows the choice of the type of PV module and inverter. As a first design choice, standard polycrystalline modules and microinverters were selected.

The simulation tool, which estimates the electricity production, accepts both measured and simulated data. In the case in which only global irradiance is available, the projection onto POA and the splitting between the direct and diffuse components of the irradiance. If real measurements are not available, typical meteorological years (TMY) for a given location can be generated using the software Meteonorm9 are used. Then, the output files are saved in.csv format and can then be used with the building electricity demand data to estimate the self-consumption at each time and thus obtain one of the necessary information to perform the environmental impact calculation.

7.2 Heat pump performances

Many factors influence the performance of a heat pump, such as:

1. **Climate and temperatures** – the "sink" temperature (indoor space and DHW) and the outdoor climate will determine the load of the heat pump. The heat source (ex: air, water, earth, etc) temperature and characteristic temperature fluctuations will impact the capacity of the heat pump to meet the load.
2. **Technology** – whether the heat pump has a fixed or variable capacity, and the main components of the heat pump (compressor, inverter, heat exchangers and expansion valve) will affect the efficiency of the heat pump, and the Seasonal Performance Factor (SPF).
3. **Size** – whether the heat pump is sized in order to cover the entire peak heating load and DGW, or on a portion of either, will affect the energy coverage and the part-load performance.

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[9] https://meteotest.ch/en/product/meteonorm

4. **Control system** – the manufacturer algorithm that dictates the performance of the heat pump in certain conditions, such as when a defrost cycle is required (generally when temperatures go below 7°C).

When heat pumps were not installed in the EcoDynBat case studies, but the heat demand and domestic hot water needs were known, it was necessary to develop an estimation of the electricity consumption for a scenario in which a heat pump would be used to provide the thermal energy. To do so, a simple generic model was developed. This model represents the performance of the heat pump in steady state, and does not account for dynamic performance characteristics of heat pumps, such as on/off and defrost cycling, start-up power draw, and transient periods.

The model estimates the COP of heat pumps based on the external temperature and condensation temperature, as this input was available for each of the case studies, and thereby computes the electric input required. The aim of this calculation method is to provide a fast but sufficiently precise calculation of heat pump performance. Using simplified performance maps is commonly used for heat pump simulation, and is considered adequate for the needs of this study. A number of assumptions and simplifications are thus required:

1. The evaporation and condensation temperatures are assumed equal to the external temperature and the delivery temperature of the heating system, respectively.
2. A heating curve, which defines the delivery temperature as a function of the external temperature, is set as follow: A linear increase has been assumed in the delivery temperature with the decrease of external temperature, capped by a minimum delivery temperature as shown in Figure 39. Cooling is not considered.
3. In the case of domestic hot water production, the condensation temperature is fixed to 55°C. It should be mentioned that in many cases the heat pump will not provide the high temperatures required for DHW, and supplementary electric elements will be sized according to the boiler size and will supply the extra heat.

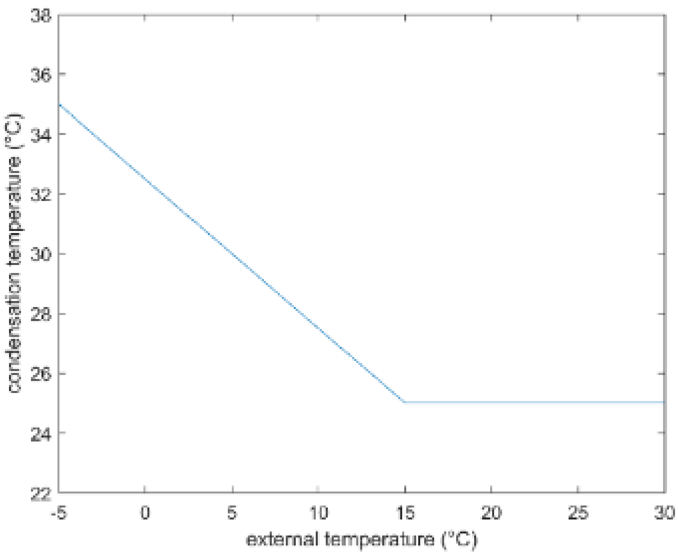

Figure 39. Example of delivery temperature curve, as a function of external temperature

The COP is calculated as a function of evaporation and condensation temperatures, by linearly interpolating from values in a lookup table of the COP of a typical air-water heat pump, extracted from the software Polysun (Vela Solaris AG, Winterthur). The lookup table is shown in Figure 40 and has been converted in a table that allows to set the parameters and calculate the COP for the project participants.

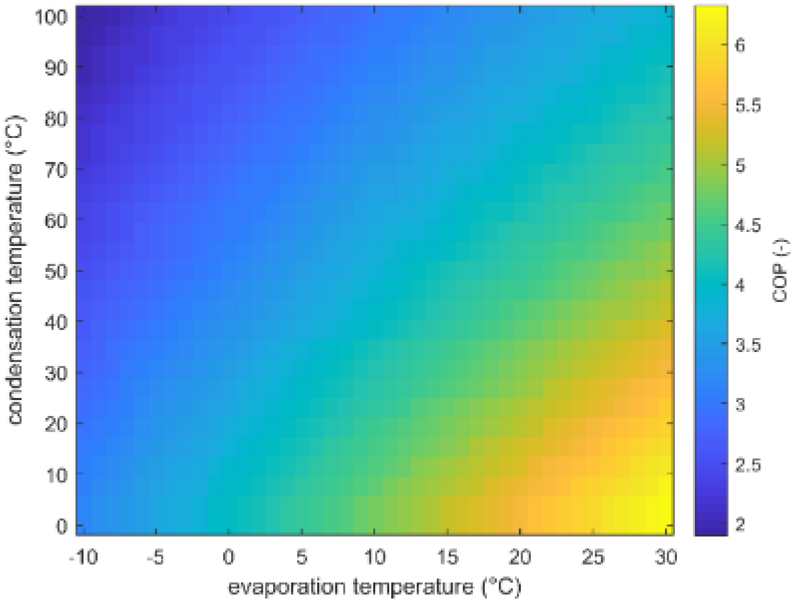

Figure 40. Lookup table of COP as a function of evaporation and condensation temperatures.

7.3 Micro-CHP performances

For the case studies, the performances of micro co-generation (CHP) energy system on building level have to be calculated. The energy systems considered here are based on two different co-generation technologies, which operate on either gas-combustion or fuel cells. Both technologies operate with gas as their primary energy carrier, but with different fuel treatment. The calculation of the system performance is based on the strict condition to supply all demand in heat and electricity. While each considered energy-system is based on a co-generation technology, it is supported by additional technologies as backup (gas boiler, electricity grid, etc.). This helps to reduce oversizing, due to peak demands and inefficient operations, resulting from fluctuations in both demands. Co-generation units are most efficient, when the demand of heat and electricity are synchronous in time and magnitude. For periods where this is not given, it is often reasonable to operate with different technologies. One type of back-up technology is selected to ensure a more efficient operation of the energy system: a conventional gas-boiler burning gas. While the system is designed to produce all demanded heat, the electricity demand is only covered when possible. The public power grid can supply electricity demand, which the system does not cover.

7.3.1 Considered systems

Two co-generation technologies are selected here:

- conventional gas-combustion, which is considered as current state of the art and well-known technology,
- fuel cell as a rather future orientated technology.

Micro-cogeneration usually operates as a band and thereby it is necessary to have a backup system to provide heat. In the present project, a gas boiler in backup has been selected as the building will be logically already connected to a gas network to run the cogeneration unit. The possible simulation scenario is presented in Figure 41 for which the cogeneration unit can change from combustion to fuel cell. The energy system is connected to two different energy networks: the public power grid and the public gas network. Apart from the different need of the primary energy carrier, the concept for both co-generation technologies is similar, only the dimensioning of the units has to be sized.

The system in Figure 41 shows a gas combustion operating as CHP and a backup gas boiler. The gas network provides the required amount of gas for both the CHP and the gas boiler to generate the demanded heat for domestic hot water and space heating; usually the generated heat is not directly used for heating purposes but is injected in tank storage to smooth the demand and supply. The storage can also be used to fulfil great demand variations and peaks.

It is assumed in all scenarios that a connection to the public grid is available, since it is often not possible to cover the full electricity demand in an economic way. The electricity demand can therefore be covered by three sources: (1) a photovoltaic system if available, (2) electricity generated by the CHP unit in addition the heat and (3) the public grid.

The photovoltaic installation can be considered in the energy system and it is either obtained by measurement or estimated with the method expressed above. In this case, the electricity is produced in an inflexible way, it will always be chosen as first provider for demand. The amount of electricity generated by the CHP unit depends on the required heat in the system, since the CHP unit only produces electricity if heat and electricity are required simultaneously. For time steps where the photovoltaic system and the CHP are not able to meet the electric demand, it is consumed from the public grid.

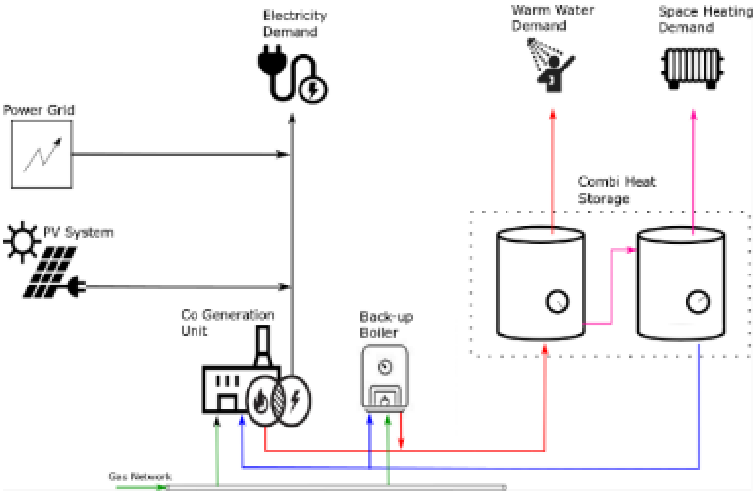

Figure 41. Energy System Scenario with back-up boiler

In order to calculate the micro-CHP performances, it is first necessary to size the system. The capacity of the co-generation unit should be designed according to the standard solution for CHP set in the MuKEn, “Mustervorschriften der Kantone im Energiebereich” (EnDK, 2015) which states that such installation should cover at least 60% of the energy for space heat and domestic hot water, as shown in Figure 42. The installed capacity of the back-up unit is equal the difference between the heat peak and the co-generation capacity. This ensure that every considered peak can be covered by the system. This sizing option has be used for micro-cogeneration using combustion technology. However, for the fuel cell this sizing option is not suitable because of the technology characteristics (fuel cell has a greater electricity over heat production efficiency ratio). Thus, for the fuel cells, the design is based in the electricity demand and should cover 3500 consumption hours, Figure 43.

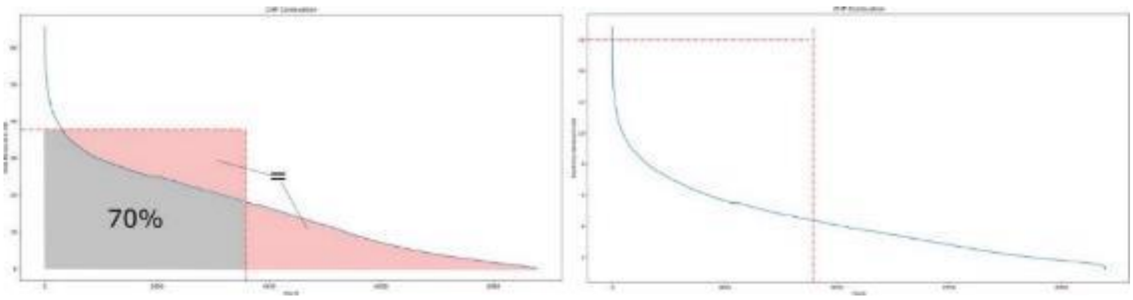

Figure 42.: Annual demand curve for dimensioning the combustion co-generation unit: heat demand for combustion. (left), electricity demand (right).

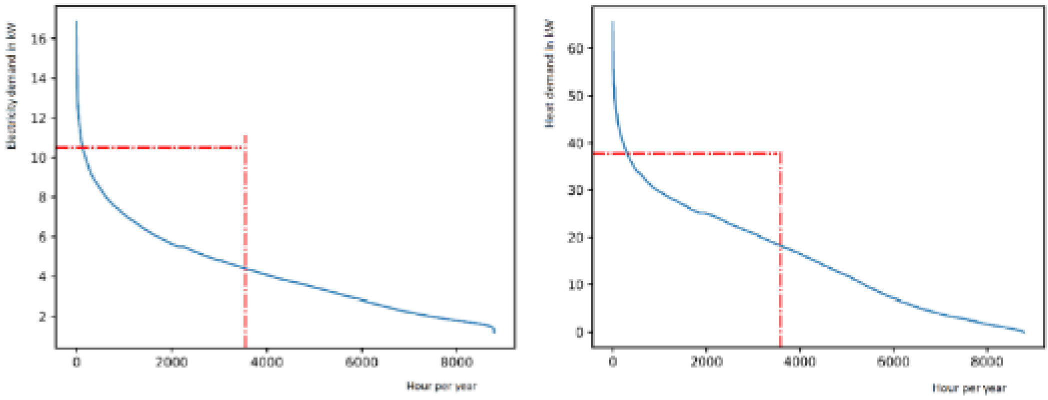

Figure 43.: Annual demand curve for dimensioning the co-generation unit: electricity demand for fuel cell (left), heat demand for combustion. (right).

The dimension of the heat storages is based on comparative scenarios and suggestions from manufacturing or installation companies.

Once the CHP unit is dimensioned, it is necessary to set up the method to calculate the system performance. The model developed to assess the operational plan for the co-generation systems, imitates the controlling software of the energy system. The time step for the model has been chosen to be 1 hour. For every hour of the year, a linear equation system is solved to minimize the cost efficient operation of the system to fulfil both energy demand for heat and electricity. Different linear programming algorithms, as simplex and branch-and-bound, solve the minimized cost function, which drives the equation system of the model:

$$\text{minimize } \left(\sum_{t=0}^{3600} \mathrm{Cost}_t\right)$$

With:

$$\mathrm{Cost}_t = \mathrm{Gas}_t \cdot \mathrm{p(gas)} + \mathrm{Elec(grid)}_t \cdot \mathrm{p(buy\ elec)} - \mathrm{Elec(sell)}_t \cdot \mathrm{p(sell\ elec)}$$

and

p the unitary prices (in ct. CHF/kWh) of the different energy carriers to be used, namely gas electricity from the grid and electricity sold to the grid

Gas_t the amount of gas consumed at time *t*,

$\mathrm{Elec(grid)}_t$ is the amount of electricity consumed at time *t*

$\mathrm{Elec(sell)}_t$ is the amount of electricity produced by the micro-CHP unit and sold to the grid.

The cost function takes into account the decision variables for gas and electricity bought from the public network and the electricity sold back into the grid. Each decision variable is defined based on constraints for each energy technology in the energy system.

Regarding the micro-CHP performances by themselves, i.e. the heat and electricity produced by the unit, the following equations accounts for co-generation technologies, combustion and fuel cell. The production is limited by its installed capacity. Since the capacity of the CHP unit ($\mathrm{cap(CHP_{therm})}$) is defined by the sizing rule (see above), it will be considered as a fixed parameters and the upper boundary for every time-step t for both production variable ($\mathrm{Heat(CHP)_t}$) and ($\mathrm{Elec(CHP)_t}$). In addition, in CHP technology, both productions of heat and electricity are connected. The quotient of both efficiencies η_{therm} and η_{elect} gives the heat to electricity ratio to express this connection between both productions.

$$\mathrm{Heat(CHP) = Elec(CHP) \cdot \eta(CHP_{therm})/\eta(CHP_{elec})}$$

<u>Note:</u> The variables description, of all presented equations, are summarized in the Table 9.

In this model, the efficiencies, for a considered situation and unit, is not influenced by the load. It is assumed, since the unit can not run below 50% of load, that the efficiencies remain constant between 50 to 100% load. In addition, It has to be noticed that the efficiency of the CHP units vary with the technology and its installed capacity. Based on the economy of scale principle, greater installed capacities profit from better efficiencies. The efficiencies as a function of the unit size are given in the Figure 44:

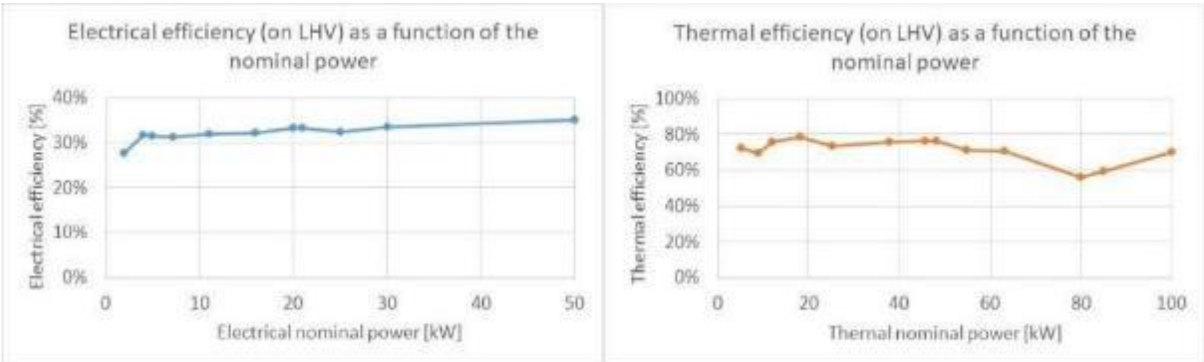

Figure 44 Micro-CHP efficiencies on LHV (combustion CHP) as a function of the unit size, source: (RMB energie, 2019)

Regarding the combustion model, an operation under 50% part load is not recommended for CHPs. Therefore, the variable part of the CHP's heat production is defined either as null or with 50% of its installed capacity as lower boundary. This ensures that the CHP unit does not operate on a partial load level below 50%.

$$\mathrm{Heat(CHP)_t} \in \{0\} \cup \{0.5 \cdot \mathrm{cap(CHP_{therm})}, \mathrm{cap(CHP_{therm})}\}$$

The boiler model operates in a similar way as the CHP model. The installed capacity defines the upper boundary of the heat production of the boiler ($\mathrm{Heat(Boiler)_t}$). For simplification, it is assumed that the boiler can run below 50% part load.

$$\mathrm{Heat(Boiler)_t} \leq \mathrm{cap(Boiler)}$$

Finally, the amount of gas purchased from the network is the sum of the gas consumed by the boiler and the CHP unit. By dividing the heat production of each component by its efficiency, we obtain the gas demand for each technology. The gas demand ($\mathrm{Gas_t}$) is a decision variable which will be minimized in the cost function.

$$\mathrm{Gas_t} = \frac{\mathrm{Heat(boiler)_t}}{\eta\mathrm{(Boiler)}} + \frac{\mathrm{Heat(CHP)_t}}{\eta\mathrm{(CHP_{therm})}}$$

In the defined system architecture, it has been decided to include a storage unit. The storage model allows differing production and consumption of heat. If there is an overproduction of heat in a time step t, the storage can be charged in t ($\mathrm{Charge(store)}_t$). If heat is required, the storage can be discharged in t ($\mathrm{Discharge(store)}_t$). The variable ($\mathrm{Store(heat)}_t$) represents the heat stored in the storage and is calculated for every time step t with the heat stored in the previous time step minus constant storage losses ($\xi\mathrm{(store)}$) and the charging and discharging balance. Each charging and discharging process is affected by additional losses: $\theta\mathrm{(charge)}$ and $\theta\mathrm{(discharge)}$, which are dependent on the amount of heat charged or discharged, respectively. It is assumed that the storage will be empty in the beginning and the end of the considered time horizon. This ensures that all required energy is also produced during this time-period.

$$\mathrm{Store(heat)}_0 = 0$$

$$\mathrm{Store(heat)}_{8760} = 0$$

For computational reasons, it should be ensured that the logical condition of charging and discharging of the storage at the same time is forbidden, which is not described here.

$$\mathrm{Store(heat)}_{t+1} = \mathrm{Store(heat)}_t - \xi\mathrm{(store)} + \theta\mathrm{(charge)} \cdot \mathrm{Charge(store)}_t - \theta\mathrm{(discharge)} \cdot \mathrm{Discharge(store)}_t$$

$$\mathrm{Store(heat)}_{t+1} \leq \mathrm{cap(store)}$$

7.3.2 Demand-Supply Balance

Based on these equations, it is then possible to estimate the system's performance when it has to supply the energy for a given building. As expressed above, the energy needs (thermal and electric) are collected from existing building case studies. Based on these demands, heat and electricity load profiles are characterized and the cogeneration-based system has to fulfil the needs.

The heat demand ($consumption(heat)_t$) has to be supplied either by heat production of one of the units or by heat stored in the storage tank. In order to discharge heat, it had to be charged into the storage in a previous time step.

$$\mathrm{consumption(heat)}_t + \mathrm{Charge(store)}_t = \mathrm{Heat(CHP)}_t + \mathrm{Heat(HE)}_t + \mathrm{Heat(Boiler)}_t + \mathrm{Discharge(store)}_t$$

$$\mathrm{consumption(elec)}_t + \frac{\mathrm{Heat(HE)}}{\eta\mathrm{(HE)}} + \mathrm{Elec(sell)}_t = \mathrm{Elec(CHP)}_t + \mathrm{Elec(grid)}_t + \mathrm{PV}_t + \mathrm{Discharge(store)}_t$$

The same concept is valid for the electricity demand ($\mathrm{consumption(elec)}_t$), with the difference that no storage is possible but instead it is possible to buy and sell electricity from the grid.

The presented model enables the estimation of the cogeneration performances. It should be noticed that it considers different assumptions to calculate the performance of the energy system, which may affect the results. Indeed, the model is based on the idea that the system operator aspires to produce the demand of a given system in an economic cost efficient way. Therefore, no investment costs of the system or other parameters are considered in the model, which could influence the operation decision. Nevertheless, the proposed model is assumed consistent with the EcoDynBat objectives to estimate the environmental impacts of the building energy demand and, if possible, identify efficient energy systems.

Finally, the parameters used in the model presented above, have been defined in accordance with experts, scientific papers and manufacturer documentation. They are listed in Table 8:

Parameter	Value	Unit	Description	Source
$\mathrm{p(gas)}$	0.083	Frs/kWh	Price for purchasing gas	(Eichenberger, 2019)
$\mathrm{p(buy\ elec)}$	0.23	Frs/kWh	Price for purchasing electricity from the public grid	(Eichenberger, 2019)
$\mathrm{p(sell\ elec)}$	0.04	Frs/kWh	Price for selling self-produced electricity	Own Assumptions
$\eta(\mathrm{CHP_{therm}})$	Combustion: 0.559-0.783	-	Efficiency of heat production of the CHP unit	(RMB energie, 2019)
	Fuel Cell: 0.33			Own Assumptions
$\eta(\mathrm{CHP_{elec}})$	Combustion: 0.278-0.35	-	Efficiency of electricity production of the CHP unit	(RMB energie, 2019)
	Fuel Cell: 0.55			Own Assumptions
$\eta(\mathrm{Boiler})$	0.9	-	Efficiency of gas-boiler	Own Assumptions
$\xi(\mathrm{store})$	0.12	kWh/h	Storage heat losses over time	(Unitec Gmbh, 2019)
$\theta(\mathrm{charge})$	0.02	-	Charging losses	(Renaldi et al., 2017)
$\theta(\mathrm{discharge})$	0.02	-	Discharging losses	(Renaldi et al., 2017)
$\mathrm{PV_t}$	Time series from the measured data or simulated with the model described above	kWh	Produced electricity via photovoltaic system in t	Either monitored values or simulated values according to the models presented in § 7.1
$\mathrm{consumption(heat)_t}$	Time series from the measured data	kWh	Heat consumption in t	Monitored values
$\mathrm{consumption(elec)_t}$	Time series from the measured data	kWh	Electricity consumption in t	Monitored values

Table 9. Parameters values for the micro-cogeneration model

Based on this model, the annual performance of each technology in the system for every hour can be calculated. Since the impact of the whole system vary with the use of each technology and its time of operation, it is important to calculate the performance of each technology separately. It is then possible to estimate the environmental impacts of the whole system for every hour and subsequently for a whole year, which is the final aim of the EcoDynBat project.

7.4 Summary of building energy demand profile models and assumptions

The calculation of building energy demand relies on real energy demand profiles collected from the EcoDynBat partners. Electricity and heat time series will be collected on an hourly basis in order to assess the influence of the time step on the buildings' environmental impact. Within the case study chapter, the influence of different variants will be tested, considering the integration of:

- decentralized energy production systems, namely photovoltaic and micro-cogeneration,
- heat pumps

Since the collected demand profile data are not necessary encompassing all the element of the variants to be tested, the above presented models and tools have been defined in order to obtain the values necessary for the environmental impact calculations. All this elements have been thus set in order to obtain all the necessary inputs for the environmental impact calculations.

8. Synthesis & conclusions

EcoDynBat WP2 had five objectives. First, it had to identify the data needs to model the electricity (supply mix) and potential sources to provide the necessary information. Then, a characterization of the data source reliability had to be made in order to specify the range of validity for the identified information. Based on this characterization, , several data sources have been merged, when needed, in order to obtain a more reliable and representative dataset to be used for the environmental impact calculation. In addition, based on the project's objective, a large quantity of data had to be handled. It was, thereby, necessary to develop a framework to gather, visualize and process them. Finally, from the building side perspective, it was necessary to develop models to obtain all the necessary data for the environmental impact calculation. Indeed, the real buildings load profiles collected in the project are dependant of the technical systems installed. Some of them were not equipped with photovoltaic installations, some had no heat pumps. The developed models aimed at providing all the elements to fully characterize the time step influence on the environmental impact of the building electricity demand considering a maximum of configurations.

Regarding the data needs, the EcoDynBat project had to consider the grid fluctuation in Switzerland by encompassing the national production means variability in quality (type of power plant used) and quantity (amount). The imports and exports had to be also characterized in quality but also in quantity. In other word, the production means in the neighbouring countries had to be known. This information has been found in several sources in Switzerland (Swissgrid, SFOE) and for the neighbouring countries (RTE in France E-Control in Austria, etc.) but also, at a European aggregated level via the European Network of Transmission System Operator (ENTSO-E). The EcoDynBat project has set a framework to collect the data in a transparent and open-source way. In addition, the project consortium has collected the data continuously and will continue to maintain the services developed in EcoDynBat over time.

The available data had shown that the electricity mixes in Europe are largely heterogeneous. France has opted for nuclear electricity as the backbone of its mix. Italy relies on fossil fuels, and show a lack of indigenous production leading to constant imports. Germany relies heavily on fossil fuels despite an already significant share of renewable. Austria is highly relying on hydro-electricity. Switzerland is relying on both hydro and nuclear electricity and imports electricity mainly from neighbouring countries between early-Fall and mid-Spring. This time interval has increased since 2005.

Once the descriptive assessment done and the key aspects highlighted, the data from ENTSO-E has been compared to national sources. For France, it has been found that the data is consistent between the two sources. For Austria, the data comparison has shown a relatively good adequacy for the production mix and the imports level, while the exports were slightly more diverging. A detailed assessment has identified the cross-border exchanges between Germany and Austria as the source of this deviation. Nevertheless, the data can be considered as sufficiently reliable for the EcoDynBat assessment. The same trends have been observed for Germany and Italy. For Switzerland, observations have been made when comparing to data from the different sources. First, the ENTSO-E production mix presents a non-negligible gap in the national monthly and daily values. The difference is mostly explained by the fact that ENTSO-E considers the electricity at high voltage while the other data sources consider the overall Swiss electricity production. A discussion with Swissgrid has confirmed this explanation for the discrepancy. The daily SFOE data, which provides 108 days of electricity production mixes in Switzerland, has clearly highlighted that the difference between ENTSO-E and the other national data sources could be found in a discrepancy for the calculation of hydro run-of-river and other (including photovoltaic) production sources. Moreover, it has been found that the ENTSO-E data are considering net imports/exports while Swissgrid information provides gross data.

In general, the hourly information, regarding the electricity production mix is hardly available in Switzerland. Because of the national electricity market structure, the data is spread among several sources, which make a compilation process complex. Based on the available data and the assessments made, it has been decided to set up adjustment rules to improve the ENTSO-E data consistency , in order to reach the EcoDynBat objectives. Thus, missing data points have been identified and an approach has been defined to fill the gaps. Then, discrepancies for the production mix between ENTSO-E and the national data have been addressed, by considering a so-called residue made of hydro run-of -river and an “other” (including photovoltaic) mix. These adjustment rules helped to obtain the EcoDynBat Swiss production mix. Then, the imports and exports have also been adjusted to consider the gross exchanges rather than the net, permitting to model the full Swiss electricity supply mix. Finally, the grid losses have been taken into account, in order to obtain the Swiss electricity consumption mix.

Based on these adjustment rules, the EcoDynBat dataset has been defined. This dataset serves, as a basis for the environmental impact calculations. The WP3 method will now develop the framework for the use of this dataset in the view of the EcoDynBat objectives.

Regarding the electricity demand, a photovoltaic production model, a heat pump performance model and a micro-CHP operating models have been defined in order to provide the necessary information to encompass the heterogeneity of building consumption profiles. Based on these models and the collected load curve profiles of real buildings, it will be possible, in the next chapters, to test the time step influence over several building configurations.

All the elements assessed and developed regarding the grid and the building models in this WP are, thus, at the root of the environmental impact calculation that will be performed, in the next EcoDynBat WPs.

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Project ECODYNBAT

Dynamic Life Cycle Assessment of Buildings

Chapter 3: Methodological framework for dynamic life cycle assessment (WP3)

Final Report

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Summary

This report presents the methodological framework for the EcoDynBat project to carry out a dynamic life cycle assessment for the energy flows in Swiss buildings. The scope defines the boundaries of the analysis and how energy flows have been represented. A lists of modeling choices and simplifications complements this information to offer a clear explanation on the limits of the analysis and how the DLCA framework could be improved in the future if more information became available. A step-by-step description of the computational structure is also proposed to help readers who would want to use the produced algorithms or replicate the DLCA for other Swiss buildings. This methodological framework will serve as a foundation for the work of WP4 and WP5.

Résumé

Ce rapport présente le cadre méthodologique du projet EcoDynBat qui permet de réaliser une analyse dynamique du cycle de vie pour les flux d’énergie dans les bâtiments suisses. Le cadre de l’étude définit les limites de l'analyse et la manière dont les flux d'énergie ont été représentés. Une liste de choix de modélisation et de simplifications vient complèter ces informations pour offrir une explication claire des limites de l'analyse et de la manière dont ce cadre pourrait être amélioré si davantage d'informations devenaient disponibles à l’avenir. Une description, étape par étape, de la structure informatique est également proposée pour aider les lecteurs souhaitant utiliser les algorithmes produits ou reproduire des ACV dynamiques pour d’autres bâtiments suisses. Ce cadre servira aussi de base aux travaux du WP4 et du WP5.

Zusammenfassung

Dieser Bericht präsentiert den methodischen Rahmen für das EcoDynBat-Projekt zur Durchführung einer dynamischen Ökobilanz für die Energieflüsse in Schweizer Gebäuden. Der Umfang definiert die Grenzen der Analyse und wie Energieflüsse dargestellt wurden. Eine Liste mit Modellierungsoptionen und -vereinfachungen ergänzt diese Informationen und bietet eine klare Erläuterung der Grenzen der Analyse und der Frage, wie das DLCA-Framework in Zukunft verbessert werden könnte, wenn weitere Informationen verfügbar würden. Eine schrittweise Beschreibung der Rechenstruktur wird auch vorgeschlagen, um Lesern zu helfen, die die erstellten Algorithmen verwenden oder die DLCA für andere Schweizer Gebäude replizieren möchten. Dieser methodische Rahmen wird als Grundlage für die Arbeit von WP4 und WP5 dienen.

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Abbreviations

ALCA: Advancing Life Cycle Assessment Group

APOS: allocation at the point of substitution

CF: Characterization Factor

DHW: Domestic Hot Water

DLCA: Dynamic Life Cycle Assessment

DLCI: Dynamic Life Cycle Inventory

DLCIA: Dynamic Life Cycle Impact Assessment

Empa: Swiss Federal Laboratories for Materials Science and Technology

EU: European Union

FU: Functional Unit

GHG: Greenhouse Gas

GWP: Global Warming Potential

HEIG-VD: Haute École d'Ingénierie et de Gestion du Canton de Vaud

HES-SO: Haute École Spécialisée de Suisse Occidentale

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LESBAT: Laboratoire d'Énergie Solaire et de Physique du Bâtiment

SUPSI: Scuola Universitaria Professionale della Svizzera Italiana

TD-LCI: Temporally Differentiated Life Cycle Inventory

TS-CF: Temporally Specific Characterization Factor

WP1: Work Package 1 – Review of methodologies

WP2: Work Package 2 – Input data with temporal variability considerations

WP3: Work Package 3 – Development of a DLCA framework for the project

WP4: Work Package 4 – Case studies

WP5: Work Package 5 – Sensitivity Analysis

WP6: Work Package 6 – Recommendations and dissemination of results

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1. Goals of the DLCA framework

The work presented in the chapter 1 and chapter 2 have respectively provided examples on how to conduct DLCA of buildings and a detailed description of the input information for the energy flows in a dynamic way. This collected knowledge and information will now be used to provide a clear description of the DLCA framework that will be used in the EcoDynBat project.

The main goal of this report is to present a clear description of the specific methodological framework that will be used to conduct a DLCA of energy flows in Swiss buildings for the EcoDynBat project. Details on the key aspects will thus be provided in the following sections. Moreover, many aspects that can be found in standard LCA (e.g. modeling assumptions) will also be found within these sections.

This DLCA framework will enable the consideration of different temporal resolutions in the description of flows that describe the dynamics of the system. Representative and precise estimates of the energy production from decentralized installations will also be an important aspect that the framework will look into. Both are therefore subsidiary goals of the framework and of the EcoDynBat project.

The scope and key modelling assumptions made within this assessment framework are provided in section 2. Explanations on the treatment of input data and the computational approach are then described in section 3.

2. Scope definition and modelling assumptions

Defining the scope of a study and listing the modeling assumptions are requirements of the first phase in all LCA studies to offer a transparent explanation on limitations of the impact assessment for any system [1, 2]. The same requirements are defined in this framework since they also apply to DLCA. Nevertheless, a specific focus on the details of temporal considerations will be visible in this section.

2.1 Scope definition

Figure 1 presents the scope and boundaries for the EcoDynBat model of energy in Swiss buildings. The figure shows all the processes and dynamic flows that are considered in the foreground for the model. It also clearly shows that the environmental impacts from the building itself are outside of the scope, which means that results will only show the impacts of the energy use.

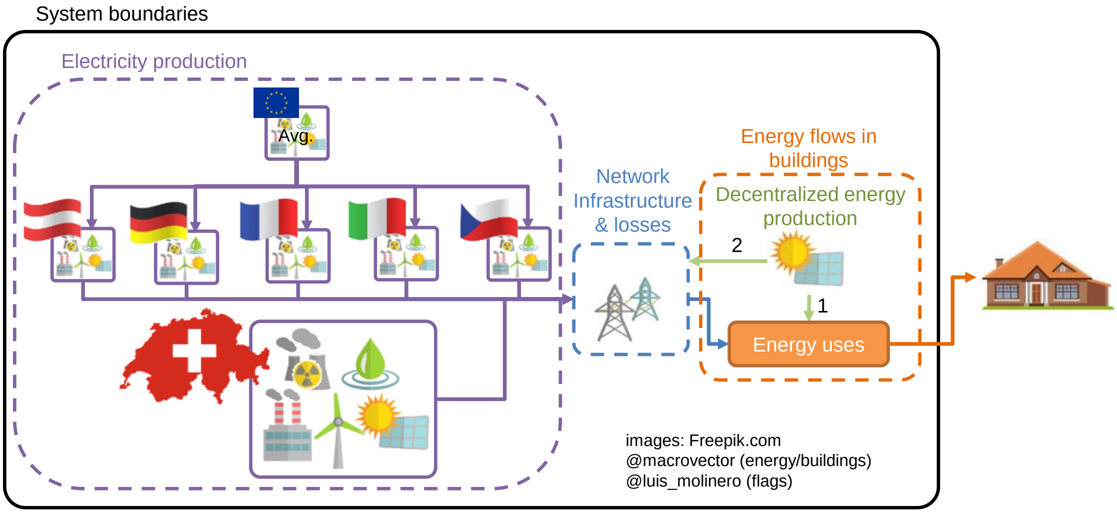


Figure 1 : Model and boundaries for the system of energy flows in Swiss buildings

The *chosen FU* to describe the function of the energy use and production in a Swiss building is:

The m^2 of ERA for a year of building use

This FU has been selected because it provides a quantified representation of the building use that offers a rather fair comparison of buildings with a similar use, but with different sizes. It will be important to avoid comparison between different types of buildings (i.e. industrial, residential and commercial). Moreover, this FU is a typical choice for publications on LCA or DLCA of buildings.

The *chosen temporal boundary of this assessment is 1 year of energy use in a building* since it offers an analysis over at least one full cycle of temperature, weather and sunlight variations. Different years can still be considered and compared with this choice, but the full lifetime of a building is not set as the temporal boundary in this framework. This is thus a limited temporal scope for the life cycle of "standard" buildings and this choice has been made mainly because of the limited availability of data for the electricity flows (i.e. 2017-2018, see also chapter 2). Nevertheless, this temporal scope is seen as adequate since the EcoDynBat project focuses on intra-annual variations of energy flows.

2.1.1 Description of the components for the model

Figure 1 provides a visualization of the key components and dynamic flows that are considered within the EcoDynBat framework. The following sub-sections offer detailed descriptions of how these components and their variations in time are modeled.

Electricity sources of different countries

The number of considered energy production means in the model of centralized electricity production is limited by the chosen data sources, which are analyzed in the chapter 2. The highest level of detail for the EcoDynBat model is thus limited by the disaggregation level of the ENTSO-E data source. Table 1 lists these means of production, which are then found in the descriptions of the hourly electricity production mixes for all EU countries.

Table 1 : List of production means in ENTSO-E (see also chapter 2)

Fossil sources	**Renewable sources**	**Others**
Lignite	Biogas	Nuclear
Coal	Waste	Hydro Pumped storage
Oil	Marine energy	
Natural Gas	Geothermal	
Gas from coal	Photovoltaic	
Fossil oil shale	Onshore wind	
Fossil Peat	Offshore wind	
Other fossil fuel (unidentified)	Hydro reservoir	
	Hydro run-of-river	
	Other renewable source (unidentified)	

The dynamics of these energy sources are described in the chapter 2. The main output of chapter 2, which is called the "EcoDynBat dataset", merges the information of several data sources (from ENTSO-E and Swiss datasets mainly) to get the Swiss production mixes and cross-border flows. It is expected that more temporal variability will be observed for some renewable sources like photovoltaic, hydro run-of-river and wind energy since they depend mostly on weather conditions. Fossil sources, nuclear and hydro reservoir are expected to follow different dynamics since humans have more control on their use and they are activated to answer the need of electricity users at different periods over the days, weeks and months.

Some simplifications for the description of the pumped storage were required in this framework. Indeed, this is not a production mean, but a storage option that is sustained by the other production means. Sadly, the used data sources do not provided information on when such pumping occurs, which prevents precise assessment of the share of production means that are stored this way for every hours of the year. The environmental impacts related to hydro pumped storage are thus linked to the annual average data that is provided in LCA databases (i.e. ecoinvent [3] & KBOB [6]).

These sources are also differentiated by their country of origin. The choice of considered countries (i.e. Switzerland [CH], Austria [AT], Germany [DE], France [FR], Italy [IT], Czech Republic [CZ] and rest of Europe) is explained by observations of WP1 (section 7.1.3) and a preliminary contribution analysis of impacts from countries' mixes in a standard LCA of the annual Swiss electricity mix. Hence, table 2 shows the shares of total potential impacts of the CH mix when different levels of details are considered. Consequently, energy flows from CZ must be differentiated in time to offer a DLCA on ~99% of annual impacts for all categories. Temporal details for flows in other European countries are then deemed unnecessary because they contribute to ~1% or less of the total impacts for the Swiss consumers' mix. The different types of countries for the EcoDynBat framework are also presented in figure 2 to identify where temporal differentiation is required (i.e. red and blue).

Table 2: Share of total impacts for the CH consumers' mix depending on details of supply chain

Levels of details in the ecoinvent model of the consumers' mix	Global warming potential	Cumulative energy demand	Ecological scarcity (UBP)
Share of total impacts from CH production (*CH_Prod*)	10.33%	65.05%	45.54%
Share of total impacts from *CH_Prod* + imports from direct neighbors (*1st_lvl_imports*)	84.52%	95.54%	92.79%
Share of total impacts from *CH_Prod* + *1st_lvl_imports* + imports from AT, CH, DE, FR, IT in neighboring countries (*2nd_lvl_imports*)	91.46%	97.98%	96.34%
Share of total impacts from *CH_Prod* + *1st_lvl_imports* + *2nd_lvl_imports* + imports from CZ (*CZ_prod*)	98.84%	99.62%	99.51%
Share of total impacts for CH consumers' mix coming from other EU countries	1.16%	0.38%	0.49%

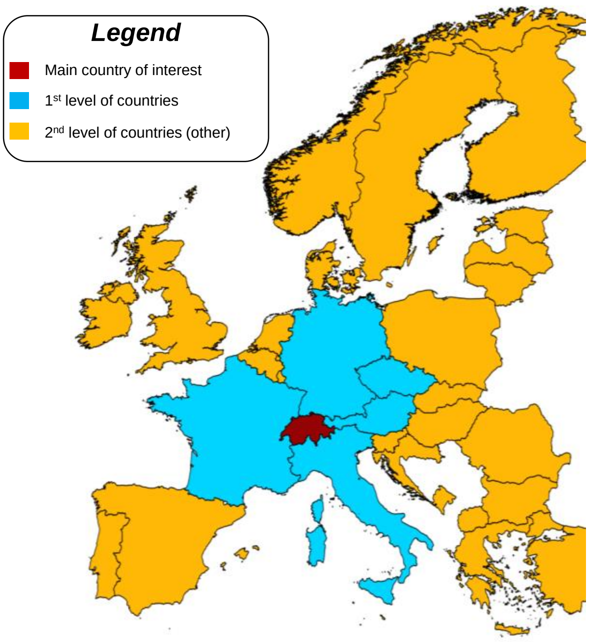


Figure 2: Types of countries based on their environmental importance

The modeling of renewable energy sources (e.g. photovoltaic) requires a temporal simplification in this dynamic model. Indeed, the "real" impacts from these sources occur mostly when components are manufactured and when installations are built. This means that allocating the impacts to the period when electricity is produced introduces a time lag between the "real" moment of impacts and the "modeled" moment of impacts. This is less of an issue for traditional energy sources (e.g. natural gas) because the burning of the fuel occurs almost at the same time as the energy production and this combustion is typically the main source of impacts. In the context of the EcoDynBat project, this temporal simplification is deemed acceptable mainly because the chosen impact assessment methods (see sub-section 2.2.2) for the EcoDynBat framework are not using different factors when elementary flows occur at different periods.

Transport infrastructure for the electricity

The electricity that is made available in all Swiss buildings is coming from a network that transports energy all over the country and manage exchanges with neighboring countries. The construction and maintenance of this infrastructure creates environmental impacts that are allocated to Swiss electricity. An approach to calculate a ratio of the infrastructure's impacts for each kWh of used electricity at low voltage is already provided in the ecoinvent database [3]. This approach is considered relevant for the EcoDynBat framework and is thus kept.

Using the ratio of ecoinvent to consider the infrastructure's impact does bring a temporal simplification in the model since the timing of impacts is thus fully linked to the moment of electricity use. At a yearly resolution, this link can be acceptable for impacts related to maintenance, but the share that relates to the network's construction, which happened a long time ago, is thus not temporally representative. At the hourly resolution, this temporal simplification is even less representative, but considering the real timing of impacts from the Swiss electricity infrastructure is deemed too complex for the EcoDynBat model. Consequently, table 3 presents the percentages of impacts that are linked to the electricity network for key impact categories (see sub-section 2.2.2) to give a transparent description of the share that is non-dynamic in the model of electricity mix within the EcoDynBat framework. These values show that the temporal discrepancies from this simplification are only somewhat significant for the ecological scarcity impact category, but the method of impact assessment for this category does not consider the effect of changing the period of emission; making this simplification acceptable.

Table 3: Share of electricity impacts related to transport infrastructure for 3 categories

Impact categories	Share of impacts from infrastructure
Climate change	2.5%
Cumulative energy demand	0.4%
Ecological scarcity	11.1%

Losses from transport and conversion

The electricity on the European network is maintained by all the production means that are connected to it, wherever they are. Hence, some energy losses will occur between the sites of production and the sites where electricity is used. Both transportation and conversion of voltage (high→medium→low) will cause energy losses. Measuring all possible energy losses from transport and conversion is almost impossible since they will vary instantly and they are based on the dynamics of electricity production and their use in different regions. Nevertheless, it is possible to obtain average monthly energy losses for the Swiss grid from SFOE. These values are presented in the chapter 2 and are considered in the EcoDynBat framework. There are thus some more temporal simplifications in this part of the EcoDynBat model since monthly averages for the Swiss grid are deemed representative and constant over smaller temporal resolutions (e.g. daily) even when electricity is produced outside of Switzerland. These losses will affect the environmental assessments of used electricity mainly by showing that more electricity must be produced to offer 1 kWh of electricity to Swiss users. The average annual values provided in ecoinvent v3.4 [3] show that 1.06 kWh of electricity must be produced to provide 1kWh in the building).

Decentralized production of electricity

Two different means of decentralized energy production are considered within the EcoDynBat project. They are photovoltaic installations and micro-CHP systems. The theoretical evaluation of dynamics for their production over a year is described in the chapter 2. When looking at the recommendations from the chapter 1 (sub-section 6.2), it becomes clear that a rather precise definition of the building's site is necessary to model a representative level of energy production when measurements are not available. The technologies, overall efficiency and lifetime of the decentralized installation are then important to find the relevant environmental descriptions in either ecoinvent or the KBOB databases.

These decentralized installations produce electricity for both self-consumption (flow 1 in figure 1) and the electricity network (flow 2 in figure 1). The goal of the EcoDynBat framework is first to assign impact values for each of the produced kWh from these installations since hourly production of energy can be evaluated for all the considered buildings in Switzerland. The total LCA impacts of the decentralized installation are thus divided by the total amounts of produced kWh over its lifetime (see explanation in sub-section 3.2.2). This value can then be used to assess the impacts of the auto-consumed energy for each time step. This also means that an impact from electricity that returns to the grid is not allocated to energy flows from the analyzed building.

This approach is based on the typical strategy that ecoinvent and KBOB use in the assessment of impacts for all energy sources even if splits between self-consumption and transfer are not useful for most production means. Consequently, the lack of consideration for the time-lag simplification also applies in this part of the dynamic model.

Electricity use in Swiss buildings

One of the key tasks for the EcoDynBat project is to carry out DLCA that offer analyses that are based on measured energy flows in "real" Swiss buildings (see also the chapter 2). These measures account for the following components:

- Heating demand
- Domestic hot water (DHW) production
- Domestic appliances (e.g. Lighting)

The full energy uses in the analyzed buildings are then compared with the decentralized electricity production to identify when there is self-consumption (see Figure 3). In this context, self-consumption is set as a priority and transmission to the grid will only occur when all the building demand is met. Conversely, the Swiss electricity grid becomes an input of energy for the building whenever the decentralized installation cannot fulfill the needs of the buildings and their users. These conditional evaluations are considered at every time-step (i.e. hour) of the dynamic energy flow model.

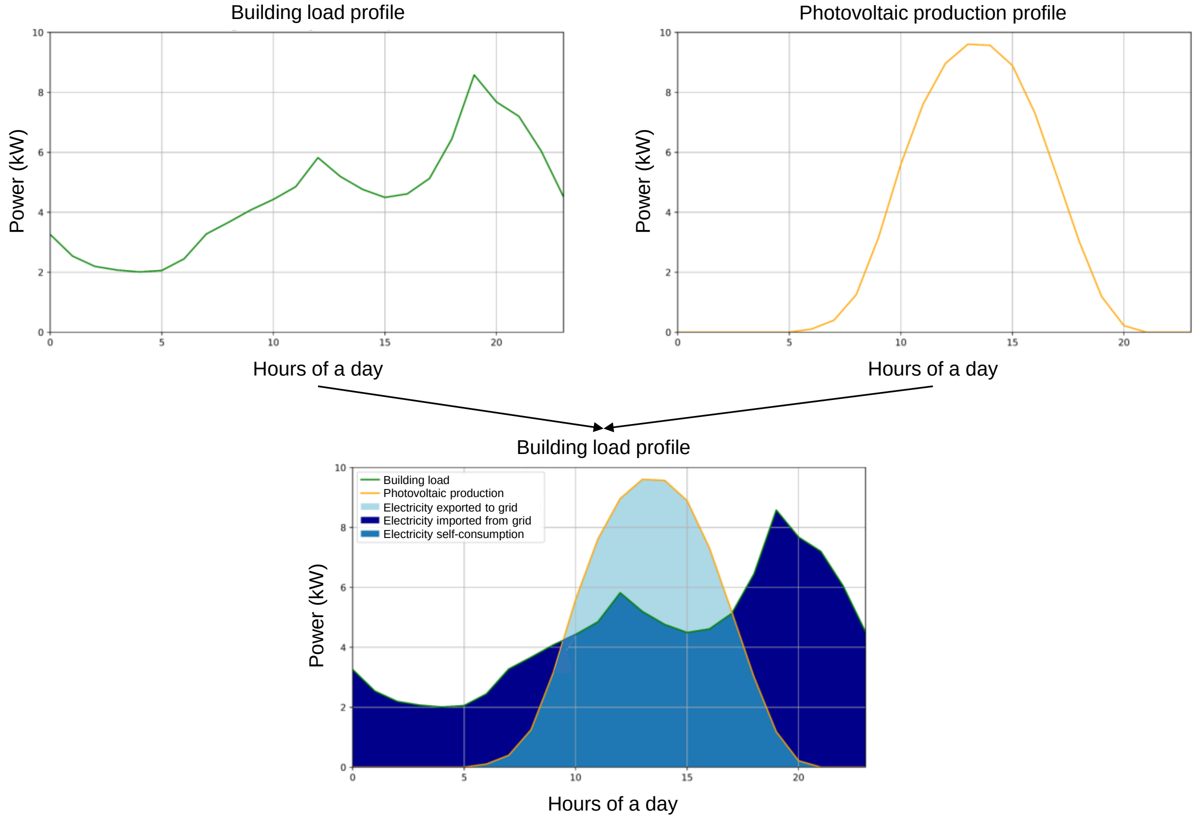


Figure 3: Self-consumption example from profiles of a building's load and its photovoltaic production

2.1.2 Approaches for electricity modeling

Five different approaches for electricity modeling have been proposed by Ménard *et al.* [4] to assess the environmental impacts of electricity mixes in different countries within the LCA framework. Four of these approaches are clearly described in a report from Itten *et al.* [5] with the schematic that is presented in figure 4 on the following page (figure 2.1 in the Itten *et al.* report). The fifth approach, which is introduced in ecoinvent v2.2, models an electricity mix by accounting for declarations from all utilities in a country and abroad, while replacing the “unknown” sources by the average ENTSO-E electricity mix. Currently, the electricity mixes in version 3 of ecoinvent use the second approach (i.e. Model 2); except for the Swiss supply mix, which is defined by the fifth approach. This fifth approach is also different because it cannot be based on physical flows of electricity.

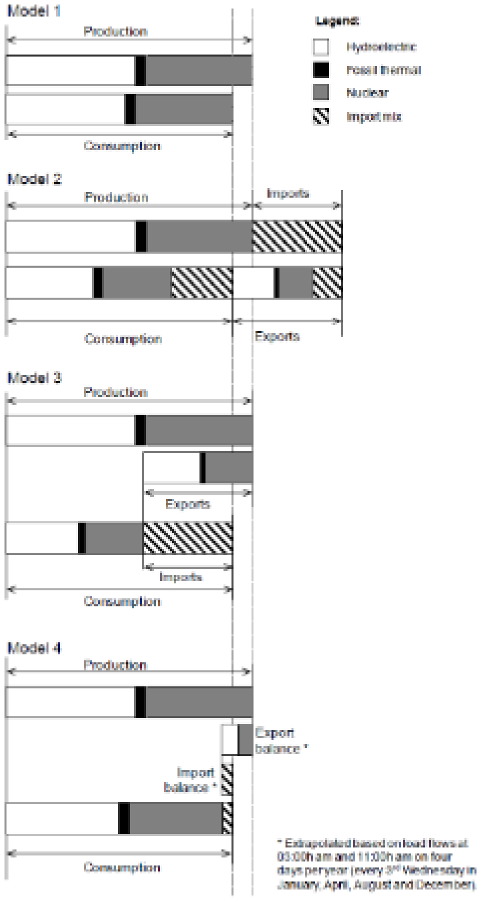


Figure 4: Possible electricity modeling approaches within the LCA framework (from [5])

The key aspects of the four approaches from figure 4 are explained as follow:

- **Model 1**: Considers only the production means of the country (supply mix = national production). This approach is expected to be a good simplification for countries with low import/export volumes.
- **Model 2**: The electricity supplied to customers is a combination of the national production means with the imported electricity. In this perspective, the exported electricity from the assessed country is considered equivalent to the electricity supplied to domestic customers.
- **Model 3**: This approach assumes that national production mix is always exported and that imported electricity is always used within the assessed country. This means that transportation of electricity through the country is not considered.
- **Model 4**: The main assumption of this approach is that simultaneous, physically measured imports and exports are due to transit trade. The exported electricity is a proportional share of the national production and the imported electricity is defined by the mix of neighboring countries. Typically, this model requires extrapolation with potentially high uncertainties.

<u>The chosen approach to model the Swiss electricity grid within the EcoDynBat framework is model 2.</u>

This choice is explained by the following reasons:

- Modeling physical flow of electricity is a priority
- Switzerland relies on significant levels of imported and exported electricity (hence ~~Model 1~~)
- The electricity imported into Switzerland is not always used within the country (hence ~~Model 3~~)

- The currently available hourly data for electricity in all European countries does not offer a precise picture for both imported and exported levels (hence Model 4 is excluded)

Model 2 is thus the only remaining option. Moreover, it is interesting to mention that model 2 can be understood as a simplified model that considers the impact of maintaining grid stability in countries with significant exchanges of electricity. Indeed, a share of the impact from electricity that is going through Switzerland is accounted for in this consumers' mix, which might be relevant because that passing electricity is also used to reach grid stability on the high-voltage network.

2.1.3 Input data

A clear and transparent description of input data is always a key aspect of the scope definition in LCA studies, which is why this sub-section provides an overview of the data sources that are chosen for the EcoDynBat model.

For electricity flows

The description of flows for electricity production and exchanges is at the core of the EcoDynBat project, which explains why the chapter 2 provides a detailed description of this aspect. The chapter 2 provides the relevant information on the used data sources (e.g. ENTSO-E statistics) and on how their representativeness has been verified.

Nevertheless, the more important information for this work package (i.e. WP3) is the examination of the output from WP2 (see chapter 2), which offers a temporal distribution that describes hourly Swiss production, exports and imports in MWh values. The temporal scope of distribution starts at the beginning of 2017 and ends at the end of 2018 thus offering 2 years of relevant input data. This information now needs to be combined with environmental data to implement the calculations of impacts in the EcoDynBat project.

For the energy flows in buildings

One of the key goals of the EcoDynBat project is to use "real-life" measurements from different Swiss buildings to analyze the importance of considering temporal variability in LCA of such buildings.

The other key aspect to consider for energy flows in buildings is the decentralized production. The description of data treatment for the measures and components' properties is thus described in details in the chapter 2 (WP2 report). Photovoltaic installation and micro-CHP will be the three considered options in the EcoDynBat project.

The description of energy flows for both electricity use and decentralized energy production follow the configuration of grid electricity representation. Indeed, temporal distribution of hourly energy production and use will be provided for different types of building. It will then be important to ensure that both types of data will cover the same period (e.g. the year 2018).

For the environmental flows of sources and infrastructures

The evaluation of environmental impacts from energy flows in Swiss buildings requires data for all the components of figure 1. In this project, the KBOB v.2016 [6] and ecoinvent v.3.4 (cut-off) [3] are used to offer such descriptions. A brief description of both databases is thus provided.

In the Swiss building sector, the KBOB database is already well known and has been used for the environmental assessment of different buildings, making it a particularly relevant source to investigate in this project. The data takes its source in the version 2.2 of the ecoinvent database with updates made by Treeze on different sectors like energy and buildings.

Version 3.4 of the ecoinvent LCA database provides information on more than 17 000 process and markets, thus offering a different model of human activities and their environmental effects around the world. The chosen system model for this project is the attributional perspective (i.e. cut-off). The M2 modeling approach for physical flows in electricity mixes is used consistently for most electricity mixes (see sub-section 2.1.2). Moreover, the consistency in the models is reinforced by a general application of allocation rules and limits.

The Simapro software tool has been used for the analysis of the KBOB and ecoinvent information, which forced the choice of version 3.4 for ecoinvent since it was the latest available version when the EcoDynBat project began.

2.2 Modelling choices and assumptions

Sub-section 2.1 mainly defines the different components and assumptions that are considered in the assessment scope of the EcoDynBat project, but more modeling choices are required to evaluate the potential impacts of Swiss buildings. This section presents these other choices that are not necessarily justified by basic requirements, but are taken to offer results that fit better with the goal of the project.

2.2.1 Key choices from WP1

The literature review from WP1 provided many ideas on how DLCA of buildings should be conducted. Some of the conclusions from the chapter 1 (WP1) are thus kept in the EcoDynBat framework. These choices are summarized in the following list:

- The focus on intra-annual variation of flows is chosen to answer the general goal of the project and because it has not yet been defined in previously proposed DCLA framework.
- A detailed model of dynamics for electricity production in the neighboring countries of Switzerland is preferred since such a level of description has not been investigated in the literature.
- The use of site-specific data for energy use and production in buildings is selected because it has often been proposed as a core aspect to increase representativeness in DLCA studies.
- The attributional modeling perspective is chosen to streamline the comparison of results between this project and previous studies, which forces the choice of the “cut-off” version of ecoinvent.

2.2.2 Chosen categories for the impact assessment

Many impact categories have been analyzed in previous DLCA studies of buildings as is reported in the chapter 1 (WP1 report). Many choices could thus be taken in the current framework, but the Swiss context of this project guides to the selection of the three following LCIA methods.

- IPCC 2013 (100 years) v1.03 to evaluate the global warming potential (GWP)
- CED v2.05 to evaluate the renewable and non-renewable energy demands
- Ecological scarcity 2013 v1.05 to offer an evaluation with a commonly known Swiss indicator

These choices are mainly explained by the desire to conduct an analysis in reference to previous values that could be obtained by most stakeholders of the Swiss building sector since these categories can be found in the Excel list of values for the KBOB v2016.

The chosen methods are not dynamic, which means that they do not offer different characterization of impacts when emissions of pollutants or extractions of resources happen at different times. This is not a problem for the CED method since primary energy demand does not change with the moment when resources are extracted or used. The ecological scarcity method might be more representative if the dynamics of impacts were considered for some of its categories, but such a DLCIA method for the Swiss context has not yet been developed.

Finally, some DLCIA methods about the GWP have been used in previous DLCA studies of buildings and could therefore be applied in this framework. Nevertheless, such methods only change the GWP of emissions when they occur in different years, which mean that the current temporal scope of 1-year in the EcoDynBat framework is too small for a relevant use of dynamic GWP evaluation. Consequently, dynamic characterization factors have not been considered because the EcoDynBat project focuses on intra-annual variability.

2.2.3 Necessary simplifications

The modelling choices and chosen scope of assessment for the EcoDynBat project impose the use of some simplifications mainly concerning temporal considerations. These simplifications are presented and explained here in an effort to offer a transparent definition of the limits in the model and analysis.

The first simplification comes from the input data, which limits the temporal resolution to a minimal period that is equivalent to an hour. In the real world, energy production for the grid and energy use in a building will vary even more quickly, but such variations are not considered in this framework.

The second simplification relates to the issue of time lag that has been presented for the electricity network. The same simplification comes up often in the description of background systems in the LCA databases (i.e. KBOB and ecoinvent), but considering them would require too much effort within the EcoDynBat project. They are thus neglected in the model.

The third simplification comes with the limited geographical precision of tools to assess the solar energy and temperature in Switzerland. Indeed, knowing the exact GPS localization of analyzed buildings will only place them within a region of the solar irradiation maps or the weather forecast. While already quite precise, such maps are still not able to offer the exact irradiation or temperature for a specific building, which brings some uncertainty in the assessment of the building's energy flows. This is a required simplification only for some standard assessments of the EcoDynBat project since most case studies are described by building-specific production of PV installations and their heat demand throughout the years.

Finally, the selected FU (see sub-section 2.1) could offer a fairer comparison if the amounts of people who use or live in the building were considered. This information has been proposed in one of the published DLCA framework (see chapter 1) as a key aspect to consider, but it will not be used in the EcoDynBat project for confidentiality reasons. Indeed, the use of statistics from real buildings precludes from declaring any personal information that might help in the identification of specific buildings in Switzerland. This simplification does not hinder the analysis of effects from using different resolution levels to describe energy flows in buildings, but limits the relevance of comparing the environmental impacts for the different buildings that will be analyzed in the project.

3. Computational structure

Section 2 with the reports of chapters 1 and 2 provides descriptions of input data, modeling choices and chosen simplifications for the EcoDynBat framework, which are the foundation for the computational structure to assess the potential environmental impacts of energy use in Swiss buildings. Hence, this section shows how such aspects are used to handle the input data and transform it in DLCA results. The general overview of the inputs, calculation steps and outputs are presented on page 136 in figue 7.

3.1 Treatment of input data

The input data on energy flows and environmental impacts of energy sources must be modified in two ways before they can become inputs for the evaluation of potential impacts for different periods. These treatments of data include an approach for temporal aggregation and a linkage of structure between the sources of data for energy flows and their environmental impacts.

3.1.1 Temporal aggregation for different resolution of energy flows

The goal of evaluating DLCA results with an analysis of flows at different temporal resolutions forces the use of an aggregation approach since the ENTSO-E data for electricity mixes is provided per hour for all the considered countries. The aggregation of this information is rather straightforward but is worth mentioning to ensure consistency in the computational structure. The basic idea is to sum the amounts of one energy production over the entire period with a lesser temporal resolution and make these sums for all energy sources, which can then be used to create new ratio for the electricity mix. For example, hourly production of all energy sources are summed up per day to acquire the share of production means per source during a day. It can be described by the following equation:

$$Mix_{resolution\ y}^{source\ i} = \sum_{resolution\ x}^{y} Production_{resolution\ x}^{source\ i} \quad when\ x < y$$

Where source *i* is one type of production means in a specific country and resolution *x* is smaller than resolution *y* (e.g. if resolution *x* is 1 day, than resolution *y* can be 1 month or 1 year)

This method is equivalent to implementing a weighted average of energy shares based on the total production volume per hour when daily shares are calculated.

3.1.2 Linking electricity data with environmental impacts

The main source of data for electricity production at different time steps (i.e. ENTSO-E) and the chosen sources of data for the environmental assessment (i.e. ecoinvent and KBOB) do not describe the energy production means with the same level of details. This discrepancy in the description of the model's components brings an issue since impacts of energy sources must fit with the description of energy production means. A mapping file was thus build to connect these two sources of information for every relevant country, energy sources and technologies (see Annex of chapter 3).

Figure 5 presents a conceptual example of how these connections have been defined while clearly highlighting how production means are described with different levels of detail in the ENTSO-E and ecoinvent data sources, mainly for the solar sector. The necessity of using ENTSO-E data in the EcoDynBat project imposes an aggregation of the data from ecoinvent. It is thus essential to find ratio of each technology in ecoinvent to describe the energy sector in ENTSO-E. This information was found in the ecoinvent database since shares of each technology are provided for the average annual electricity production in 2014. Using these values is a simplification because market shares of different technologies have changed, but such changes are expected to have very small effects on the impacts of a sector even for novel technologies such as photovoltaic installations.

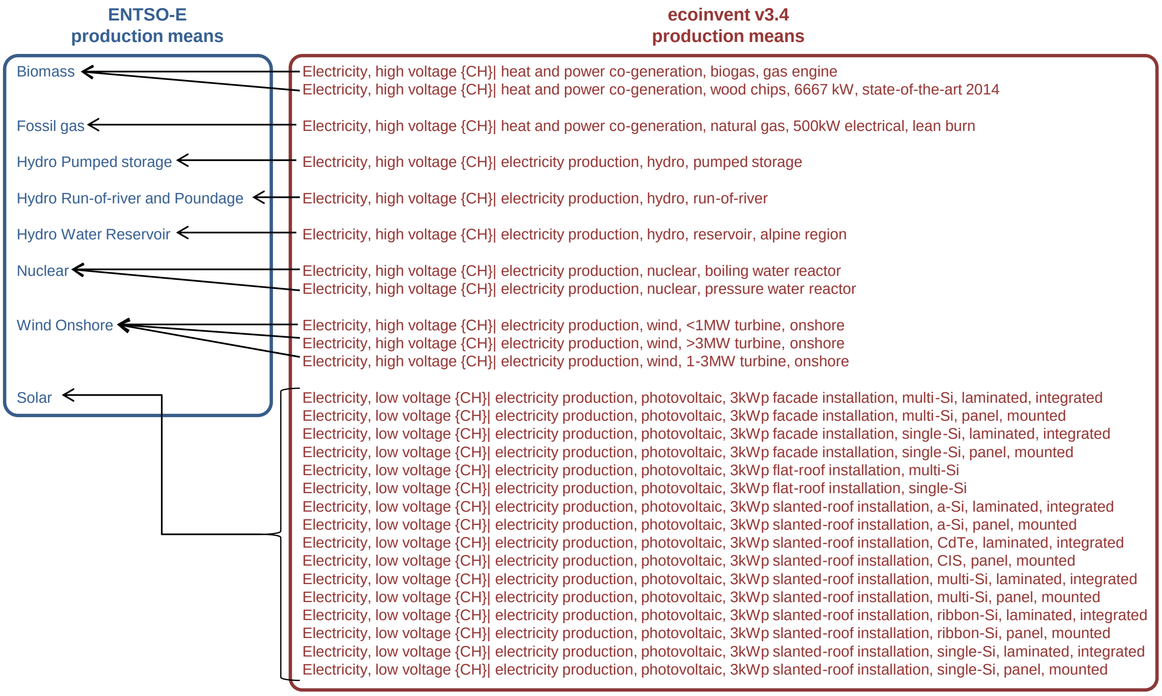


Figure 5: Example of mapping connections between ENTSO-E and ecoinvent in Switzerland

A few more ideas on the mapping approach are worth mentioning:

- It is important to understand that the example of Switzerland is provided to show the key aspects of mapping connections, but that each country will have their own specificities.
- Using average annual share of technologies might also bring some temporal discrepancy in the model if some technologies are used only for part of the year. For example, maybe some biomass plants are running only during the periods of the year when waste wood is produced in significant volumes. Such trends would not be identified within the current framework.
- The importance of correctly mapping the share of each technology increases when two options are linked to very different levels of impacts (here “very different” is subjective to the comparison).
- The “other fossil” and “other renewable” sector in ENTSO-E data have been linked to technologies with the worst impact levels of Europe in ecoinvent based on the application of precautionary principle. Consequently, impacts of unknown sources will become significant if they represent a high share of the electricity mix during some periods in a year.

3.2 Calculations of impacts for electricity inputs

After the treatment of input data (see sub-section 3.1) for energy flows and a restructuring of data from the ecoinvent database, the evaluation of environmental impacts from energy use in Swiss buildings can be implemented. The following sub-sections thus present the calculation steps that will then be applied for different case studies in WP4 and WP5 of the EcoDynBat project.

3.2.1 Calculating the impacts of production means from the mix

The first calculation step takes the EcoDynBat dataset (see chapter 2) and assesses the share of all production means at every period (e.g. hour, day) for all countries. The key concepts that regulate this evaluation are the M2 electricity modeling approach (see sub-section 2.1.2) and the suggestion of WP1 to use a matrix-based structure. They both will be used to consider the exchanges between the electricity mixes of different countries. Consequently, all imports from neighbors of Switzerland will become a part of the consumer's mix, which will then be used in Swiss buildings. The imports of these neighbors will also be considered, but in a simplified manner as an average EU mix (ENTSO-E mix in ecoinvent)(see also figure 2).

A simplified example of this matrix-based calculation is provided in figure 6. The main simplifications of this example are in the aggregation of production means for a country and a limited number of considered EU countries. Moreover, such a calculation must be done for every time step over the year (i.e. 8760 calculations for the hourly resolution). In this example, values in the technology matrix represent the input process from that row into the process from that column. For instance, 0.6 kWh of produced electricity in Switzerland is needed for the Swiss electricity mix during that period as well as 0.2 kWh from Austria, 0.1 kWh from France, 0.25 kWh from Germany and 0.03 kWh from Italy. These are only the direct needs and uncovering the full energy requirements over the entire supply chain requires the step of matrix inversion. It is only then that this inversed technology matrix is multiplied by the reference vector to obtain the life cycle energy flows for the consumption of 1 kWh of electricity in Swiss buildings at a specific time step.

Technology matrix

	Swiss electricity	Swiss production	Austria electricity	Austria production	French electricity	French production	German electricity	German production	Italy electricity	Italy production
Swiss electricity	0.00	0.00	0.05	0.00	0.02	0.00	0.02	0.00	0.05	0.00
Swiss production	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Austria electricity	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.00
Austria produciton	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00
French electricity	0.10	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.12	0.00
French production	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00
German electricity	0.25	0.00	0.25	0.00	0.07	0.00	0.00	0.00	0.00	0.00
German production	0.00	0.00	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.00
Italy electricity	0.03	0.00	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Italy production	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00

(Technology matrix)$^{-1}$

	Swiss electricity	Swiss production	Austria electricity	Austria production	French electricity	French production	German electricity	German production	Italy electricity	Italy production
Swiss electricity	1.01	0.00	0.06	0.00	0.02	0.00	0.02	0.00	0.06	0.00
Swiss production	0.61	1.00	0.04	0.00	0.01	0.00	0.01	0.00	0.03	0.00
Austria electricity	0.03	0.00	1.01	0.00	0.00	0.00	0.03	0.00	0.03	0.00
Austria produciton	0.02	0.00	0.66	1.00	0.00	0.00	0.02	0.00	0.02	0.00
French electricity	0.13	0.00	0.04	0.00	1.01	0.00	0.10	0.00	0.13	0.00
French production	0.12	0.00	0.04	0.00	0.91	1.00	0.09	0.00	0.12	0.00
German electricity	0.27	0.00	0.27	0.00	0.08	0.00	1.02	0.00	0.03	0.00
German production	0.23	0.00	0.23	0.00	0.07	0.00	0.87	1.00	0.03	0.00
Italy electricity	0.03	0.00	0.05	0.00	0.01	0.00	0.00	0.00	1.00	0.00
Italy production	0.03	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.80	1.00

×

Reference vector
(i.e. 1 kWh of consumer's mix)

Swiss electricity	1
Swiss production	0
Austria electricity	0
Austria produciton	0
French electricity	0
French production	0
German electricity	0
German production	0
Italy electricity	0
Italy production	0

=

Share of production means
when 1 kWh is consumed in the
Swiss building

Swiss electricity	1.01
Swiss production	0.61
Austria electricity	0.03
Austria produciton	0.02
French electricity	0.13
French production	0.12
German electricity	0.27
German production	0.23
Italy electricity	0.03
Italy production	0.03

Figure 6: Simplified example of the matrix-based calculation to account all production means.

The obtained shares of production means from each country to offer electricity to Swiss consumers can then be multiplied by their respective environmental impacts (see annex of the chapter 3). The impacts for all production means is calculated, with Simapro v7.4, for both KBOB and ecoinvent while mapping (sub-section 3.1.2) is accounted for to offer information in the ENTSO-E structure. This calculation thus provides the environmental impacts of the mix for each period (e.g. hour) during the one or two year's assessment of buildings.

3.2.2 Calculating the impacts of decentralized electricity production

The other important source of impacts from energy flows in buildings comes from the decentralized energy production. Assessing these impacts requires the estimation of impacts from the installation divided by the site-specific energy production of the same installation.

The following equation explains this calculation:

$$Impact_{energy}/kWh = \frac{Impact_{installation} + \ Impact_{use\ phase}}{Lifetime\ Production\ (kWh)}$$

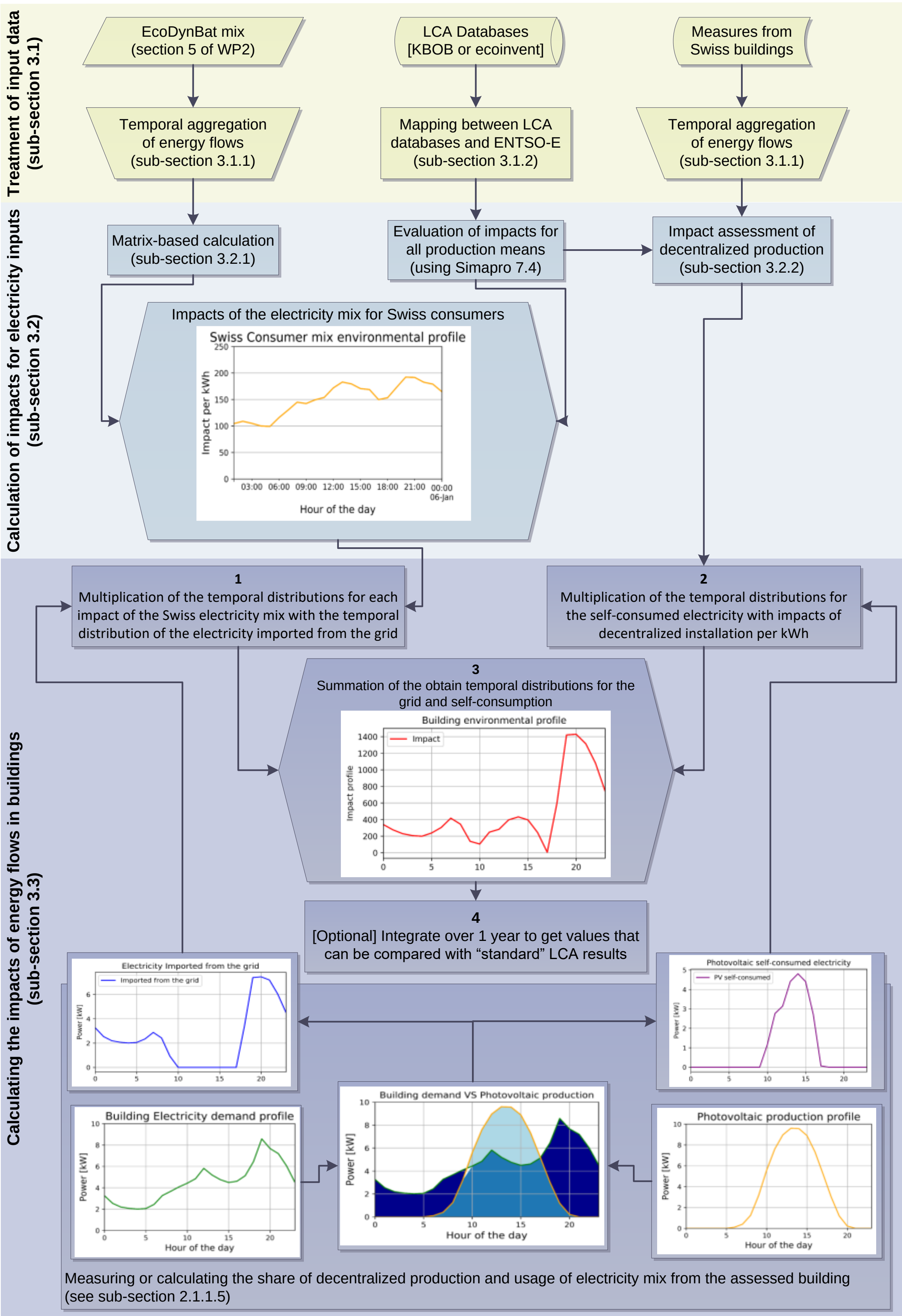
The impacts of photovoltaic installations and micro-CHP systems and its use can be found directly in the ecoinvent database. On the other hand, the lifetime production of energy from this installation requires some information on the technologies and site-specific weather conditions (see chapter 2). It is important to remember here that the lifetime production accounts for all energy even the electricity that might be feed back to the grid. Once the impact per kWh is calculated, it is the possible to estimate the total impacts of energy use in a building over a year.

3.3 Calculating the impacts of energy flows in buildings

The two previous steps (sub-section 3.2.1 and 3.2.2) provide important information that can then be combined with the environmental impacts of all energy sources and the temporal distribution of energy use in the assessed Swiss building to obtain the global results of this framework. The following calculation steps are followed to reach these results (see also figue 7 on the next page for a diagram of inputs, calculation steps and the output results).

1. Multiplication of one of the four different temporal distributions describing the impacts of the Swiss electricity mix for consumers with the temporal distribution of the electricity imported from the grid.
   - ⇨ This step evaluates the impacts of the electricity use in the building when it is provided by the grid for every time step over the full period of assessment (i.e. 1 year).
2. Multiplication of the temporal distributions for the self-consumed electricity with impacts of decentralized installation per kWh
   - ⇨ This step evaluates the impacts of electricity produced by the decentralized installation when it is used in the building for every time step over the full period of assessment (i.e. 1 year).
3. Summation of the obtain temporal distributions for the grid and self-consumption
   - ⇨ This step combines the impacts of all electricity uses in the building for every time step over the full period of assessment (i.e. 1 year). Values can be divided by the m^2 ERA of the building to provide the results per FU. It is the main output of the EcoDynBat framework.
4. [Optional] Integrate over 1 year to get values that can be compared with “standard” LCA results
   - ⇨ This summation of impacts over the full year is necessary to compare results from this DLCA framework with results from a “standard” LCA of the same building.

These calculation steps are mainly carried out with Python algorithms for each time step (e.g. hours) over the two-year period for which data is available (i.e. 2017-2018). The format of output temporal distributions is useful to analyze the variations during a year, but its values over the year can be summed up to compare the results of this DLCA framework with results from “standard” LCA.



Figue 7: Graphical example of the computational structure for the EcoDynBat framework

4. Conclusions

The description of the DLCA framework for the EcoDynBat project is divided between a scope definition (chapter 2) and the computational structure (chapter 3). The following tables summarize the key modeling assumptions of the scope and the main steps of the computational structure.

Key modeling assumption for the EcoDynBat framework (chapter 2)
Scope definition (sub-section 2.1)

- The functional unit is the m^2 ERA for 1 year of energy use in the assessed building
- The model of the system considers:
    o 20 different production means in 6 countries
    o The infrastructure to transport electricity
    o The losses from the transporting electricity on the grid
    o Decentralized production from the building
    o All electricity uses in the building
- The modeling approach for the electricity mix is based on production and imports
- The input data comes from WP2 and the KBOB and ecoinvent databases

Key modeling assumptions (sub-section 2.2)

- Focus on intra-annual variations with a resolution up to the hourly time step
- Use of site-specific information on buildings when available
- Attributional modeling perspective
- Choice of 4 impact categories:
    o Global warming potential
    o Renewable cumulative energy demand
    o Non-renewable cumulative energy demand
    o Ecological scarcity
- Neglecting the existing time-lag in background database and the electricity infrastructure

Main steps of the computational structure (Chapter 3)
Treatment of input data (sub-section 3.1)
- Temporal aggregation of information to provide different temporal resolution levels - Mapping for the connection between LCA databases and ENTSO-E data structure
Calculation of impacts for the electricity inputs (sub-section 3.2)
- Matrix-based calculation of all production means in important countries - Impact assessment for all production means in the framework - Impact assessment for decentralized electricity production
Calculating the impacts of energy flows in buildings (sub-section 3.3)
- Evaluation of impacts from the use of electricity from the grid - Evaluation of impacts from the self-consumed electricity in the building - Combination of impacts from all energy flows in the building - Summation over the assessment period for comparison with “standard” LCA results

5. References

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ECODYNBAT PROJECT

Dynamic Life Cycle Assessment of Buildings

Chapter 4 – Part a: Case studies (WP 4-a)

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Summary

In this chapter, the results of previous work-packages are used to calculate:

- The environmental impacts of electricity consumption in Switzerland
- The influence of considering different time steps in calculating the environmental impacts of the electricity demand of buildings for 6 case studies by considering 20 possible configurations to meet the demand (heat pump to meet the heat and hot water demand, presence of photovoltaics, etc.).

A comparative analysis of the electricity impact results according to the approach developed with the data usually used in Switzerland (KBOB and ecoinvent) is also proposed.

The environmental impacts of electricity consumed in Switzerland, according to the EcoDynBat approach, show a significant temporal fluctuation for the climate change impact category. Environmental indicators dealing with primary energy are less sensitive. The "Ecological Scarcity" indicator has an intermediate sensitivity compared to the other indicators. According to the approach developed, interannual fluctuations are also significant and depend on the availability of means of production on the network each year. It therefore appears necessary to take these interannual fluctuations into account when calculating the environmental impacts related to electricity demand.

Comparison with the data normally used in Switzerland shows significant differences that can be explained by several factors. On the one hand, the reference years for the Swiss electricity mix are different. On the other hand, the impacts proposed in the KBOB and ecoinvent are based on a different calculation methodology than that of EcoDynBat. Ecoinvent considers the certified origin of electricity (*stromkennzeichnung*), whereas EcoDynBat only considers the physical flows present on the grid at a time t. This difference explains most of the differences. It seems necessary to define a consensual approach for the calculation of the environmental impacts of electricity consumed in Switzerland.

The influence of the time step on the calculation of environmental balances of the energy demand of buildings varies according to the environmental indicator selected. For the primary energy categories, the time resolution does not improve the accuracy of the calculations. For the Ecological Scarcity category, the improvement is modest. The Climate Change Impact category is the most sensitive to the choice of temporal resolution. For buildings, where there is seasonal demand, taking into account a higher temporal resolution improves the accuracy of the environmental balances. This is the case, for example, for an electricity demand linked to the use of a heat pump for space heating. Conversely, for electricity demand that remains constant throughout the year (domestic hot water or domestic use), increasing the temporal resolution does not imply an improvement in the accuracy of the results. When considering the global demand of buildings (heating + domestic hot water + domestic use), taking into account a higher temporal resolution increases the accuracy by less than 10% for the climate change category. The other indicators do not seem to present a sufficient improvement in accuracy to justify fully the consideration of a finer temporal resolution in the calculation of environmental impacts.

In summary, the work presented in this report therefore shows:

- It would be necessary to agree on a generic approach for defining the electrical flows that define the Swiss consumed electricity mix (physical versus certificate of origin approach).
- That it would be appropriate to give priority consideration to inter-annual fluctuations. This will be of prime importance since the Swiss energy mix is likely to change significantly in the future as a result of the national energy strategy and the corresponding developments in the neighboring countries.
- That a fine temporal resolution is to be considered in the case of a significant seasonality in the demand for the building.

Résumé

Dans ce chapitre, les résultats des précédents WorkPackages sont utilisés pour calculer :

- Les impacts environnementaux de l'électricité consommée en Suisse
- L'influence de la prise en compte de différents pas de temps dans le calcul des impacts environnementaux de la demande d'électricité des bâtiments pour 6 cas d'études en considérant 20 configurations possibles pour répondre à la demande (pompe à chaleur pour assurer la demande en chaleur et en eau chaude sanitaire, présence de photovoltaïque, etc.)

Une analyse comparative des résultats d'impacts de l'électricité selon l'approche développée avec les données usuellement employées en Suisse (KBOB et ecoinvent) est également proposée.

Les impacts environnementaux de l'électricité consommée en Suisse, selon l'approche EcoDynBat, présente une fluctuation temporelle importante pour la catégorie d'impact sur le changement climatique. Les indicateurs environnementaux traitant de l'énergie primaire sont moins sensibles. L'indicateur « Ecological Scarcity » présente une sensibilité intermédiaire par rapport aux autres indicateurs. Selon l'approche développée, les fluctuations interannuelles sont également importantes et dépendent de la disponibilité des moyens de production sur le réseau à chaque année. Il apparait donc nécessaire de tenir compte de ces fluctuations interannuelles pour le calcul des impacts environnementaux liés à une demande d'électricité.

La comparaison avec les données usuelles en Suisse présente des différences significatives qui s'expliquent par plusieurs facteurs. D'une part, les années de références pour le mix électrique Suisse sont différentes. D'autres part, les impacts proposés dans la KBOB et ecoinvent reposent sur une méthodologie de calcul différentes que celle d'EcoDynBat. En effet, celles-ci considèrent le marquage de l'électricité alors qu'EcoDynBat considère uniquement les flux physique présent sur le réseau à un instant t. Cette différence explique la majeure partie des écarts. Il apparait nécessaire de définir une approche consensuelle pour le calcul des impacts environnementaux de l'électricité consommée en Suisse.

L'influence du pas de temps sur le calcul des bilans environnementaux de la demande énergétique des bâtiments est variable en fonction de l'indicateur environnemental sélectionné. Pour les catégories portant sur l'énergie primaire, la résolution temporelle n'améliore pas la précision des calculs. Pour la catégorie « Ecological Scarcity », l'amélioration est modeste. La catégorie d'impact sur le changement climatique est la plus sensible au choix de la résolution temporelle. Pour les bâtiments, lorsque ceux-ci ont une demande saisonnière, la prise en compte d'une résolution temporelle plus fine améliore la précision des bilans environnementaux. C'est ainsi le cas pour une demande d'électricité liée à l'utilisation d'une pompe à chaleur pour le chauffage des locaux. A contrario, pour les demandes électriques constantes au cours de l'année (eau chaude sanitaire ou usages domestiques), l'augmentation de la résolution temporelle n'implique pas une amélioration de la précision des résultats. En considérant la demande globale des bâtiments (chauffage + eau chaude sanitaire + usage domestique), la prise en compte d'une plus grande résolution temporelle augmente la précision de moins de 10% pour la catégorie sur le changement climatique. Les autres indicateurs ne semblent pas présenter une amélioration de la précision suffisante pour justifier pleinement la prise en compte d'une résolution temporelle plus fine dans le calcul des impacts environnementaux.

En synthèse, les travaux présentés dans ce rapport montrent donc :

- Qu'il serait nécessaire de définir une approche générique pour la définition des flux électriques qui composent le mix consommateur Suisse
- Qu'il serait pertinent de considérer en priorité les fluctuations interannuelles. Cela sera primordiale puisque le mix Suisse est amené à profondément se modifier dans le futur du fait de la stratégie énergétique nationale ainsi que des stratégies des pays avoisinants
- Que la prise en compte d'une résolution temporelle fine est à envisager dans le cas d'une saisonnalité importante de la demande du bâtiment.

Zusammenfassung

In diesem Kapitel werden die Ergebnisse vorhergehender WorkPackages (WP) zur Berechnung folgender Punkte verwendet:

- Die Umweltbelastungen des Stromverbrauchs in der Schweiz
- Der Einfluss des Einbezugs verschiedener Zeitschritte bei der Berechnung der Umweltbelastungen des Strombedarfs von Gebäuden, wobei 6 Fallstudien unter Berücksichtigung von 20 möglichen Konfigurationen zur Deckung des Bedarfs (Wärmepumpe zur Deckung des Wärme- und Warmwasserbedarfs, Vorhandensein von Photovoltaik, usw.) herangezogen werden.

Zusätzlich wird auch eine vergleichende Analyse der Strombelastungsergebnisse nach dem entwickelten Ansatz dargelegt und dies mit den in der Schweiz üblicherweise verwendeten Daten (KBOB und ecoinvent).

Gemäss des EcoDynBat-Ansatzes weisen die Umweltbelastungen des in der Schweiz verbrauchten Stroms für die Wirkungskategorie Klimawandel eine signifikante zeitliche Schwankung auf. Die Umweltindikatoren, die sich mit Primärenergie befassen, sind weniger spürbar. Der Indikator "Ecological Scarcity " weist im Vergleich zu den anderen Indikatoren eine mittlere Sensitivität auf. Nach dem entwickelten Ansatz sind auch die zwischenjährlichen Schwankungen erheblich und hängen von der jährlichen Verfügbarkeit der Produktionsmittel im Netz ab. Es erscheint daher notwendig, diese zwischenjährlichen Schwankungen bei der Berechnung der mit der Stromnachfrage verbundenen Umweltbelastungen zu berücksichtigen.

Der Vergleich mit den in der Schweiz üblichen Daten zeigt signifikante Unterschiede, die sich durch mehrere Faktoren erklären lassen. Einerseits sind die Referenzjahre für den Schweizer Strommix unterschiedlich. Andererseits basieren die in der KBOB und ecoinvent vorgeschlagenen Auswirkungen auf einer anderen Berechnungsmethode als die von EcoDynBat. Letzteres berücksichtigt die Kennzeichnung von Elektrizität, während EcoDynBat nur die zu einem bestimmten Zeitpunkt t im Netz vorhandenen physikalischen Stromflüsse verwertet. Dieser Unterschied erklärt die meisten Abweichungen. Daher sollten einheitliche Leitlinien für die Berechnung der Umweltbelastungen des in der Schweiz verbrauchten Stroms definiert werden.

Der Einfluss des Zeitschrittes auf die Berechnung der Umweltbilanzen des Energiebedarfs von Gebäuden variiert je nach ausgewähltem Umweltindikator. Bei den Kategorien Primärenergie verbessert die Zeitauflösung die Genauigkeit der Berechnungen nicht. Bei der Kategorie «Ecological Scarcity » ist die Verbesserung nur mässig. Die Kategorie Auswirkungen des Klimawandels antwortet am deutlichsten auf die Wahl der zeitlichen Auflösung. Bei Gebäuden, bei denen eine saisonale Nachfrage besteht, verbessert die Berücksichtigung einer feineren zeitlichen Auflösung die Genauigkeit der Umweltbilanzen. Dies ist z.B. bei einem Strombedarf der Fall, der mit dem Einsatz einer Wärmepumpe zur Raumheizung verbunden ist. Im Gegenzug verbessert eine Erhöhung der zeitlichen Auflösung die Genauigkeit der Ergebnisse nicht, wenn der Strombedarf das ganze Jahr über konstant bleibt (Warmwasser oder Hausgebrauch). Bei der Betrachtung des globalen Gebäudebedarfs (Heizung + Warmwasserbereitung + Hausgebrauch) erhöht die Berücksichtigung einer höheren zeitlichen Auflösung die Genauigkeit für die Kategorie Klimawandel um weniger als 10%. Die anderen Indikatoren scheinen keine ausreichende Verbesserung der Genauigkeit darzustellen, um die Berücksichtigung einer feineren zeitlichen Auflösung bei der Berechnung der Umweltauswirkungen vollständig zu rechtfertigen.

Zusammenfassend zeigt die in diesem Bericht vorgestellte Arbeit daher:

- dass es notwendig wäre, einen generischen Ansatz für die Definition der Stromflüsse zu definieren, aus denen sich der Verbrauchermix Schweiz zusammensetzt
- dass es angebracht wäre, vorrangig die zwischenjährlichen Schwankungen zu berücksichtigen. Dies wird von wesentlicher Bedeutung sein, da sich der Energiemix der Schweiz aufgrund der nationalen Energiestrategie und der ihrer Nachbarländer in Zukunft stark verändern dürfte
- dass eine feine zeitliche Auflösung im Falle einer starken Saisonabhängigkeit des Gebäudebedarfs in Betracht zu ziehen ist.

Table of content

Acronyms

AT : Austria
A-W: Air-Water
CH : Switzerland
CHP : Combined Heat and Power
COP: Coefficient Of Performance
CS: Case Study
CZ: Czech Republic
DE : Germany
DHN: District Heating Network
DHW: Domestic Hot Water
DLCA: Dynamic Life Cycle Assessment
ENTSO-E : European Network Transmission System Operator
ES: Ecological Scarcity
FR : France
GHG: Greenhouse Gas
GHGe: Greenhouse Gas emissions
GW: GigaWatt
GWh: Gigawatt hour
GWP: Global Warming Potential
HP: Heat Pumps
IT : Italy
KBOB: Ökobilanzdaten im Baubereich 2009/1:2016
LCA: Life Cycle Assessment
MFH: multi-Family House
MW : MegaWatt
MWh : Megawatt hour
NRE: Non Renewable primary energy
PV : Photovoltaic
RE: Renewable primary energy
SFH: Single Family house
STEP: Station de Turbinage et Pompage
UBP: Eco-Points
WP: Work Package
WP1: Work Package 1 – Review of methodologies
WP2: Work Package 2 – Input data with temporal variability considerations
WP3: Work Package 3 – Development of a DLCA framework for the project
WP4: Work Package 4 – Case studies
WP5: Work Package 5 – Sensitivity Analysis
WP6: Work Package 6 – Recommendations and dissemination of results

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1. Introduction

In the EcoDynBat project, the WP1 highlighted key methodological aspects for the Dynamic Life Cycle Assessment (DLCA) of electricity demand in buildings based on a literature review of past publications on the subject.

Following that, available data for the electricity production has been identified and analyzed in chapter 2, from the various existing sources (national statistics, Transmission System Operator data, etc.). The necessary information for the DLCA of electricity flows in Swiss buildings has then been gathered and merged into a single dataset, called the "EcoDynBat dataset".

Finally, the EcoDynBat methodological framework has been defined in WP3. It provides a way to consider environmental impacts of the electricity demand in Swiss buildings with different time steps.

Based on the aforementioned WP outputs, the environmental impacts are calculated for various building configurations and time steps within this chapter 4.

1.1 WP4: Structure

The WP4 chapter is divided into three sections:

1- The results for the grid electricity impacts are first presented and then compared to the existing values (KBOB 2016 and ecoinvent v3.4):
   a. This first step shows the evolution of the grid electricity impacts from 2017 to 2018, using different time steps (yearly, monthly, daily and hourly) and four indicators namely, climate change (CO_2 eq/kWh), non-renewable primary energy (MJp/kWh), renewable primary energy (MJp/kWh) and ecological scarcity (UBP/kWh).
   b. The comparison of the EcodynBat dataset to existing datasets (KBOB and ecoinvent) underlines the influence of the EcoDynBat assumptions and the influence of the production mix over different years.

2- Using the results of the first step, the impacts of the electricity demand for six case studies are calculated:
   a. Three building types are considered, i.e. one office building, one multi-family residential building and four single-family buildings.
   b. For these case studies, electricity from the grid is used for domestic needs, space heating with heat pumps and domestic hot water production. The influence of a photovoltaic (PV) installation is also considered.
   c. Based on this assessment, the influence of time step on the environmental impacts of electricity needs in buildings is identified while considering the various building types and technical installations (PV, HP). The inter-annual influence is also discussed, since the analysis is performed for a two-year period.

3- Finally, the environmental assessment of buildings, equipped with a micro-cogeneration unit (combustion-based and fuel cells), is performed. Five case studies of residential multi-family buildings are considered. Different shares of biomethane (0%, i.e natural gas, 10%, 20% and 100%) are taken into account in evaluation of the micro-cogeneration unit's impacts. The results related to the micro-cogeneration are given in a dedicated report, separated from the present one.

A total of 20 scenarios have been considered for part 2 and 36 for part 3. With the four time step considered, the two years of measurement (only for part 2), and the fours environmental indicator, a total of 1'668 results have been computed.

In order to keep the report readable, the detailed results and assessment of the case studies are found in appendix. The main findings are presented in the core of this chapter and illustrated with some specific facts from the case studies.

2. Environmental impacts of the Swiss electricity mix

In this section, the environmental impacts of the Swiss electricity mix are presented for the four selected indicators, i.e. climate change (CO_2 eq/kWh), non-renewable primary energy (MJp/kWh), renewable primary energy (MJp/kWh) and ecological scarcity (UBP/kWh). The impact contributions are presented per country, i.e. Swiss production and imports (France, Germany, Italy, Austria and Czech Republic as introduced in the chapter 2) and per energy carrier, as well (fossil, renewable, nuclear, pumping storage).

2.1 Swiss electricity mix

Based on the EcoDynBat dataset, and using the matrix inversion method presented in WP3, the contribution of each country to the Swiss electricity consumption mix is presented in Figure 8. The Swiss consumption mix correspond to the electricity that is consumed in the Swiss buildings (i.e including imports, transport and distribution losses).Results are displayed on a monthly basis for the sake of clarity. The detailed shares, per country, are presented in detail in annex of chapter 4-a.

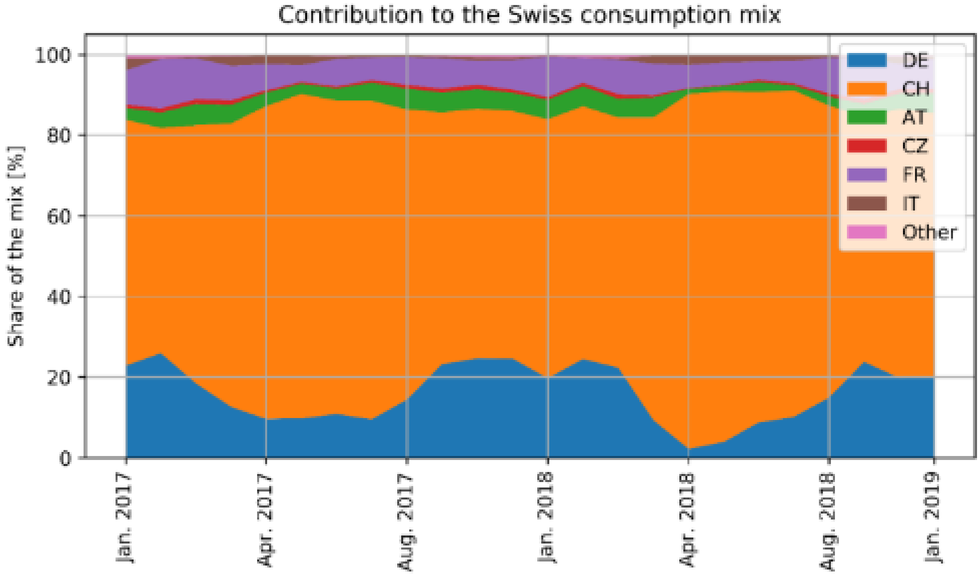

Figure 8: Contribution to the Swiss consumption mix per countries.

From the results of Figure *8*, it is noted that the Swiss consumer mix significantly varies every month and between 2017 and 2018 especially between summer and winter. From April to September, the Swiss production covers on average 79% of the mix, while from October to March, the Swiss share is 62% on average. Consequently, the other countries contribute more in autumn and winter. The neighboring countries' contributions are:

- 1.4 to 5.3 % for Austria (AT),
- 4.1 to 12.4% for France (FR),
- 0.1 to 3% for Italy (IT),
- 0.2 to 1.2% for Czech Republic (via Austria and Germany),
- 0.1 to 0.9% for other EU countries,
- 2.3 to 25.9% for Germany (DE)

The matrix-based approach, used within EcoDynBat, intends to identify the countries' and the energy carriers' contributions at each time step. This approach allows, thus, a significant increase in the level of details and accuracy, regarding the assessment of the Swiss electricity environmental impacts.

Switzerland imports electricity, mostly from Germany and France. These imports occur when there is a high demand for electricity, which the Swiss national production means cannot sufficiently cover. It should be noted that the imports were more important in 2017 (29%), than in 2018 (25%), because of the smaller capacity of the Swiss nuclear power plants in 2017, compared to 2018 (mostly Leibstadt and Beznau 1). In addition, the Swiss consumption mix is sensitive to seasonal variations. In spring and summer, the Swiss production adequately covers the demand, while imports become necessary during the cold seasons.

It is also worth mentioning that, despite the fact that Czech Republic (CZ) has no common border with Switzerland, its mix contributes to the Swiss mix, on average by 0.9%. Indeed, CZ exchange electricity with DE and AT which are then exchanged with CH. Including CZ in the Swiss assessment is relevant because of its production mix which rely on fossil fuels and thus influence the Swiss electricity impact. Conversely, all other countries (for example Poland, Belgium, Spain, etc.) altogether contribute to the Swiss consumed electricity, on average by 0.4% and has a low impact contribution (considering Poland, Belgium, the Netherlands, Sweden, Norway, Spain, Portugal , United Kingdom and Denmark increase the level of accuracy by maximum 0.32% in term of environmental impacts). Thereby, including additional countries into the assessment implies an insignificant increase in the accuracy of the results, which confirm the initial hypothesis made in WP3.

In a second step, in order to assess the Swiss consumption mix, the different production means of each country have been aggregated by the following categories: Nuclear, Fossil fuels, Renewable energies (EnR), Pumping storage and others. This choice has been made in order to lighten the results presentation, it has been decided to present the contribution with these macro-category segmentation. Indeed, the matrix-based approach enables to know, at each time step, the production means from each country that contribute to the Swiss consumer mix. In the current study, 122 productions means are represented (coal, oil, wind onshore, hydro, etc, for all the considered countries). Thus presenting the results for all of the production means appeared to be misleading. The numerical results per the defined macro categories are presented in Figure 9 and annex of chapter 4-a.

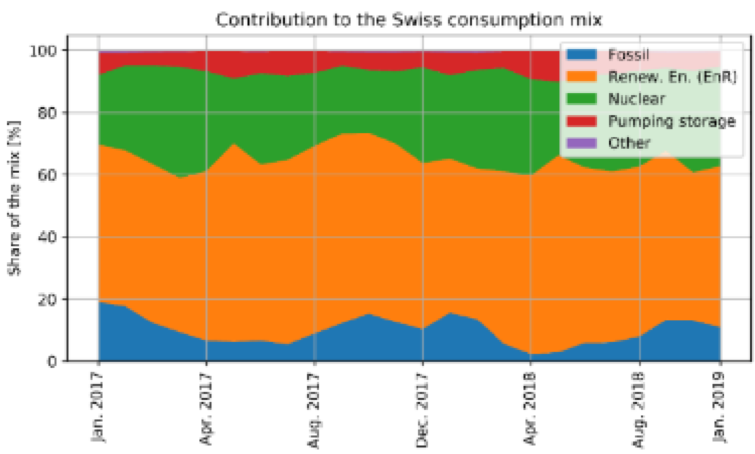

Figure 9: Contribution to the Swiss consumption mix per energy carriers categories.

Note: In this report, pumping storage refers to the electricity production from pumped hydro storage.

There is an increase of the imports from Germany (mostly relying on fossil fuels) in autumn and winter. According to the overall Swiss electricity consumption (see chapter 2), it corresponds to the periods when Switzerland has consumption peaks. Thereby, the fossil fuel-based electricity production share increases during these periods, i.e. from 6% on average in spring and summer to 13.8% during the other seasons. The overall fossil fuel contribution ranges from 2.3 to 19%, which confirms that the Swiss electricity mix (according to the EcoDynBat assumptions) is balanced with the fossil fuel production sources, i.e. the seasonal electricity peaks are covered by an increase of the fossil fuel energy sources in the production mix.

The nuclear share ranges from 20 to 35%. The higher shares of the nuclear energy occur in spring. The inter-annual variability (between 2017 and 2018) is also important and is related to the Swiss demand and production capacity. Indeed, since in 2017, the Swiss nuclear energy production was not sufficiently high, the average share of nuclear energy was lower (26.3%, including nuclear contribution from the neighboring countries among which 18% were out of Switzerland), compared to 2018 (30%, including nuclear contribution from the neighboring countries among which 22.7% were out of Switzerland).

The pumping storage contribution ranges from 4 to 10%, and the highest share occurs at the end of spring / early summer. Finally, the contribution of renewables ranges from 48 to 64% mostly from hydroelectricity, with peaks in spring.

Thereby, within the Swiss consumer mix, the energy contributions from the different countries vary, because of:

- The Swiss production means availability: if the Swiss production is reduced during a year, (such as 2017 with national nuclear power plants), it is necessary to increase the level of imports from the neighboring countries,
- The seasons: in autumn and winter, the Swiss consumer mix strongly relies on the imports, because of the national inability to meet the demand.

In general, the Swiss electricity balance is mostly covered by imports from Germany, which relies on fossil fuels for its electricity production. The imports from France are also significant in term of share (4 to 12 % depending of the time of year), but they are mostly related to nuclear energy. The dynamics observed in the Swiss consumer mix, thereby, will imply fluctuation in terms of environmental impacts. These fluctuations are presented below.

2.2 Influence of the time step on the mix

In this section, the environmental impacts of the Swiss consumer mix are presented for the four considered impact categories. For each one of them, the environmental impact profiles are displayed in figure 3 for the two considered years (2017 and 2018) and for the four considered time steps (Hourly, Daily, Monthly and annually), additional information can be found in the appendix. From the results, it can be seen that by diminishing the time resolution, from a daily to a yearly time step, the curve is smoothed and the peaks are reduced, for all the indicators. Looking at the climate change and the ES, the impacts in spring are lower than in autumn and winter. This seasonal variation is related to the increased imports from Germany during these months, since both impacts are mostly influenced by the fossil fuels and nuclear energy production means. The variability of the climate change and the ES impact is observed mainly on a monthly basis. In addition, for both the climate change and ES impact, significant intra-days peaks can be observed quite rarely (3% of the time). These peaks (observed on the hourly impact profile) are due to a sudden increase of imports, mostly from Germany. When these peaks occur, reactive production means (generally fossil fuel-based power plants) are switched on, which induces a large increase of the climate change impacts. For the ES and climate change impact categories, there are also intra-day peaks (see appendix). Nevertheless, these peaks, that occurs in the early morning and late afternoon, have smaller amplitudes than the seasonal amplitude (daily amplitude on average = 75 g CO_2 eq/kWh, monthly amplitude = 143 g CO_2 eq/kWh).

Looking at the NRE and RE impacts their trends show less variation than the climate change indicator. For the NRE, this trend is explained by the fact that the NRE unitary impacts of the nuclear and fossil-fuel based electricity are similar while their cumulated shares has a low fluctuation. Thus, even if in winter the imports are increased, the NRE impacts is less fluctuating than the climate change impact. The RE impact trend is reversed compared to the NRE impact, as they are linked and relate portion of the grid mix that is either from non-renewable or renewable energy sources. During the night when Switzerland imports nuclear energy from France, the RE portion of the Swiss grid mix decreases, and as such, so does the RE impact factor . Conversely, when the NRE impact decreases during the day (for example in the morning), the RE impact increases. In addition, the peaks occur throughout the year. Concerning the NRE and RE variability, the variability is of the same order of magnitude within a day and when considering a year unlike the climate change impact and the ES variability which is more pronounced on when considering the annual profile rather than the intra-day variation. The peaks of the NRE and RE impacts occur throughout the year, with only a limited seasonal effects related to the hydroelectricity production availability that increase during spring.

The time step influence is more important when choosing between the hourly and the daily resolution. However, between the daily and the yearly resolution, the fluctuation is less significant (see Figure 10 and Figure 11).

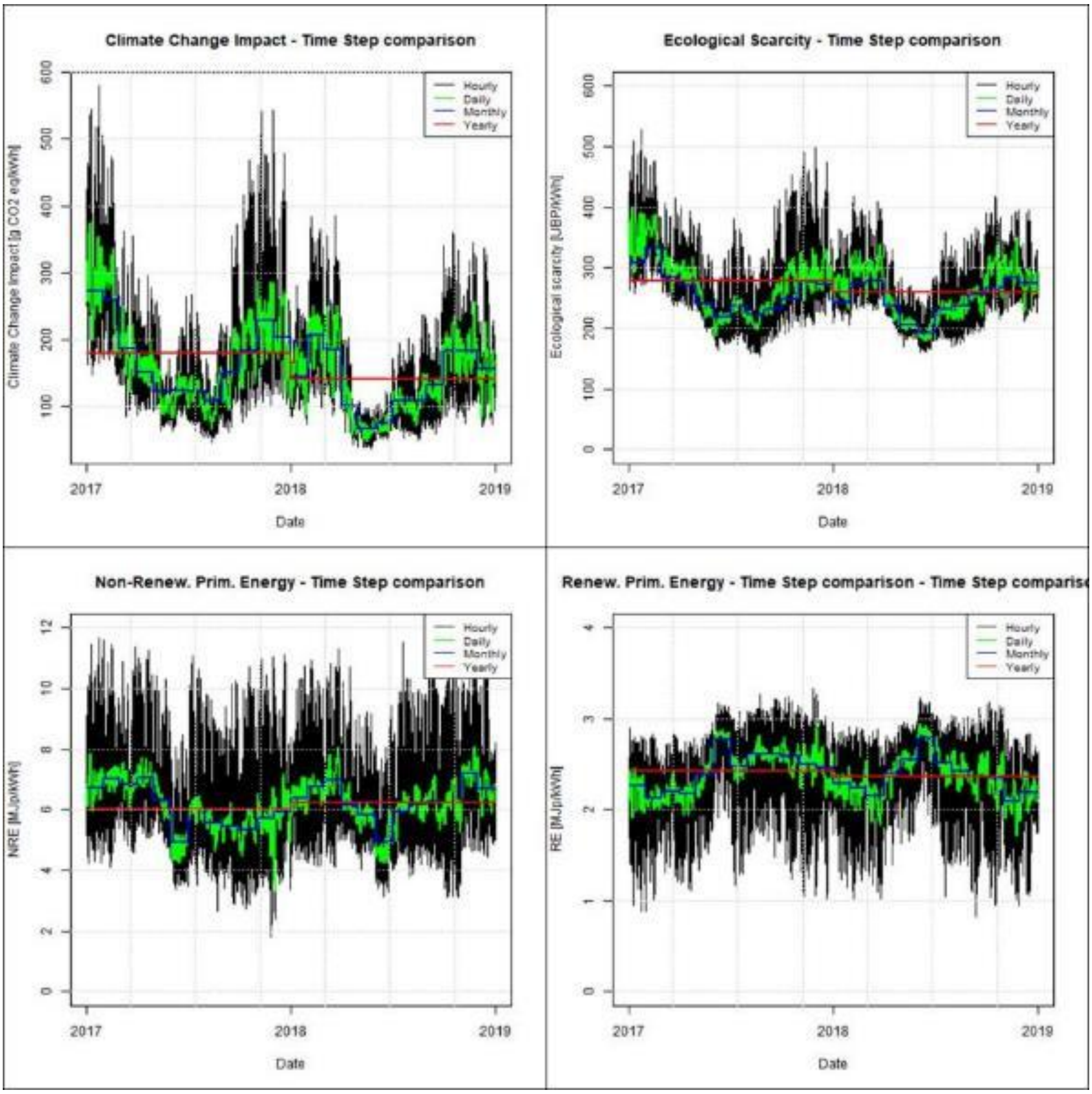

Figure 10: Impacts of the electricity mix, for the four studied time steps and indicators.

Figure 11 presents the variation of the impacts for the Swiss consumed electricity, for the different examined time steps. It cans be seen that for all the indicators, the range diminishes for smaller time step resolutions. The difference of the interquartile ranges, between the hourly and the annual time step, is a 70%, 32%, 18% and 13% for the climate change, the ES, the NRE and the RE, respectively. The results show that the climate change and the ES impacts are more influenced by the time step resolution than the primary energy indicators. The variability of the hourly impacts between the minimum and maximum values is 98%, 84% and 92%, for the climate change, the ES, the NRE and RE impacts, respectively. In addition, no significant differences can be found for the interquartile range and the median, between the hourly and daily time step, for the climate change and ES impacts. However, this is not the case for the NRE and RE impacts, concerning the interquartile range, for which there is a difference of 24% and 72%, respectively. However, looking only at the median value for the ES impacts, between the monthly and the daily time step, there is approximately a 15% difference. Thereby, considering the latter time step could lead to underestimation of the environmental impacts, for both the Swiss electricity mix and on building level, as well. As far as the other indicators are concerned, this difference is insignificant.

Thus, the ES and climate change impacts of the electricity demand in buildings can be affected, as soon as the demand varies throughout the year. As such, it can be expected that the fluctuating demand leads to higher climate change impacts, when considering hourly time step, instead of yearly time step. Conversely, a constant electricity demand (i.e a demand that would not fluctuate over the year and with a low intra-day variability) would not be affected by the choice of time-step.

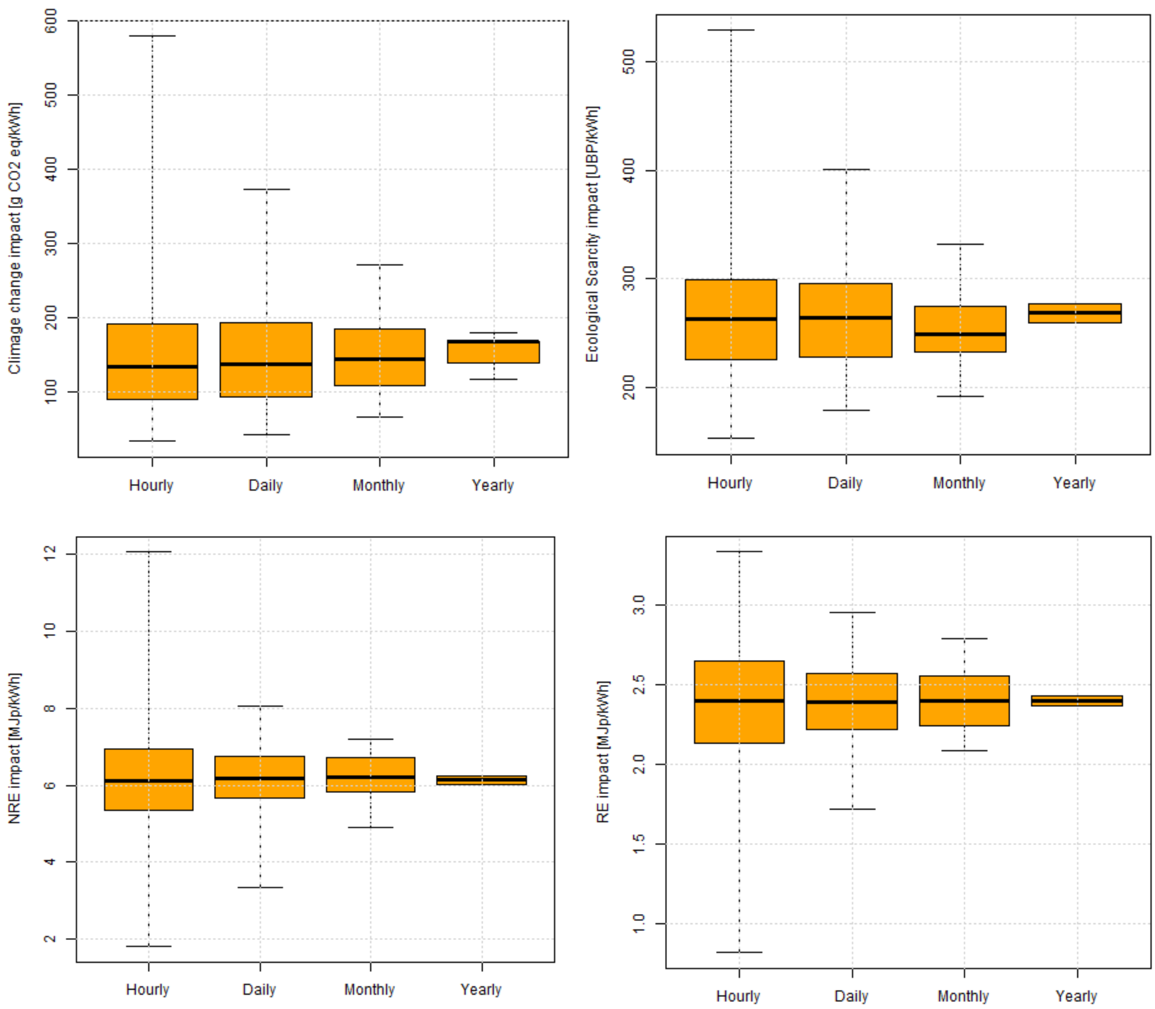

Figure 11: Boxplots of the impacts' variability, as a function of the time step.

2.3 Electricity mix per country and energy carrier

2.3.1 Electricity mix per country

Figure 12 presents the electricity mix per country, for all the studied indicators, under a monthly step. The main contributor of the Swiss electricity mix is Germany, which also has the highest CO_2 eq content. The French imports' share is also important, but normally has a low CO_2 eq content because of the large nuclear share of the French electricity production. In addition, the share of the electricity imported from Austria is relatively low and has a relatively small CO_2 eq content. Although the CZ is at the second order interaction level, its contribution is similar as the IT, FR and AT contributions, for the climate change. The other second order and higher levels (named as *'other'*) contributions have a small impact contribution, confirming that it is not necessary to include in the national Swiss grid mix calculation imports from more than the five neighboring countries in the EcoDynBat dataset. As far as the intra- and annual variation is concerned, it is a result of the high imports from Germany that are reduced during the summer. During winter, the peaks related to the imports are clearly visible, while in summer the climate change impact is less than 120 g CO_2 eq/kWh (e.g. for 2018). The inter-annual variation is linked to the fact that in 2018 the climate change has significantly decreased (23%), mostly due to the lower imports from Germany (19% in 2017 versus 16% in 2018).

The ES impacts are driven by the Swiss national production, followed by the German and finally French imports. This observation confirms that both nuclear and fossil fuel production means are the most influencing factors regarding this impact category. The German contributions are the main responsible for the monthly variations (higher imports imply higher impacts). The French imports are mostly responsible for the intraday variation (nuclear imports during the night / early morning). The other countries have only a minor influence on the ES impacts. In addition, the intra- and inter–annual variations, observed on the ES impacts, are linked to the imports from Germany, as already described.

As far as the NRE impacts are concerned, the first contributor is the Swiss national nuclear energy. The German imports are the second contributor; since the German electricity production mix is composed of a large share of fossil fuel but also a significant share of nuclear electricity (13.4% on an annual average). The contributions of the exchanging countries are however varying depending of the period of the year. Thus, the German contribution increases in autumn and winter, because of the increased energy demand, during this period. The French mix is the third contributor, because of the high share of nuclear energy. Its contribution, except for the spring period, is relatively constant over the years. AT, CZ, IT and the other countries do not contribute significantly to the overall NRE impacts. The intra – annual variation of the NRE is observed in both years and specifically in May, when there is a decrease of the impacts. This NRE negative peak corresponds to an important increase of the renewable electricity production, related to the increase of the hydroelectricity production (see next section for the production mix breakdown). This observation corresponds to the period when snow melts, leading to the increase of the hydroelectricity production.

Finally, regarding the RE impacts, the highest contribution comes from the Swiss national production. The Swiss contribution increases in April/May and, in general, is more important in spring/summer. This observation, regarding the RE impact, has to be related to the production mix (see next section), which shows an increase of the Swiss indigenous production during this period. This increase is mostly related to the hydroelectricity production, which is more important at these periods, because of the snowmelt. Germany is the second contributor and even though it heavily relies on fossil fuels, it has also a large share of renewables (solar + wind). In autumn, the wind electricity production in Germany is important (23% in autumn compared to 18% on average for the other seasons) and when Switzerland imports electricity from Germany, it implies a significant RE contribution due to these imports. Austria is the third contributor. The impact contribution is slightly decreased in spring because Switzerland imports less. Nevertheless, looking at the general trend, the Austrian contribution is relatively constant over time. The French contribution is quite low, while its import share is more significant than e.g. Austria. This is related to the French mix, which strongly relies on nuclear energy. Czech Republic (via DE and AT) and Italy have only a minor contribution to the Swiss consumed electricity RE impacts.

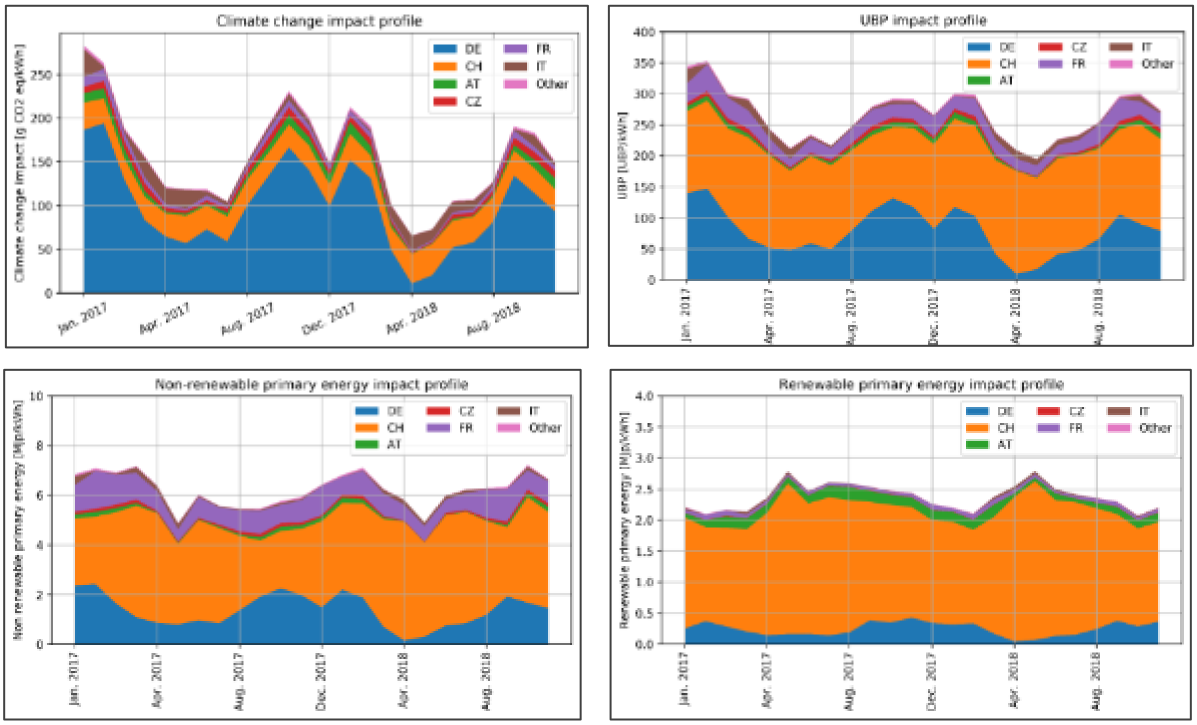

Figure 12: Monthly electricity impact profile per country

Figure 13 presents the impacts of the electricity mix, as a function of the import shares from the main contributors, i.e. DE, FR and national production, for all the four studied indicators. Looking at the climate change impact, the higher the Swiss production share, the lower is the impact. On the contrary, the higher the imports from Germany, the higher is the climate change impact. The trend is almost linear for an import share below 20%. For values higher than 20% the trend is more scattered because of the increased share of the contributions from other countries. By performing a linear regression to the CO_2 eq content of the Swiss consumed electricity, as a function of the German imports, it appears that for each point of additional percentage of imports, the impact increases by 6.3 g CO_2 eq/kWh. For France, there is no clear trend, since the impact of the imported French electricity is low, i.e. there is no clear correlation between the share of imported electricity from France and the impact of the Swiss consumed electricity, because France relies mostly on nuclear energy.

The results for the ES impact confirm the important influence of the Swiss production and German imports, on the electricity mix. There is a high correlation regarding the ES impact and the German import share, i.e. the higher the German imports, the higher the ES impact. Furthermore, the Swiss national production has a high correlation with the ES impact, as well; the higher the national production share, the lower the ES impacts, since when the production increases, the share of the renewable sources to the mix is increased, as well. Finally, as far as the French are concerned, there is no clear trend, but increasing the French imports seems to increase the ES impacts.

As far as the NRE impacts are concerned, the correlations are less pronounced compared to climate change and ES indicators. It seems that the higher the French imports, the higher are the NRE impacts of the Swiss consumed electricity. This trend is also observed, concerning the German imports but in a smaller extent. In addition, the higher the national Swiss production, the lower are the NRE impacts. Indeed, the higher share of Swiss production corresponds to a higher hydroelectricity production and thus the impacts are decreased. It should be also noticed that the general trend of the NRE impacts is scattered. Thus, these observations only provide tendencies which are less clear than for the climate change and ES indicator.

Regarding the RE impacts, similarly to the NRE impacts, the points are scattered. It seems that the higher the share of national production, the higher is the RE impact. Indeed, the Swiss production mix (see chapter 2) strongly relies on hydroelectricity production and its increased share is generally related to a higher production of hydroelectricity (because of snowmelt in spring). Thereby RE impacts are largely driven by the Swiss indigenous production. Both Germany and France have an identical trend that is contrary to Switzerland.. Higher contributions from these two countries imply lower RE impact. The two countries (DE, FR) indeed rely on nuclear and fossil (respectively), which increases the NRE impact while decreasing the RE impact.

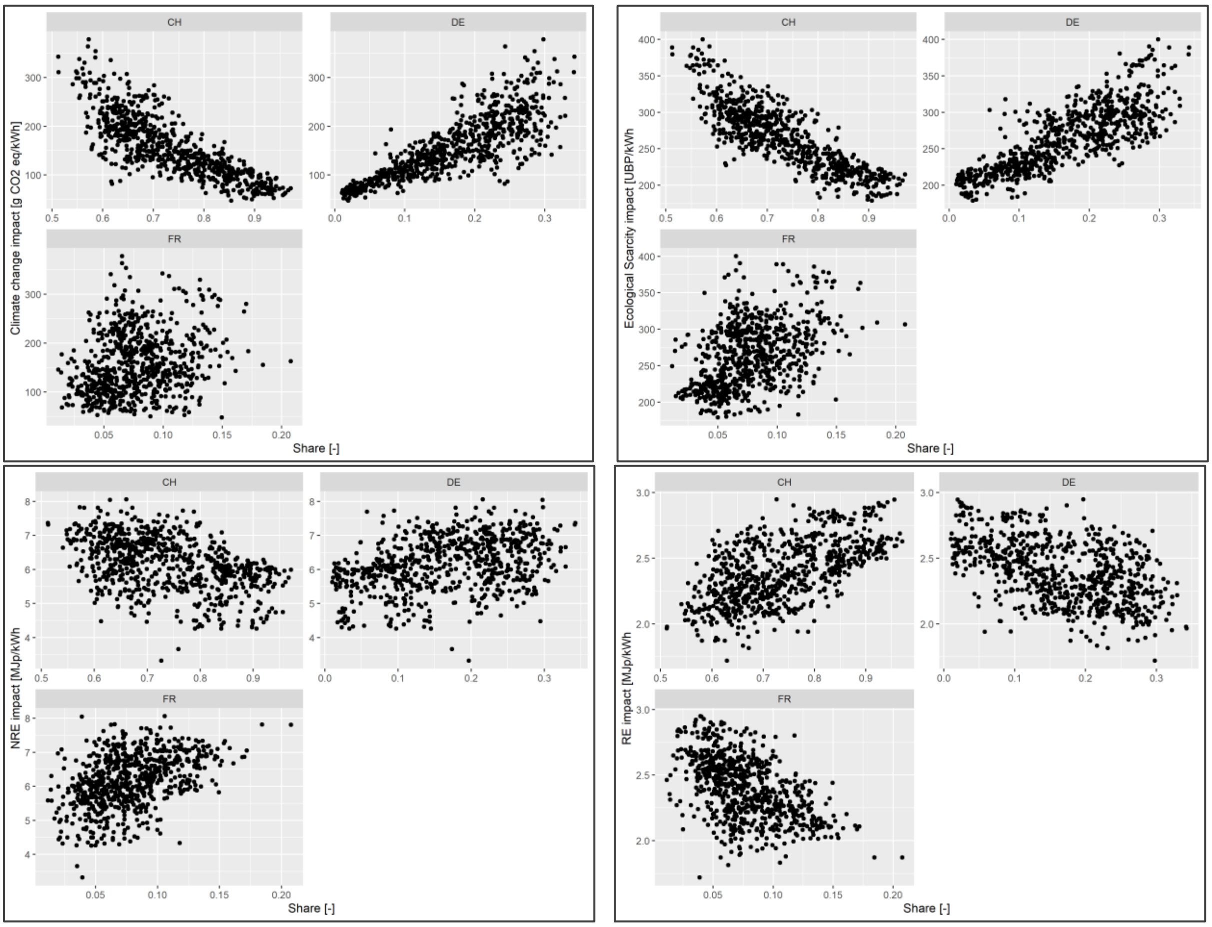

Figure 13: Swiss electricity mix impact as a function of the importing shares for DE and FR and the national production share, for all the four indicators.

2.3.2 Electricity mix per production means

Figure 14 presents the impact profiles of the electricity mix for all the studied indicators, per energy carrier. The fossil fuel-based electricity production means represent, on an annual basis, an average of 74% of the Swiss electricity mix climate change impact. This contribution is exclusively related to imports. The nuclear energy represents 2.7% of the total impact because of its low CO_2 eq content per kWh. The renewable sources (including hydro, solar, biomass, etc.) represent 12.5% of the total impact. This impact is mostly related to the biomass and the photovoltaic electricity production. Indeed, while these production means have a small contribution in term of mix, they have higher impacts than other renewable sources. The pumping storage represents 11% of the total impact. In EcoDynBat, we used as impact per kWh for pumping storage the average value of the ecoinvent database. Because of its relative important contribution, it could be necessary, in a further project, to calculate the impact of the pumping storage electricity considering the time when the water is stored (implying a specific impact relating to the moment when these facilities are operating rather than a constant value).When looking specifically to the climate change impacts of the Swiss mix, it appears that the German imports are the main contributors. When there are import peaks, especially in winter, then the climate change impact is increased. The other countries' imports play a minor role compared to German imports. In spring and summer when Switzerland imports are reduced, the climate change impact of the Swiss consumed electricity is very low, confirming that the Swiss production means have a low CO_2 eq intensity. In addition, it appears that there are significant impact variations from 67 g CO_2 eq/kWh in May 2018 to 271 g CO_2 eq/kWh in January 2017. These fluctuations occur both at inter and intra-annually levels. This suggest that both aspects should probably be considered when aiming at assessing the environmental impacts of the electricity consumption in Swiss buildings since such consumption will also vary in these two timeframes.

Looking at the ES impacts by energy carrier, it is observed that the main contribution of the impacts come from the fossil fuels, while the nuclear, the renewable and the pumping storage follow. There is a seasonal variation for the fossil fuel, because of the seasonal imports from DE, while the nuclear share is relatively constant (monthly time step resolution). The renewable share of the ES impacts has a relatively stable trend, since it is mostly related to the biomass electricity production. Finally, the pumping storage shows a small variation during the examined years, since electricity from the grid is used (based on the ecoinvent database, i.e with impacts constant over the hours) to pump and store the water. The general trend of the ES indicator, in terms of the influence of the time step, lies between the high seasonal fluctuation of the climate change trend and the low seasonal fluctuation of the NRE impacts. The intraday fluctuation of the ES impacts derives from the nuclear energy, while the seasonal one, lies on the fossil fuel energy imports. The reason why the seasonal trend of the ES impacts is less pronounced than that of the climate change, comes from the fact that the ES is influenced by both the nuclear and the fossil fuel energy production. Conversely, the climate change indicator is mostly influenced by the fossil fuel energy carriers.

Regarding, the NRE, the main contributor is the nuclear energy (coming from FR, DE, CH). The second contributor is the fossil-fuel energy carrier, while the third comes from the pumping storage (STEP, French acronym for "Station de Turbinage Et de Pompage). The unitary impacts (impact per kWh of the production means) for the fossil fuel-based electricity production are comparable to the unitary impact of the nuclear electricity production (see chapter 3 annex for the details). Since a significant share of the Swiss national production comes from nuclear energy, the Swiss nuclear energy is thereby the main contributor. The lower impact in May for both examined years are related to an important decrease of the nuclear share and consequently an increase of the renewable energy production (mainly Swiss hydroelectricity), which has a low NRE impact. The fossil fuel contribution follows the seasonal trend of the German imports, thereby, its contribution is higher in autumn and winter. Finally, the STEP impact is constant over the two years, because its share is also constant. In addition, it appears that the NRE impact of the Swiss mix has a lower fluctuation over time when compared to the climate change profile. As a conclusion regarding the NRE impact of the Swiss consumed electricity, it appears that the significant fluctuations mainly occur at the hourly time resolution. The peaks are related to an increase of the French imports, based mostly on nuclear energy. Thereby, at the building level, the specific time of day when there is an electricity demand could influence the NRE impacts when considering various time steps. When performing the environmental assessment, using the NRE impact for a building, there should not be significant differences on the result, if the daily or the yearly time step is used, since no important fluctuation of the NRE impacts for the Swiss consumed electricity are found for these time resolutions. Thus, it is highly plausible that the time step influence will be low regarding the impact of the building electricity demand, as long as there is no consumption peak at night.

For the RE impact, which measures the renewable amount of the electricity production, its highest share comes from the hydroelectric energy production and it covers more than 50% of the RE impacts. The same peaks, as the ones observed in Figure 12, are observed in May and in summer, showing the time that the Swiss hydroelectric production increases, which consequently decreases the imports. The pumping storage is the second contributor, since it uses electricity from the grid to pump the water (in the EcoDynBat project, the average Swiss electricity impact from ecoinvent is considered). There are small seasonal fluctuations but rather intraday fluctuations, contrary to the NRE impact. In addition, in general, the lower the imports share, the higher are the RE impacts.

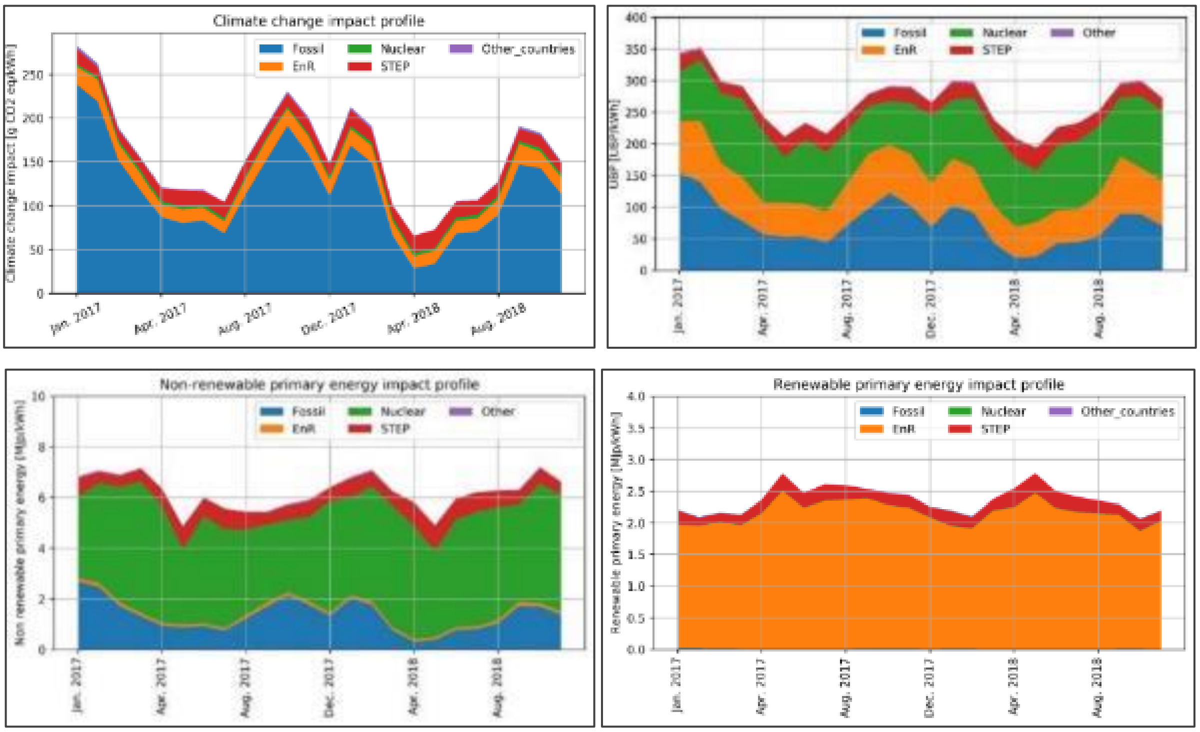

Figure 14: Impact profiles per energy carrier, for all the indicators.

2.4 Summary table of the Swiss electricity mix

The four impact categories, considered within the EcoDynBat project, describe the Swiss grid electricity impacts from different perspectives. Considering all four impact categories is relevant, when performing the environmental assessment of the grid electricity consumption on a building level, since all the impact categories provide an outlook of the environmental impacts from electricity usage in buildings, while this procedure gives adequate information, about the time step influence, as well. In addition, these impact categories, such as presented in the WP3, are used for the Swiss framework regarding the building environmental impact calculation (for example KBOB) Depending of the impact category, the general trend of the grid electricity varies, i.e. mostly seasonal, intraday or both. The impacts are clearly influenced by the variation of the imports and the Swiss domestic production shares. It is thereby worthwhile to consider them. For the climate change impact category, the impacts are influenced mainly by the German imports, which are mainly based on fossil fuel energy production, since this impact category is sensitive to the latter. The NRE impact category is more sensitive to the nuclear energy production and thus is mostly influenced by the Swiss domestic nuclear production. Finally, the ecological scarcity indicator lies between the climate change and the NRE indicators, since it measures both the fossil fuels and nuclear energy production. Table 4 summarizes the main conclusions of the aforementioned results of the previous section.

Table 4 : Summary table of the results for the electricity mix.

	Climate change	Non-Renewable primary energy	Renewable primary energy	Ecological scarcity
Fluctuation range	10th percentile = 76 g CO_2 eq/kWh (-48% compared to median) Median = 145 g CO_2 eq/kWh 90th percentile = 255 g CO_2 eq/kWh (+76% compared to median)	10th percentile = 4.72 MJp/kWh (-23% compared to median) Median = 6.13 MJp/kWh 90th percentile = 7.77 MJp/kWh (+27% compared to median)	10th percentile = 1.91 MJp/kWh (-20% compared to median) Median = 2.40 MJp/kWh 90th percentile = 2.83 MJp/kWh (+18% compared to median)	10th percentile = 201 UBP/kWh (-24% compared to median) Median = 263 UBP/kWh 90th percentile = 334 UBP/kWh (+27% compared to median)
Observation	- Large seasonal variation - Intraday variation less pronounced than seasonal variations - Important inter-annual variation - Peaks also occurs when Swiss demand is high	- Important intraday fluctuation related to an increase of imports from France btw. 4 to 7 am - Intra-day fluctuation at the same order of magnitude than seasonal variation - Less fluctuation than climate change	- Low seasonal fluctuation, small peaks in May because of an increase of the Swiss hydroelectric production (snowmelt) - Intraday fluctuation: increase during the day decrease at night (when French imports increase) - Less fluctuation than climate change	- Seasonal and intraday variations but higher amplitude for seasonal variations - Seasonal variation related to increase of imports from Germany mostly (fossil fuel contribution) - Intraday fluctuation related to increase of imports from France at night/early morning
Parameter of influence for variations	- German Imports are the key element that influence the climate change impacts	- National nuclear production and imports from France (mostly nuclear) are key - Fossil fuel also influence the impact because the NRE impact of both fossil fuel and nuclear technologies are close	- Swiss hydroelectricity production is the biggest contributor - Share of imported electricity is influent. The higher the share of the Swiss production is, the lower the impacts are	- Influence of nuclear + fossil fuels - Imports are thus significant but also Swiss production share - Renewables play also a role because of biomass

	Climate change	Non-Renewable primary energy	Renewable primary energy	Ecological scarcity
Time step influence	- Because of the seasonal variability, considering low resolution time step (annual) would lead to underestimation of the environmental impacts	- Since the peaks are occurring during a day, the aggregation might decrease representativeness when switching from hourly to daily data. Then lowering the resolution (monthly, yearly) have no significant influence	- Same as NRE	- The time step choice might be important, in a smaller extend than climate change but higher extend that the NRE. In between situation. Thus ES has a moderate sensitivity to both intra-day and seasonal fluctuations
Relation with the building electricity demand	- If the building electricity demand is seasonal (for example space heat covered by heat pump), the impacts could be influenced by the time step choice	- If the building electricity demand has an important consumption btw 4 and 7am, the impacts might be influenced by the time step choice (only btw. Hourly time step and the other). Nevertheless, the influence should remain low	- Possible influence rather small and strongly related to the building electricity demand profile. If the demand is high during the working hours, the impact could be influenced by the time step choice (only btw. Hourly time step and the other).	- High seasonality in the demand could lead to difference in impact as a function of the time step choice - If big demand btw 4 and 7am, the time step could be influent - The influence should be smaller than for climate change

	Climate change	Non-Renewable primary energy	Renewable primary energy	Ecological scarcity
Comments	- The climate change impact is very sensitive to the seasonality. Indeed, the Swiss national production is low CO_2 eq intensive thereby, a small amount of imports based on fossil fuel technology will greatly modify the impacts - The inter-annual variability is important and related to the production means availability. Thereby, from one year to another, there is a large uncertainty regarding the climate change impact of the Swiss consumed electricity	- The NRE category is less sensitive to the production mean fluctuation than the climate change impact. This is related to the fact that the Swiss national production rely importantly on nuclear electricity with already a quite important NRE impact. Nevertheless, very specific variations are observed mostly when the share of nuclear imports (from France) increase - The inter-annual variability is low. It could however change in the near future when the Swiss nuclear production will be switched off.	- The RE impact category as a small sensitivity to the fluctuation. - It could evolve when the share of renewable electricity production means will increase in the future	- This indicator appears to be an intermediate between NRE and climate change impact categories

3. Comparison of the Ecodynbat electricity impacts with other sources

This section presents the comparison of the EcoDynBat impact results for the Swiss grid electricity impacts, to the two main Swiss sources of information that are currently used in practice i.e. the KBOB (2016) database which relies on the 2011 Swiss mix and the ecoinvent V 3.4 database which relies on the 2014 Swiss mix. The mix shares are given in the Table 5. The results are displayed for the four considered indicators in Figure 15, on an annual basis, since this is the only available time step resolution in ecoinvent and KBOB. Figure 16 shows the results of the four indicators on a relative scale for different energy sources. For each indicator, the maximum impact from a source is set at 100% and the relative results of the other sources are calculated accordingly. The absolute values are also displayed.

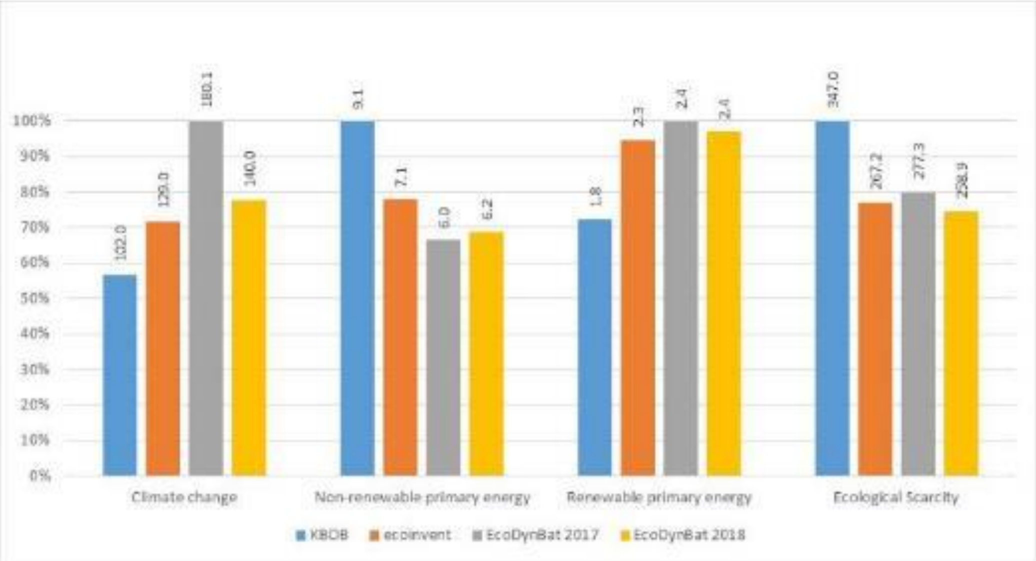

Figure 15: Comparison of impacts from EcoDynBat, KBOB and ecoinvent.

Compared to the KBOB, the EcoDynBat results are higher for two of the four considered categories:

- For the climate change impact category, the EcoDynBat results are significantly higher than the KBOB results, approximately 180% for 2017 and 140% for 2018. Since, the climate change impact category is sensitive to the inter-annual variability, the difference between KBOB and the EcoDynBat results for 2017 are more important than for the year 2018. It has to be reminded here that KBOB impacts are calculated for the Swiss consumption mix shares of 2011. Not considering the same year for the mix affects the difference, however, as it is presented right below, this is not the main reason of the difference between KBOB and Ecodynbat results
- For the NRE category, the EcoDynBat results are found to be lower than KBOB results, approximately 34%. This difference is valid for both examined years, since the NRE is not sensitive to the inter-annual fluctuation of the energy production.
- For the RE category, the results of EcoDynBat are higher than that of the KBOB database by about 33%.
- For the ES category, the KBOB results are about 25% higher than that of the EcoDynBat results.

The ecoinvent and EcoDynBat results comparison can be summarized as follow:

- For the climate change category, the EcoDynBat results are approximately 40% higher than the ecoinvent results, for 2017. The difference between ecoinvent and the EcoDynBat results for 2017 are more important than for the year 2018, since the climate change impact category is sensitive to inter-annual fluctuations.
- For the NRE category, the EcoDynBat and ecoinvent results are comparable, i.e. the former are 15% less than the ecoinvent results.
- For the RE category, the EcoDynBat results are similar to the ecoinvent results, i.e. difference approximately 4%.
- For the ES category, the ecoinvent results are again in the same range as the EcoDynBat data, i.e. 4% difference for 2017.

There are mainly three reasons that explain the observed differences:

1- The unitary impacts of the electricity production means (impact per kWh of each type of electricity source) are different ofbetween KBOB and EcoDynBat (or ecoinvent v3.4). In KBOB, the ecoinvent V2.2+ database is used. In the EcoDynBat project a mapping procedure was developed, in order to calculate the environmental impact of the different sources of the electricity production, which was based to the ENTSO-E data (see chapters 2 and 3). This mapping procedure relies on ecoinvent V3.4. However, this procedure is less detailed that the ecoinvent database, since ENTSO-E does not detail the production means as much as ecoinvent. It has to be noticed that the mapping procedure has been set according to the ecoinvent production mix shares, thereby, both ecoinvent and EcoDynBat impact values for the various production means are equivalent.

2- The Swiss electricity mix is modelled for different years, i.e. 2011 for KBOB, 2014 for ecoinvent and 2017 and 2018 for EcoDynBat. Thereby, the share of the production energy carriers are different.

3- The way the electricity flows are accounted for varies among EcoDynBat, KBOB, and ecoinvent v3.4. EcoDynBat relies solely on physical flows and thus it measures the real environmental impact of the Swiss grid electricity. At each time step, the Swiss electricity mix is a function of the domestic energy production (nuclear, hydro or renewable energy) and the cross border energy flows. On the contrary, KBOB and ecoinvent (for Switzerland) rely on commercial exchanges including the certificate of origin, which are only available on an annual level. The difference between ecoinvent and KBOB lies in the way to fill the gap between the certificate of origin data and the Swiss national consumption. KBOB fill the gap with a share of “unknown electricity”. The impact of this electricity is taken as the average European mix. Ecoinvent fill the gap with the exchange flows between Switzerland and its neighboring countries.

The relative differences between the KBOB and EcoDynBat for the environmental impacts of the Swiss domestic production of the different energy carriers, are displayed in Figure 16. The same mapping procedure has been used for the KBOB dataset (ecoinvent V2.2+), as for the EcoDynBat dataset. Each energy carrier has been evaluated using the KBOB and the EcoDynBat energy carrier unitary impact. When the results are positive, it means that the EcoDynBat unitary impacts are higher than the KBOB dataset. From Figure 16, it appears that using the EcoDynBat dataset results in higher impacts for the different the energy carriers, except for nuclear energy. The absolute relative differences are 26% for ES, 3.5% for RE, 11.4% for NRE and 17% for the climate change indicator.

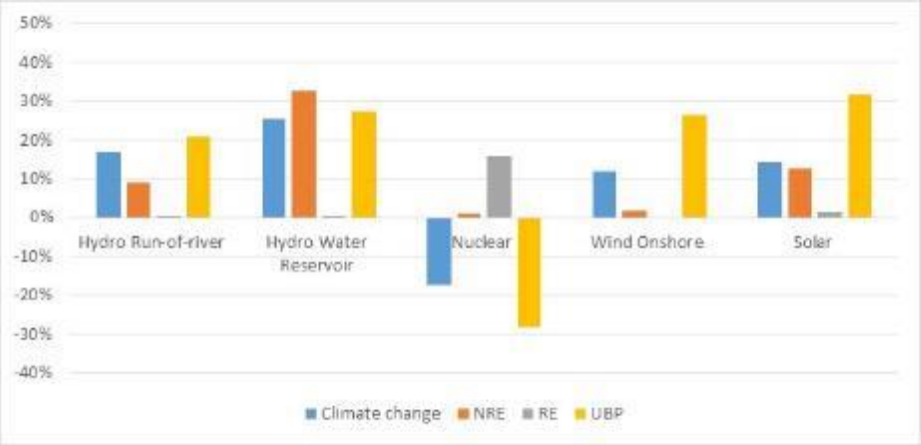

Figure 16: Relative difference between the KBOB dataset and EcoDynBat dataset for impacts of different energy carriers.

In order to totally understand the influence of the dataset for unitary impacts, the EcoDynBat calculation procedure has been applied by replacing the initial unitary impacts (based on ecoinvent data V3.4, see chapter 2 and 3 for details) by the values from the KBOB (based on ecoinvent V2.2+ unitary impacts). The result for the annual time step resolution are presented in Figure 17. From these results, it can be concluded that:

- Regarding the climate change impact, using the KBOB unitary data results in smaller impacts than when using the ecoinvent unitary data, i.e. 8.5% for 2017 and 3.7% for 2018.
- Regarding the NRE, using the KBOB unitary data results in smaller impacts than when using the ecoinvent unitary data, i.e. 4.8% for 2017and 5% for 2018.
- Regarding the RE, using the KBOB unitary data results in insignificant differences than using the ecoinvent data, i.e., 1.5% for 2017 and 0.5% for 2018.
- Regarding the ES impact, using the KBOB unitary data results in higher impacts than when using the ecoinvent unitary data i.e. 2.8% for 2017 and 9.2% for 2018.

The observed influence of the unitary impacts from different database is therefore small. The ES impact category is the only category, for which the nuclear unitary impacts are lower for the EcoDynBat initial impact data than to the KBOB data. The ES impact of the Swiss consumed electricity according to the EcoDynBat method is higher when using the KBOB unitary impact for the calculation. Thereby, it seems that the main reason of the overall differences presented in the Table 5 have to be found in the production mix differences (i.e. years of data gathering and modelling choices).

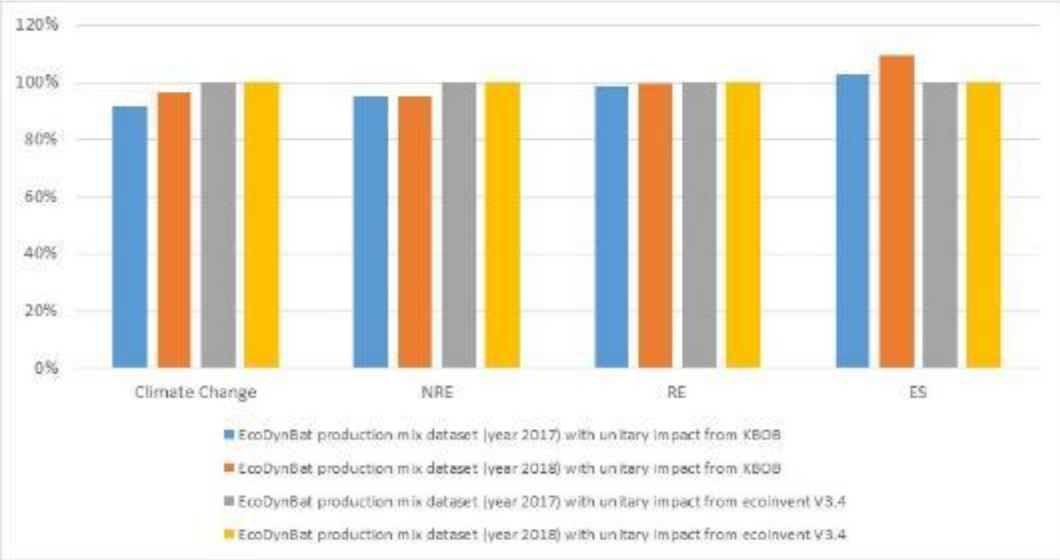

Figure 17: Comparison of annual electricity impacts when using a mapping file base on ecoinvent and on KBOB data for the unitary impacts

Regarding the production electricity mix, the values from the KBOB and ecoinvent have been extracted and compared with the EcoDynBat annual results, see Table 5.

Table 5: Comparison of the EcoDynBat impact results, ecoinvent and KBOB results

		KBOB (production share for 2011)	Ecoinvent (production share for 2014)	2017	2018
CH	***Swiss prod***	***61.6%***	***60.5%***	***68.3%***	***72.1%***
	Renewable	**24.2%**	*37.4%*	**50.9%**	**50.3%**
	Hydro	26.1%	35.8%	40.8%	40.9%
	Other renewables	0.8%	1.7%	10.1%	9.4%
	Non-renewable	**37.4%**	**23.0%**	**17.4%**	**21.8%**
	Nuclear	37.2%	23.0%	17.4%	21.8%
	Fossil	0.2%	0.0%	0.0%	0.0%
Imports	***Imports***	***38.3%***	***39.5%***	***31.4%***	***27.5%***
	Renewable	**10.8%**	**15.4%**	**11.5%**	**10.5%**
	Hydro	10.1%	11.6%	3.7%	3.4%
	Other renewables	0.7%	3.8%	7.8%	7.1%
	Non-renewable	**13.6%**	**22.7%**	**19.9%**	**16.9%**
	Nuclear	11.6%	14.0%	8.1%	7.5%
	Fossil	2.1%	8.7%	11.9%	9.4%
	Not identified	**13.9%**	**1.4%**	**0%**	**0%**

Since the years for the calculation of the Swiss electricity mix are different and the flows are either physical (EcoDynBat) or virtual (based on certificate of origin), the shares are consequently different.

Ideally, updating annually the environmental impact of the KBOB would be of interest. Considering this non updated situation, the contribution of the Swiss domestic production is higher for the EcoDynBat dataset compared to the KBOB (year 2011) and the ecoinvent (year 2014). The renewable production share is also higher for the EcoDynBat dataset. One of the main reasons for this difference derives, in the so called *"residue"* approach, used in the EcoDynBat project, in order to cover the difference between the ENTSO-E dataset and the national production statistics (see chapter 2 for more details, regarding the residue definition). The non-renewable share of the Swiss domestic production is coherent between the EcoDynBat data and the ecoinvent data. The KBOB data present a more important share of non-renewable energy production, especially because of the higher nuclear production share.

The higher contribution of the Swiss national production to the Swiss electricity mix should inevitably lead to smaller impacts, at least for the climate change indicator. Nevertheless, the EcoDynBat results are significantly higher than the KBOB for this impact category. For the climate change impact category, the difference can be explained by the import shares. Indeed, the Swiss consumed electricity, as it has already mentioned, is strongly dependent to the imports. While the imports share is lower for EcoDynBat compared to KBOB and ecoinvent, the non-renewable share and especially the fossil fuel share of the imports are significantly higher for EcoDynBat. This difference is explained by the physical flow approach that has been applied in the EcoDynBat project. Indeed, within this project, at each time step, the physical flows of the different energy carriers, crossing the border and for all considered countries (CH, AT, DE, IT, FR, CZ) have been taken into consideration.

In ecoinvent and KBOB, the import shares rely on commercial or economical flows, between the countries. This approach relay of the energy bonds that are annually purchased by the ESCOs. Thus, ESCOS purchase on annual basis renewable energy certificates. However, the certificate approach is not valid on hourly basis since the time dimension is not embedded into the purchase mechanism. Thereby, based on this approach, which can be applied only on an annual basis, the imports can be apportioned to specific energy carriers. For example, in the ecoinvent dataset, 6.3% of the Swiss electricity mix related to imports are attributed as hydro-electricity coming from France, 3% as nuclear electricity also from France, 0.6% as wind energy from Germany and 0.3% as natural gas electricity also from Germany. Then, the residual imports are attributed as imports from AT, DE, IT, FR, considering the national production mixes of these countries and imports from other countries, as well. In this way, the share of the different energy carriers that are included in the imports to Switzerland significantly changes. It is worth to notice that this economical approach is applied by ecoinvent (V 3.4) only for the Swiss consumed electricity. For the other countries, the electricity mixes are based on physical flows.

A similar commercial flow approach is applied to the KBOB database. However, one of the differences between the KBOB and ecoinvent for the Swiss consumed electricity derives from the fact that in KBOB a part of the imported flows cannot be apportioned, by using the commercial approach and thus a residual share (13.9% of the Swiss consumed electricity) is named as unknown. This "unknown" electricity is set to have an impact that corresponds to the average European electricity mix. This average mix has a significant part of fossil fuel production, but also renewable and nuclear energy. Thus, the final impact of the imports are lower for the climate change category in the KBOB database than in the EcoDynBat project.

It should be noted though, that the fact that ecoinvent, KBOB and EcoDynBat do not consider the same year for the Swiss consumed electricity mix, partially explains the observed differences. If we could use the 2011 or 2014 data with the physical EcoDynBat framework we would probably end up with much higher values. It worth to mention that changes between years has reduced the differences between EcoDynBat and KBOB or ecoinvent v3.4. The physical flow method used to calculate the imports is the second very important aspect that explain the differences. Considering certificate of origins make sense when performing environmental accounting but it cannot be applied so far for higher time resolutions e.g. hourly. On the contrary, the physical flow approach represents the impacts of the electricity that is consumed at each moment in Switzerland without purchased certified electricity. In the EcoDynBat method, the certified electricity is not considered in the impacts of the electricity but is recognized as the consumer's willingness to participate in the development of renewable electricity production systems, from which the whole community can benefit.

Nevertheless, even if the KBOB and ecoinvent databases do not use the same approach to account for the impacts of the electricity mix, it was estimated necessary in the EcoDynBat project to compare the obtained results with these sources, since they are the two principal used and recognized sources in Switzerland for the environmental impact calculation of the Swiss consumed electricity. This comparison confirms the general trend of the environmental impact for the consumed electricity in Switzerland, which has a low CO_2 eq intensity compared to other European countries and has a significant renewable and nuclear share, which imply a significant renewable and non-renewable primary energy consumption. It also confirms that the impacts of the Swiss consumed electricity is highly dependent of the imports which is less the case for other countries (Germany, France, etc.).

4. Environmental impacts of case studies

4.1. Introduction

This section presents the environmental impacts from energy uses in different buildings (building energy consumption impact), which is evaluated with a DLCA approach for different case studies. At first, the energy consumption profiles and the total environmental impacts of the buildings are presented (chapter 4.2). The analysis, concerning the influence of the time step on the impacts follows (chapter 4.3), as well as the influence of the different technical systems on the environmental impacts (chapter 4.3.3 and 4.5).

4.2. Description of case studies

Six buildings located in the Swiss territory are analyzed. The first four case studies correspond to Single-Family Houses (SFHs) and they are located in the broader district of the Basel Canton. The fifth case study represents a Multi-Family House (MFH) located in the canton of Vaud, while the sixth one corresponds to an office building located in the canton of Geneva. The Köppen-Geiger system classifies the climate of these regions as Cfb [1], i.e. oceanic climate, *"characterized by equable climates with few extremes of temperature and ample precipitation in all months"*[2]. The case studies have different years of construction and present different energy performance levels. Table 6 summarizes the key characteristics of the case studies.

Table 6: Technical characteristics of the case studies.

	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
Building Type	SFH	SFH	SFH	SFH	MFH	Office
ERA [m2]	247	273	149	130	2663	14'195
onstruction year	1975	2000	2000	1987	2013	2013
ating system and DHW	A-W HP*	A-W HP	A-W HP	A-W HP	istrict heating based on Gas cogeneration	A-W HP
PV size [kWp]	10 (installed in 2012)	.7 (installed in 2013)	.4 (installed in 2013)	.6 (installed in 2014)	No	230

* A-W HP = Air-Water Heat Pump

A measurement campaign was set for all case studies, in order to collect the important information, of the energy consumption thein se buildings. More information about the details of the measurements can be found in Annex 4.3.

Figure 18 presents the electricity consumption (electricity supplied from the grid) and the PV production, under a daily time step, for the different domestic uses, i.e. DHW, space heating (for the heat pump) and the other domestic uses. The heat pump electricity consumption has a seasonal profile for these four case studies. The electricity for the DHW and the other domestic uses is relatively stable intra- and inter- annually, for all the case studies, except for the second case study, for which a seasonal trend is observed for the DHW needs (no clear explanations were found for this observation). The seasonality of the PV power production and consumption is evident, with low electricity production during winter, while the opposite trend is observed during the summer months. The PV power varies between zero to three kW per day, for this region and the specific installed PV power, while the small differences among the case studies derive from the different installed PV power, (between 6.6 and 10.7 kWp). Annex 4.3 presents in detail the shares of the different energy uses, as well as the part of the produced electricity that it is consumed on-site or sent back to the grid.

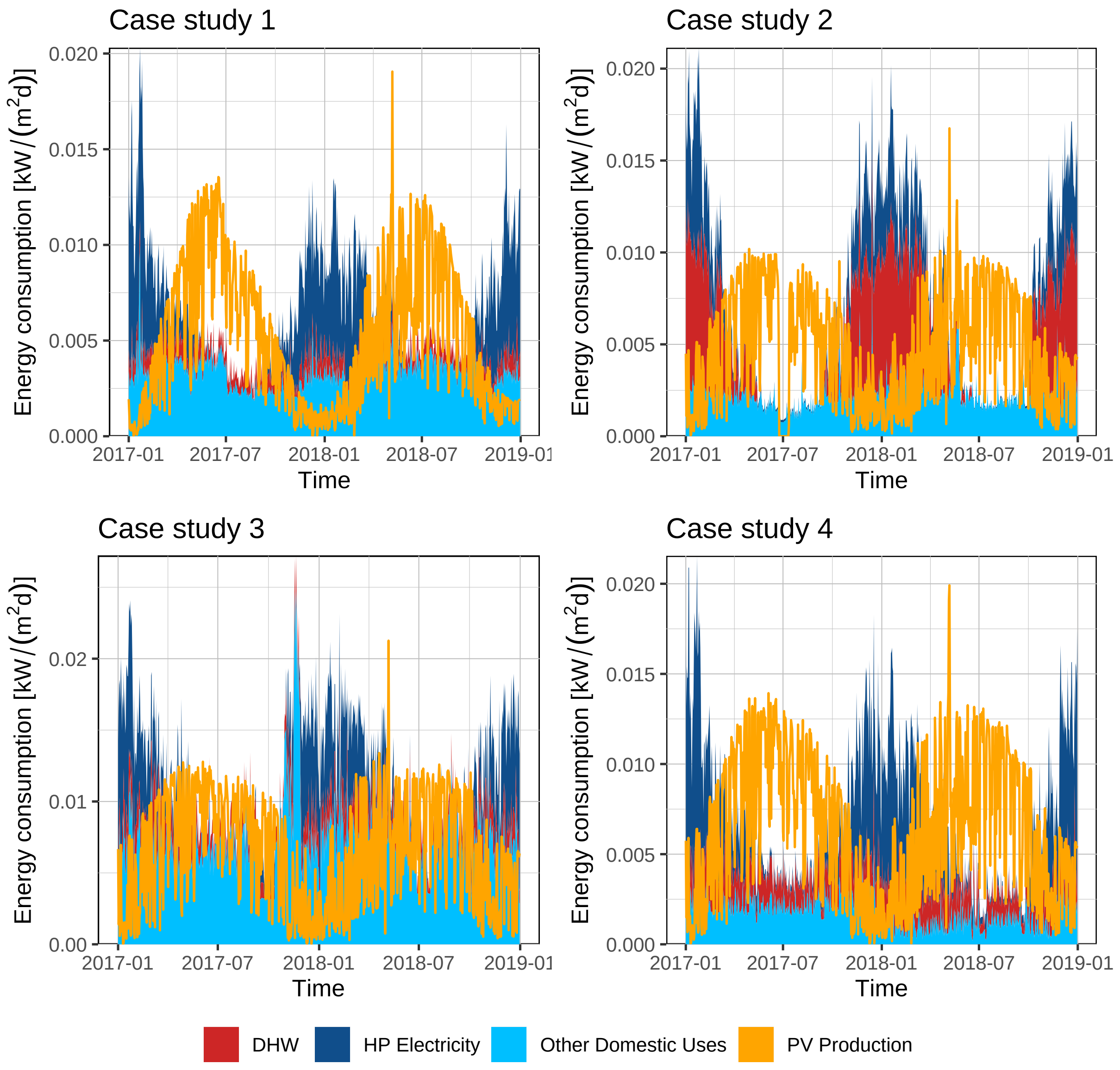

Figure 18: Electricity consumption of case studies 1 – 4.

For the fifth case study, the heating needs and the DHW are covered by district heating, while the electricity for the other domestic uses is provided by the grid. The energy consumption of the measured data for the years 2017 – 2019 is presented in Figure 19 (left). The energy profile shows that there is a high seasonality of the heating needs, while a stable trend characterizes the energy consumption for the DHW and the electricity for the other domestic uses, throughout the year. Annex 4.3 presents the total energy consumption of this case study.

The data of the sixth case study correspond to measurements during the year 2018. A heat pump covers the heating needs, which is designed, according to the methodology, presented in chapter 2. The consumption profile for the different domestic needs is presented in Figure 19 (right), while Annex 4.3 presents a summary of the total energy consumption. The total electricity needs for the heat pump and the other electricity uses are provided from the grid and the PV installation. The PV consumption follows a seasonal profile, with high electricity production in summer. In addition, the profile of the heating needs shows an important seasonality and it is characterized of an intermittent trend, since this case study is an office building. The electricity profile of the other electricity uses shows a relative fluctuation, which is mainly related to the intermittent electricity use in this building.

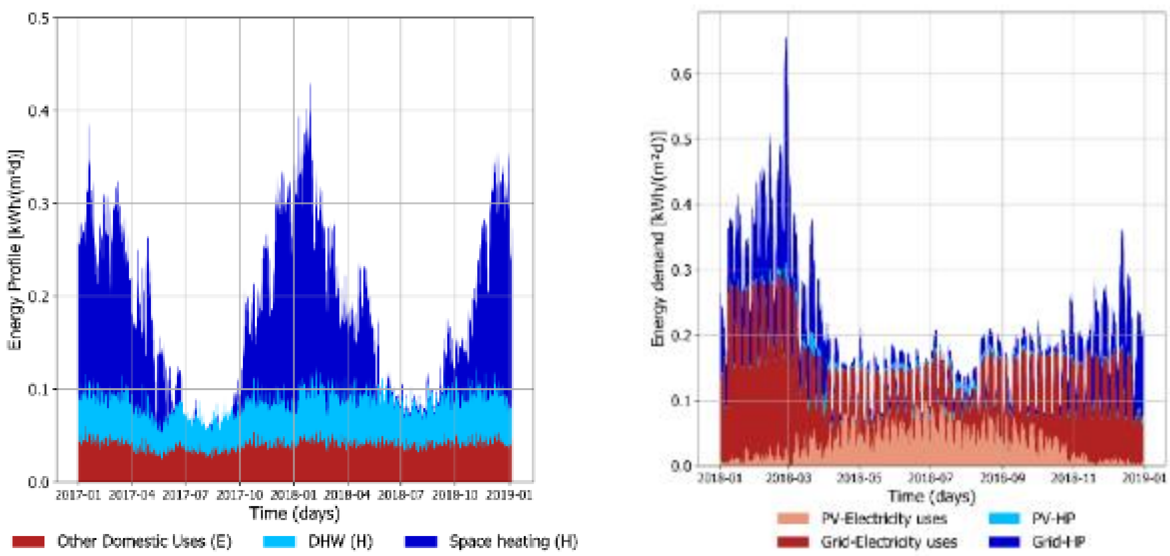

Figure 19: Energy profiles of case study 5 (left) & 6 (right).

Apart from the existing real technical configurations of the case studies, a number of theoretical scenarios were considered for all the case studies, as presented in Table 7. Hence, the impact of the PV installation, the choice of the technical system (HP, district heating, gas), as well as the time step of the electricity consumption of the case studies on the total environmental impacts, and the different energy needs, i.e. electricity for heating, DHW and the other domestic uses can be evaluated. Annex 4.3 presents the energy consumption profiles for all the different considered scenarios.

Table 7: Studied scenarios of the case studies.

Case study	Scenario	Heat Pump		District heating	Natural gas	PV		Grid Electricity	Time step
		Constant COP	Variable COP			Yes	No		
1 to 4	A	Heating & DHW							Annual, monthly, daily, hourly
	B	Heating & DHW							
5	Reference			Heating & DHW					
	B			Heating & DHW					
	C	Heating & DHW							
	D		Heating & DHW						
	E	Heating & DHW							
	F		Heating & DHW						
6	Reference		Heating						
	B				Heating				
	C				Heating				
	D	Heating							
	E		Heating						
	F	Heating							

4.3. Results

The following sub-sections present the environmental impacts of the energy demand of the case studies, which are evaluated through four environmental indicators, i.e. GHG [$kgCO_{2eq}/(m^2y)$], NRE [$MJ/(m^2y)$], RE [$MJ/(m^2y)$] and ES [UBP, ecopoints/(m^2y)]. At first, the environmental impacts of the reference scenarios for the case studies are presented for the GHG emissions, as well as the influence of the time step on the environmental impacts of all the different scenarios for the GHG and the NRE indicators (chapter 4.3.1). The design alternatives of the different scenarios and their influence on the environmental impacts are also discussed (chapter 4.3.3), as well as the PV benefit on one case study, i.e. the fifth case study (chapter 4.5) .This case study was choosen because it offered the highest number of collected data and it offered thus more flexibility to test different design alternatives such as PV installation.

4.3.1. Environmental impacts of the reference scenarios

The first building shows representative trends for all case studies of SFHs. The GHG emissions of the reference scenario for this case study, under a daily time step are presented in Figure 20, both for the grid and the PV electricity. As far as the grid electricity is concerned, the GHGe (Greenhouse Gas emissions) of the space heating follow the energy consumption profile of the building, which varies intra- and inter-annualy. The intra-annual fluctuation is linked to the seasonal profile of the space heating (high energy demand during the winter months), while the inter-annual fluctuation is linked to the reduced electricity imports from Germany that leaded to lower GHGe in 2018, as already explained in the beginning of WP4. The impacts of the electricitiy for the other domestic uses and the DHW show a seasonal profile with lower GHG emissions during summer and higher during winter, unlike their energy consumption profile which is constant over the year. Their intra-annual fluctuation derives from the seasonality of the grid electricity, i.e. lower imports during the summer and consequently lower GHG emissions, while the opposite trend is observed in winter. As far as the PV electricity impacts are concerned, they follow a seasonal profile, i.e. higher energy production during the summer months. The inter-annual differences are linked to the available solar radiation of these years. All the results of the other SFHs and the other ondicators are presented in Annex 4: Environmental impacts of the case studies.

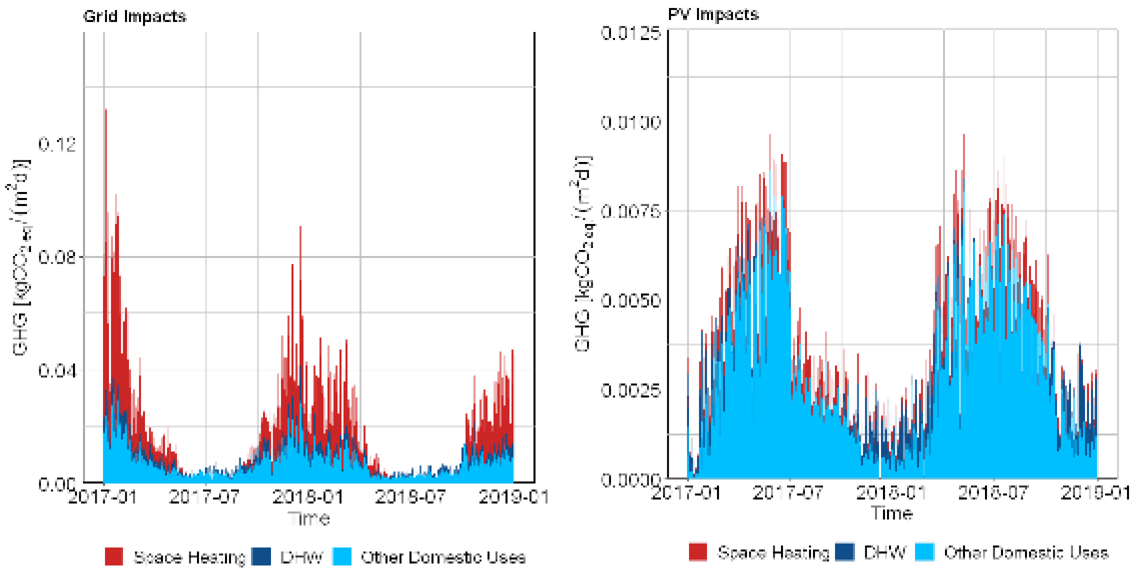

Figure 20: GHG emissions of first case study (daily time step representation).

The GHG emissions, under a daily time step, of the fifth and sixth case studies are presented in Figure 21. Concerning the fifth case study (Figure 21 - left), the impacts of the heating needs follow the energy consumption of the building and they show an intra-annual fluctuation, because of the energy peaks of the winter period. The impacts of the DHW remain relatively stable intra- and inter-annually, not only because of the relatively stable energy profile, but also because of the constant environmental impacts of the district heating, throughout the examined period. However, the impacts of the electricity for the other domestic uses show an intra-annual seasonality (high impacts during winter and lower impacts during summer, reflects the Swiss electricity consumption mix GHGe), unlike their relatively constant annual energy consumption profile. The reduced GHG emissions of the summer months are linked to the reduced electricity imports, which are high carbon intensive. A relatively small inter-annual fluctuation is observed in the GHG emissions of the other domestic uses, which derives from the fact that a higher percentage of indigenous electricity production and consumption occurred that year.

Concerning, the sixth case study (Figure 21 – right), the impacts of the space heating and the other domestic uses follow the energy consumption profile as they are both electric loads. For both load impacts, the intermittent trend is obvious, because of the intermittent occupant profile, i.e. office building. The seasonal trend is more pronounced for the impacts of the space heating, i.e. high impacts during the winter months, than for the electricity for the other uses. The lower impacts of the other domestic uses, during the summer months, come not only from the fact that a PV installation is used, but also because of the reduced electricity imports during summer; imports mainly from Germany. All the other results of the different scenarios and the different indicators are presented in Annex 4: Environmental impacts of the case studies.

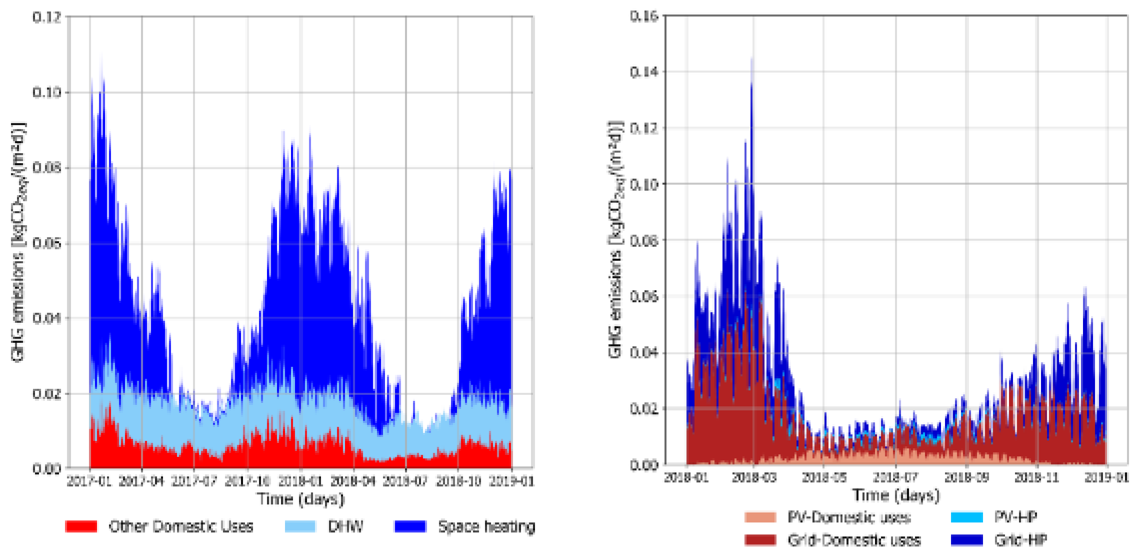

Figure 21: GHG emissions of MFH (fifth case study) and office building (sixth case study), representation for the daily time step.

4.3.2. Influence of the time step on the environmental impacts

Figure 22, Figure 23 and Figure 24 present the relative differences of the GHGe between the monthly/daily/hourly and the annual time step.

Figure 22 corresponds to the GHGe of heating needs. All the case studies and the different scenarios are considered, which include heat pump, district heating and gas, for the heating needs. It can be observed that the highest GHG results are obtained when an hourly time step is considered for the calculation of the electricity impacts. It means that considering annual calculation does underestimate the impacts. Thus, the higher the time step resolution, the higher the impacts and the influence of the choice of the time step. This is valid for all the case studies. Low differences are observed on the GHGe, between the annual and the other two time steps (daily and monthly), for all the case studies. The highest influence of the time step is observed for the SFHs, i.e. case studies 1 – 4, with or without PV.

Figure 23 presents the relative differences of the GHG emissions, among the different time steps for the DHW. The impacts of the monthly and daily time steps are relatively lower than the impacts of the annual time steps. In addition, there is no significant difference of the impacts, when the monthly or the daily time steps are used. However, when the hourly time step is used, the impacts are higher than the annual environmental impacts. The SFHs are more influenced than the other case studies by the time step choice, as it was the case for the impacts of the heating needs. The second case study (with and without PV), for which the electricity profile of the DHW presents high seasonality, is the most influenced by the time step choice, among the case studies. This observation reveals that the impacts of the energy profiles that strongly fluctuate throughout the year, tend to be more influenced by the choice of the time step. The same conclusion can be drawn by comparing the two figures (

Figure 22 and Figure 23). The energy profiles of the heating needs exhibit high seasonality, unlike these of the DHW, and this is the reason why the choice of the time step has higher influence on the former.

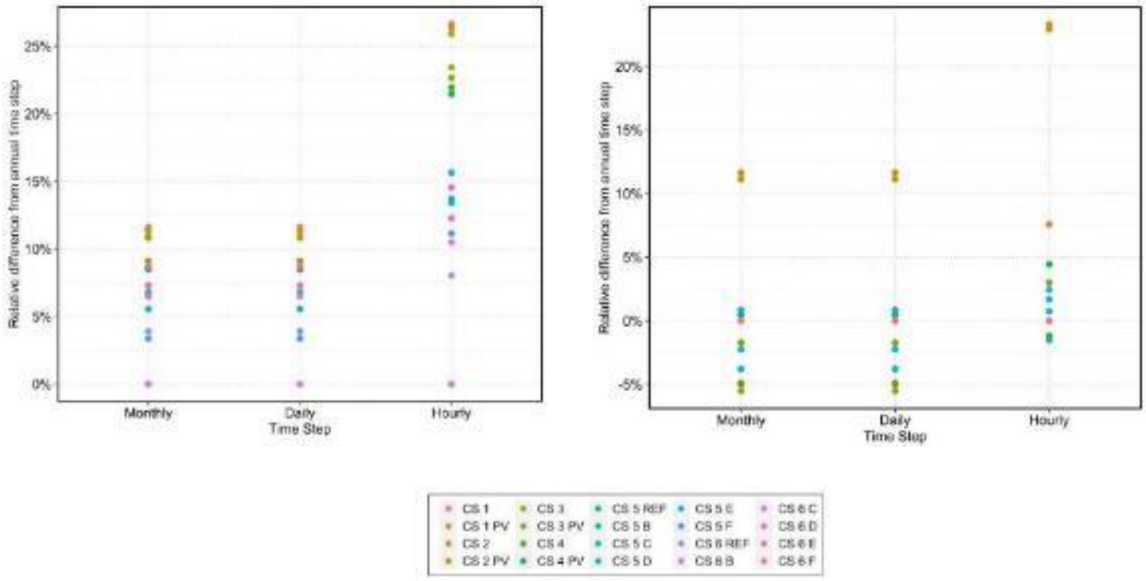

Figure 22(left) & Figure 23 (right): Relative difference (in percent) from the annual time step, of all the scenarios for the GHGe of the space heating (left) and DHW (right).

Looking at the relative differences for the other domestic uses in Figure 24, for the GHGe, it can be noticed that a majority of the scenarios presents higher impacts when the time step resolution is increased (from monthly to hourly), the higher the impacts. The impacts calculated under a monthly or a daily time step show no specific difference and negative differences are observed from the annual time steps, as it was the case for the impacts of the DHW, too. The same conclusion, as before can be drawn, by comparing the three figures, i.e. energy profiles with significant fluctuation, over the year, tend to be more influenced by the time step choice. Between the impacts of the DHW and the other domestic uses, the latter tend to be more influenced by the time step choice.

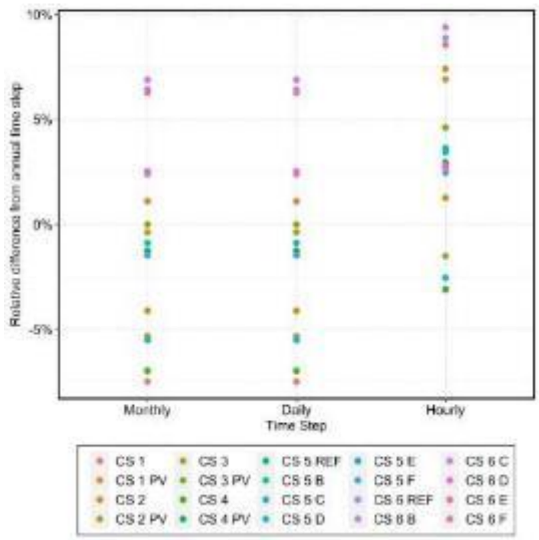

Figure 24: Relative difference from the annual time step, of all the scenarios for the GHGe of the other domestic uses.

Similar plots were computed for the NRE indicator; see Figure 25, Figure 25 and Figure 27. Looking at the results for the space heating, it can be seen that the highest differences are observed between the hourly and the annual time step, while no significant differences are observed between the monthly and the daily time step. All the case studies are slightly affected by the time step resolution. As far as the DHW is concerned, the NRE is more sensitive to the time step resolution, compared to the results for the space heating need. In addition, there are no significant differences among the results of the three time steps. Regarding the impacts of the other domestic uses, it is observed that there are no differences between the monthly and daily time step, while the impacts of the hourly time step are slightly higher. These compendious figures for the other two indicators are presented in Annex 4.5: Time step influence.

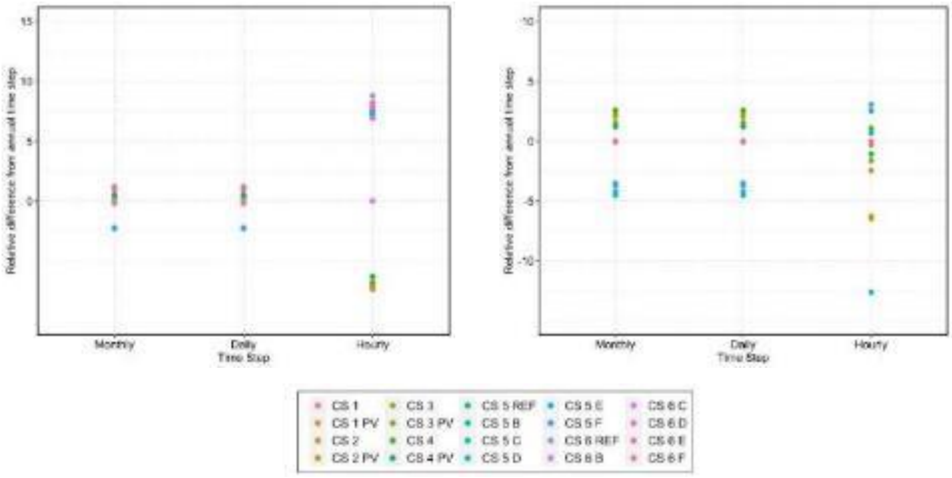

Figure 25(left) & Figure 26 (right): Relative difference from the annual time step, of all the scenarios for the NRE of the space heating (left) and DHW (right).

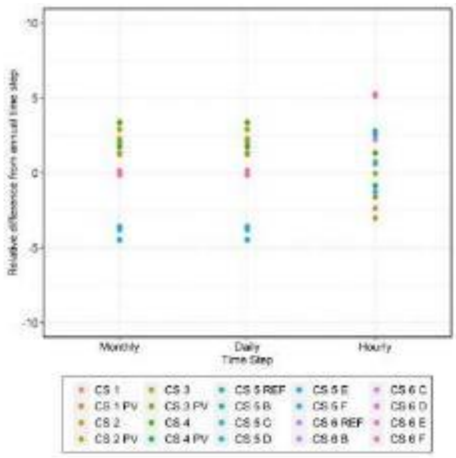

Figure 27: Relative difference from the annual time step, of all the scenarios for the NRE of the other domestic uses.

Figure 28 presents the influence of the time step in detail, concerning the GHG emissions and the NRE indicator, for all the scenarios and domestic uses. Additional details about these results as well as for the other indicators, are presented in Annex 4.5: Time step influence. The figures present each domestic use for all the time steps. It can be observed that for the SFHs, the higher the time step resolution, the higher the GHG emissions, mainly for the electricity use in space heating, except for the second case study, for which the DHW is also influenced by the time step resolution. As already discussed, the influence of the time step resolution is due to the fact that the space heating (and the DHW for the second case study) has a seasonal variable profile. For the two extreme time steps and the space heating needs, these differences are on average 25%, for the case of the SFHs and the GHGe.

As far as the NRE indicator, no systematic trend can be observed for the different uses, because of the different time steps. Taking into account the results for the GHGe and NRE indicators, as well as the results for the RE and UBP indicators, in Annex 4.5: Time step influence, it can be observed that the GHG emissions are the most influenced by the time step resolution, among the four studied indicators, e.g. approximately 9% between the two extreme time steps for the total GHG emissions, for the first case study.

Looking at the GHG emissions of the SFHs and comparing between the scenarios with and without PV, it can be observed that the influence of the time step on the electricity for space heating needs is approximately similar for the two scenarios. In addition, the PV benefit (i.e impact reduction) between the scenarios with and without PV, for the first case study is approximately 8% and 10% for the hourly time step, for the GHGe and the NRE, respectively. For the second, third and fourth case study, the PV gain is 6% and 10%, 4% and 12%, 3% and 9% for the GHGe and the NRE, respectively.

As far as the fifth case study is concerned, the time step choice influences more the scenarios that include a heat pump to cover the space heating needs, i.e. CS5C, CS5D, CS5E and CS5F. For these scenarios, the higher the time step resolution, the higher the GHGe as the HP energy source is electricity, and therefore reflects the time-step sensitivity of the GHGe impact factor of the electric grid. It should be noted though, that the differences between the two extreme time steps, i.e. between the yearly and hourly time steps, are less pronounced for this case study, than for the SFHs. More specifically, there is a 14% difference on average, between the two extreme time steps, for the electricity of the space heating needs and the GHGe. As far as the NRE is concerned, no systematic trend can be observed for the different time steps, among the different uses. The influence of the time step resolution on the total building impacts is higher for the GHGe than for the NRE indicator, i.e. between the two extreme time steps, there is a 6% and 3% difference on average, for the GHGe and the NRE, respectively. It should be also noticed that there is no difference, concerning the influence of the time step, between the scenarios with or without PV.

Concerning the sixth case study, there is no systematic trend among the different time steps and the different uses, for both the GHGe and the NRE indicator. The most important differences between the two extreme time steps are noticed for the scenarios that include a heat pump, i.e. CS6-Ref, CS6D, CS6E, and CS6F. Between the two extreme time steps, there is an 11% difference on average, concerning the electricity of the space heating needs, for the GHGe. In addition, comparing the scenarios with (reference scenario) and without PV installation (scenario CS6E), the time step influence is almost similar, 8% and 7%, respectively. As far as the total building impacts are concerned, between the two extreme time steps, there is 8% and 5% difference on average, for the GHGe and the NRE respectively. All the detailed results for all the case studies and environmental indicators, concerning the time step influence are given in Annex 4.5: Time step influence.

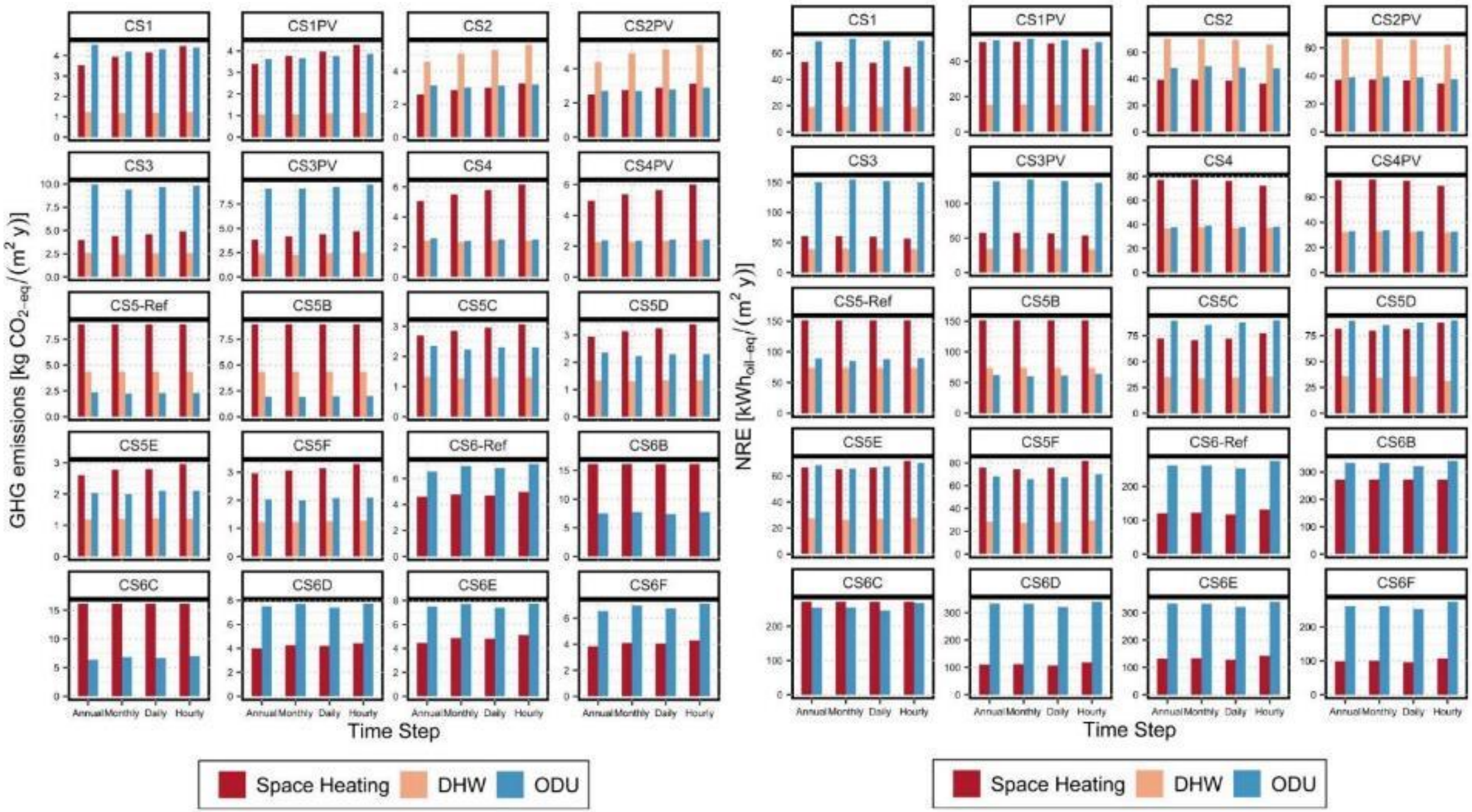

Figure 28: Influence of time step on the GHGe and the NRE indicators, for all the scenarios.

4.3.3. Influence of the design alternatives on the environmental impacts

SFH – Representative case study CS1

All the SFHs are equipped with PVs and part of the produced electricity is consumed on site, or sent to the grid. One alternative scenario without PV was developed for each SFH, for which no PV installation is considered.

Figure 29 presents the GHGe daily impact profile of the two considered scenarios, i.e. with and without PV installation. Looking at the GHGe of the scenario without PV, it can be noticed that the GHGe of the space heating follows the energy consumption profile of the building, which varies intra-annually with a seasonal trend. There is also a relatively small inter-annual fluctuation, for all the different uses. However, the fluctuation is more pronounced for the GHGe of the space heating. This inter-annual seasonality can be explained by the fact that in 2018, the electricity imports diminished and consequently the GHGe (less imports imply a lower GHGe impact). The GHGe of the DHW and the other domestic uses show a seasonality, with slightly reduced impacts during the summer months, which is due to the lower impacts of the grid electricity, because of the reduced imports from Germany. Looking at the GHGe of the scenario with the PV installation, the same conclusions can be drawn for the GHGe of the grid, as for the previous scenario. The GHGe of the PV installation present an intra- and inter- annual fluctuation, i.e. higher impacts during the summer months and reduced impacts during the winter months.

Comparing the two scenarios, the one with the PV installation has approximately 10% lower GHGe than that without the PV, see Annex 4: Environmental impacts of the case studies. For the other indicators, i.e. the NRE, RE and UBP, this percentage is approximately 17%, 28% and 11%, respectively see Annex 4: Environmental impacts of the case studies. In total, the PV electricity covers approximately 30% of the energy needs of the building, and this PV electricity corresponds to almost 17% of the total GHGe, 16% of the total NRE, and 19% of the total UBP.

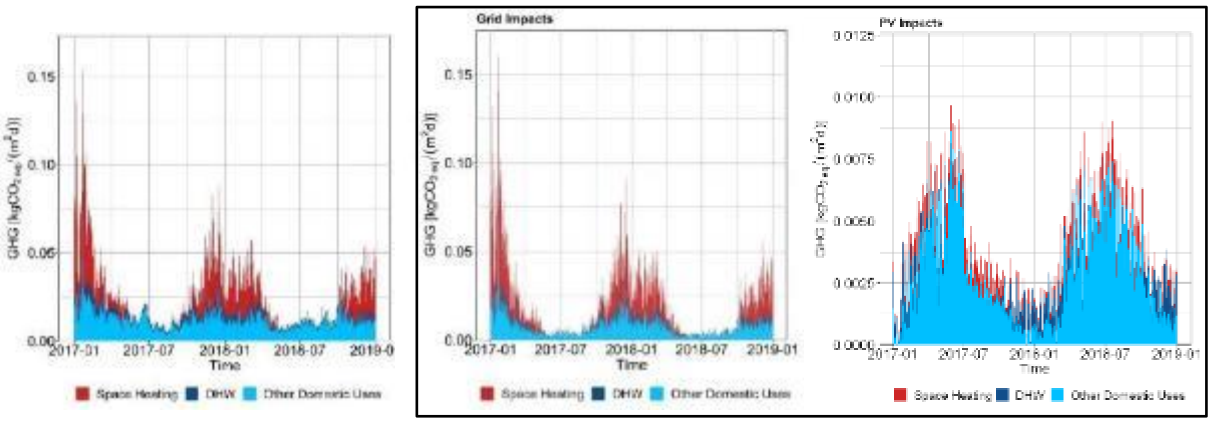

Figure 29: GHG emissions of CS1 without (left) and with PV installation.

The results of the other SFH case studies are presented in detail in the Annex 4: Environmental impacts of the case studies. From the results, the following conclusions can be drawn:

a) The environmental impacts of the different uses present an intra-annual fluctuation, with lower impacts during the summer months and higher during the winter. This is valid not only for the seasonal electricity energy profiles (e.g. space heating), but also for the intra-annual stable ones (e.g. other domestic uses). This is explained by the fact that during the summer months the electricity imports from Germany diminish and also because the PV self-generation increases.

b) The environmental impacts of all the different uses show an inter-annual fluctuation, with lower impacts during the year 2018. This is explained by the fact that during this year, there was a higher nuclear production in Switzerland and lower electricity imports from Germany (see chapter 2).
c) The buildings with PV installations present approximately 10% lower GHGe for the first and the second case study, for which the PV electricity covers approximately 30% and 17%, respectively of the electricity needs. For the third and fourth case study the buildings with PV installations have 5% and 3% lower GHGe, respectively for approximately 25% electricity coverage.

Case study 5 – MFH

The GHGe of the impacts for all the different scenarios of the fifth case study are presented in Figure 30, with a daily time step. The impacts of all the other indicators are presented in Annex 4: Environmental impacts of the case studies. For all the scenarios, the impacts of the heating needs follow the energy consumption profile and exhibit high seasonality, caused by the increased energy demand in the winter period. For all the scenarios, the impacts of all the different uses show an inter-annual fluctuation, due to the lower electricity imports from Germany, of the year 2018. Concerning, the impacts of the DHW, they remain relatively stable intra- and inter -annually, for the two first scenarios, not only because of the relative stable consumption profile, but also, because of the constant environmental impacts of the district heating. For the other scenarios, the electricity of the DHW is covered by the grid. These impacts follow the energy consumption profile and are relatively stable intra-annually. In addition, they show a small inter-annual fluctuation, because of the lower imports in 2018. As far as the electricity of the other domestic uses is concerned, it comes from the grid, for all the studied scenarios. The impacts do not follow consumption profile and they present and intra- and inter- annual fluctuation. The intra-annual fluctuation is related to the higher electricity imports, during the winter period, while the inter-annual fluctuation is related to the lower imports in 2018, as already explained.

Comparing the two first scenarios, for which the heating needs and the DHW are covered by district heating, to the CS5C and CS5D for which a heat pump is used, it can be concluded that the latter scenarios result in lower environmental impacts. The difference of the GHGe for the heating needs is on average 65%, for the CS5C and CS5D scenarios, while for the DHW this difference is 70%. The same difference is observed when comparing the two first scenarios with the CS5E and CS5F scenarios that include both a HP and a PV installation. Because of the heat pump, there is in total 60% impact benefit, compared to the district heating solution. In addition, comparing the CS5C and CS5D scenarios (without PV installation), for which a heat pump with a constant and variable COP is used, respectively, it can be concluded that the latter scenario presents 5% higher total impacts, while specifically for the impacts of the space heating, this difference is approximately 10%. Between the scenarios with a PV installation, there is a similar increase of the impacts, because of the variable COP. Looking at the reference CS5A scenario (without PV) and the CS5B (with PV), the PV gain is approximately 14% for the electricity of the other domestic uses, while for the total GHGe the gain is approximately 2%. Comparing the scenarios CS5C (without PV) and CS5E (with PV), there is approximately an 8% environmental gain, because of the PV installation. A similar difference is observed between the scenarios CS5D and CS5F, for which a variable COP is considered for the heat pump.

The following conclusions can be drawn for all the scenarios of the CS5 case study.

a) The most favorable solution, in terms of environmental impacts, between the heat pump and the district heating, is the heat pump, with a 60% total gain, because of the heat pump. This means that heat pumps, even with the electricity impact fluctuating have lower impact than District heating network.
b) The choice of the type of the COP (constant or variable) has an insignificant influence on the environmental impacts of the building. Between the scenarios, with and without a PV installation, this difference is approximately 8% for the total impacts.
c) In the case that district heating is used for the space heating and the DHW, the PV benefit on the GHGe electricity impact is 14%.
d) In the case that a heat pump is used for the space heating and the DHW, the PV gain is approximately 8% for the GHGe.

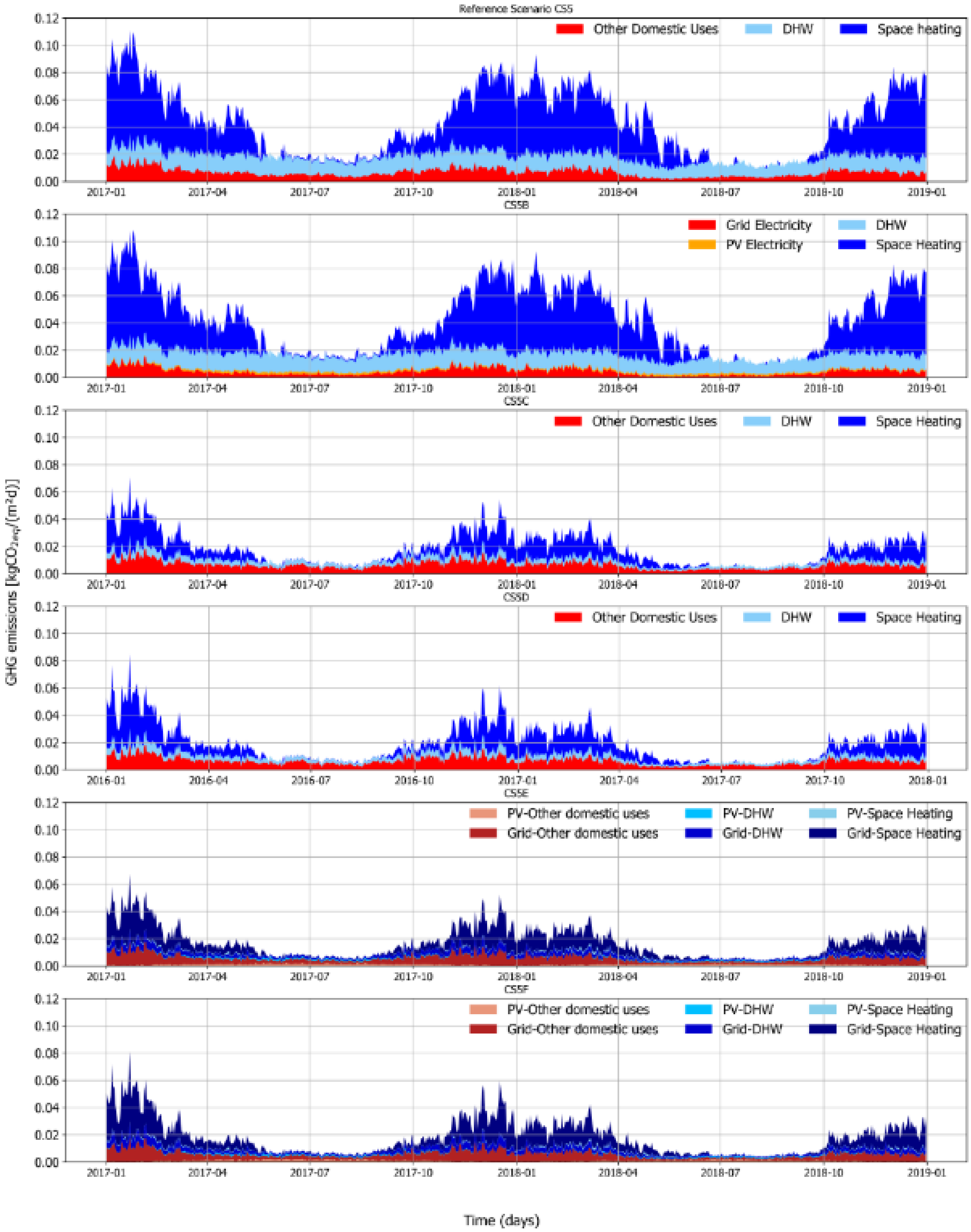

Figure 30: GHG emissions of CS5, of all the examined scenarios.

Case study 6 – Office building

Figure 31 presents the GHGe of all the different scenarios of the sixth case study during 2018, under a daily time step. The environmental impacts for the other three indicators are presented in Annex 4: Environmental impacts of the case studies. For all the scenarios, the GHG emissions follow the intermittent profile of the energy consumption, linked to the use of the case study, i.e. office building. As far as the impacts of the heating needs are concerned, they follow the energy consumption profile and exhibit a high seasonality peaking in winter. This trend is present for all the scenarios. Regarding the electricity for all the other uses, its impacts follow the energy profile as well.

Comparing the scenarios for which gas is used for the heating needs to the scenarios with the heat pump, it can be observed that the latter present lower GHG emissions. For example, comparing the reference scenario, to the CS6B, there are approximately 50% lower total impacts for the second scenario, while only for the heating needs, the reference scenario, present approximately 70% lower GHG emissions. Between the scenarios CS5B (without PV) and CS5C (with PV), the PV benefit is approximately 3%. Looking at the reference scenario (with PV) and the CS6E (without PV), there is a 6% gain, because of the PV installation. This difference is approximately 2.5% for the impacts of the space heating and 8.5% for those of the other uses. In addition, comparing the reference scenario (variable COP – with PV) with the CS6F (constant COP – with PV), the total GHG emissions of the latter is approximately 6% less for the reference scenario, because of the constant COP. Separately for the heating space, this difference is 13%, while there is no difference, concerning the impacts of the electricity for the other uses. A similar difference is observed for the scenarios CS6D and CS6E.

The following conclusions can be drawn from the analysis of the sixth case study:

a) Comparing the heat pump solution with that of natural gas, the latter scenario presents the double impacts in terms of GHGe.
b) For an office building, a heat pump with a variable COP results to approximately 6% higher impacts for all the indicators, than a heat pump with a constant COP.
c) When a heat pump is combined with a PV installation, there is approximately 6-7% gain on the GHGe, because of the PV installation.
d) When natural gas is used as the energy carrier for the space heating, the PV benefit is approximately 3%, in terms of lower GHGe.

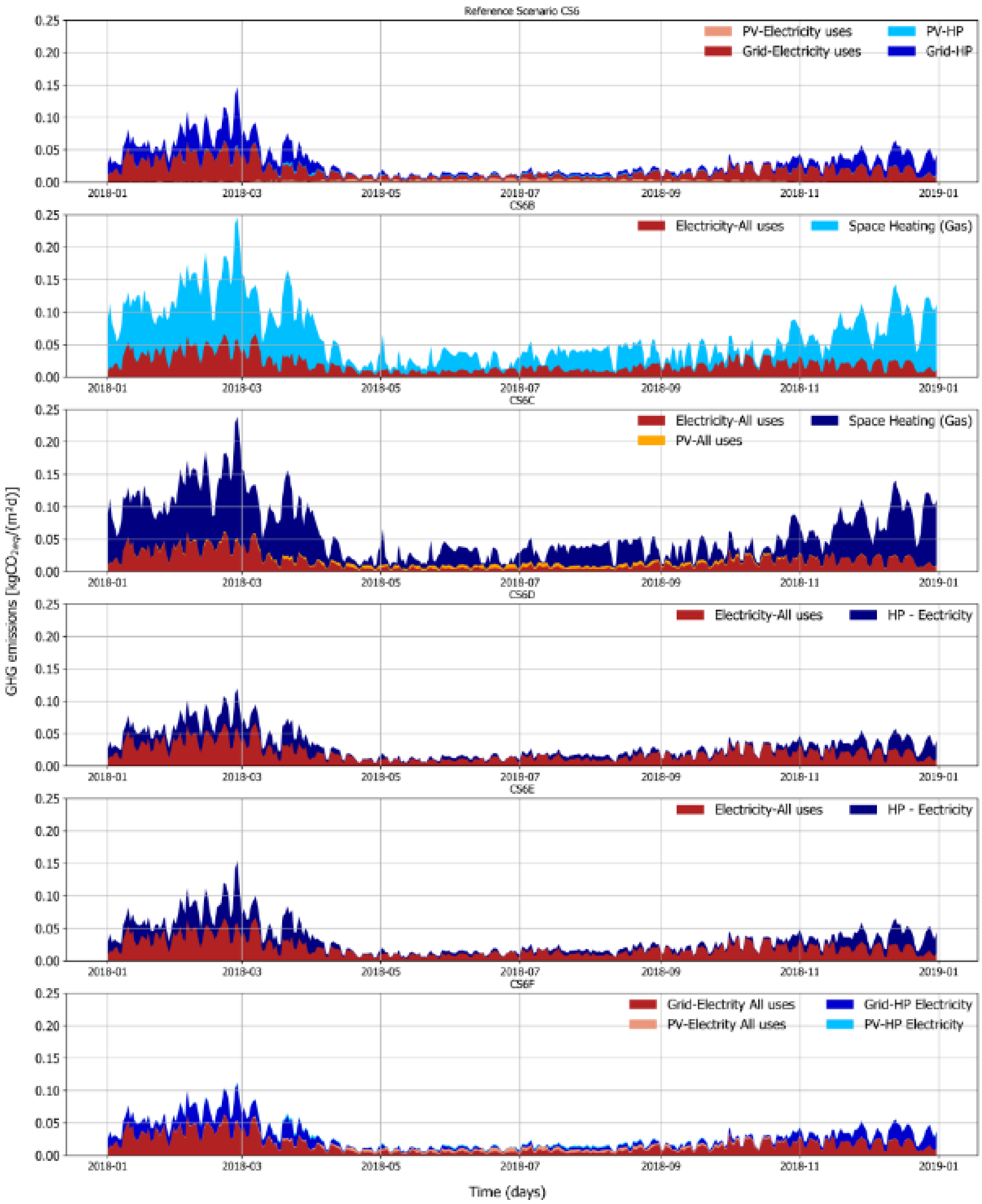

Figure 31: GHG emissions of CS6, of all the examined scenarios.

4.4. Summary of the case studies results

Comparing all the different case studies and their scenarios, the following similarities could be identified:

1) The higher the temporal resolution, the higher the environmental impacts, for the majority of the scenarios. This trend is particularly pronounced for seasonal energy profiles, e.g. space heating. For relatively stable annual energy profiles, the time step resolution has a small influence on the evaluated impacts.
2) The GHG emissions tend to be more influenced by the time step resolution than the other indicators.
3) The PV gain on the GHG emissions is 10% at most.
4) In terms of GHG emissions, the heat pump presents the most environmental friendly solution, compared to natural gas and district heating.
5) No significant differences can be observed between the GHG emissions of the scenarios with constant and variable COP.

Table 32 presents a summary of all the scenarios, concerning the results. The summary tables for the other indicators are presented in Annex 4.6: Summary tables of the results.

Table 8: Compendious table of the results of the sixth case studies, for the GHG emissions.

Case studies	CS1 - 4				CS5					CS6				
	Energy consumption profile	**General trend of the impacts**	**Time step Influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time Step Influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time Step Influence**	**PV gain**
Space Heating	Seasonal	Intra- and inter -annual fluctuation. High seasonal profile, lower GHGe in 2018.	On average 24% between the yearly and annual time step, for the GHGe. (With and Without PV)	Hourly time step for GHGe: 3%-5%	Seasonal	Intra- and inter -annual fluctuation. High seasonal profile, lower GHGe in 2018.		GHGe between annual and hourly : 11% - 16%	Hourly time step for GHGe: 3%-4%	Seasonal and intermittent use	Inter-annual seasonality		**Without PV and GHGe**: 0 - 14% **With PV** and GHGe :8% -12%	Hourly time step for GHGe: 3%
DHW	Stable and seasonal only for the CS2	Inter-annual fluctuation, lower GHGe in 2018.	**Without PV and GHGe:** 0% - 23% . (for CS2 that has a highly DHW seasonal profile). On average 6%. **With PV and GHGe**: 0%- 23% (for CS2 that has a highly DHW seasonal profile). On average 10%	Hourly time step for GHGe: 2%-7%	Stable	Inter-annual fluctuation, lower GHGe in 2018.		GHGe : 1.5% - 3%	Hourly time step for GHGe: 6%-7%					
Other domestic Uses	Stable	Inter-annual fluctuation, loewr GHGe in 2018.	**Without PV:** On average 2% **With PV:** On average 6%	Hourly time step for GHGe: 3%- 12%	Stable	Inter-annual fluctuation, loewr GHGe in 2018.		GHGe : 2.5-4%	Hourly time step for GHGe: 9%-13%	Moderate seasonality and intermittent use	Inter-annual seasonality		**With PV:** hourly time step GHGe: 9% -11% **Without PV** for hourly time step GHGe: 3%	Hourly time step for GHGe: 8%-9%

Case studies	CS1 - 4				CS5					CS6				
	Energy consumption profile	General trend of the impacts	Time step influence	PV gain	Energy consumption profile	General trend of the impacts	Impact of COP	Time step influence	PV gain	Energy consumption profile	General trend of the impacts	Impact of COP	Time step influence	PV gain
Total impacts without PV installation			GHGe between annual and hourly time step: 5% - 17 % (in case that there are two highly seasonal energy profiles, i.e. CS2)	Hourly time step: 4% - 8%			GHGe: 6 % for the hourly time step	GHGe : 0.4%- 6%	Hourly time step: 2% - 6% for the GHGe			Hourly time step for GHGe: 6%	GHGe between annual and hourly time step: 1% - 7%	Hourly time step: 3% - 6% for the GHGe
Total impacts with PV installation			GHGe between annual and hourly time step: 12% - 20% (in case that there are two highly seasonal energy profiles, i.e. CS2)				GHGe: 6% for the hourly time step	GHGe : 0.5% -7%				Hourly time step for GHGe: 6%	GHGe between annual and hourly time step: 3% - 10%	

4.5. Photovoltaic influence

CS5 Reference vs CS5B – Representative case study

This section presents the influence of the PV installation for the fifth case study. It is the only case study that was examined in detail, concerning the PV benefit. The reference scenario is compared with the CS5B scenario, which does not include a PV installation. For both scenarios the space heating and the DHW are provided by district heating. The other domestic uses are covered by the electricity from grid. Figure 32-left presents the environmental gain of the PV installation, evaluated through the GHGe, while Figure 32-right presents the NRE gains, under a daily time step. As far as the GHG emissions are concerned, it can be observed that during a short summer period, the electricity provided by the PV installation has a negative environmental impact on the GHGe of the building. The reason for this result is that the Swiss grid electricity has, in general, low carbon content, since the indigenous energy production mainly comes from nuclear and hydro power. This fact is particularly obvious, in summer, since the imports (mainly from Germany) diminish. However, looking at the overall impact of the PV installation, it should be noted that during one-year period, the PV installation has a positive gain on the GHGe of the building and it allows the mitigation of the electricity peaks and the reduction of the GHGe during the winter, when the electricity imports are significant. In addition, the influence of the PV installation on the NRE indicator is always positive, diminishing the NRE impacts of the building energy consumption.

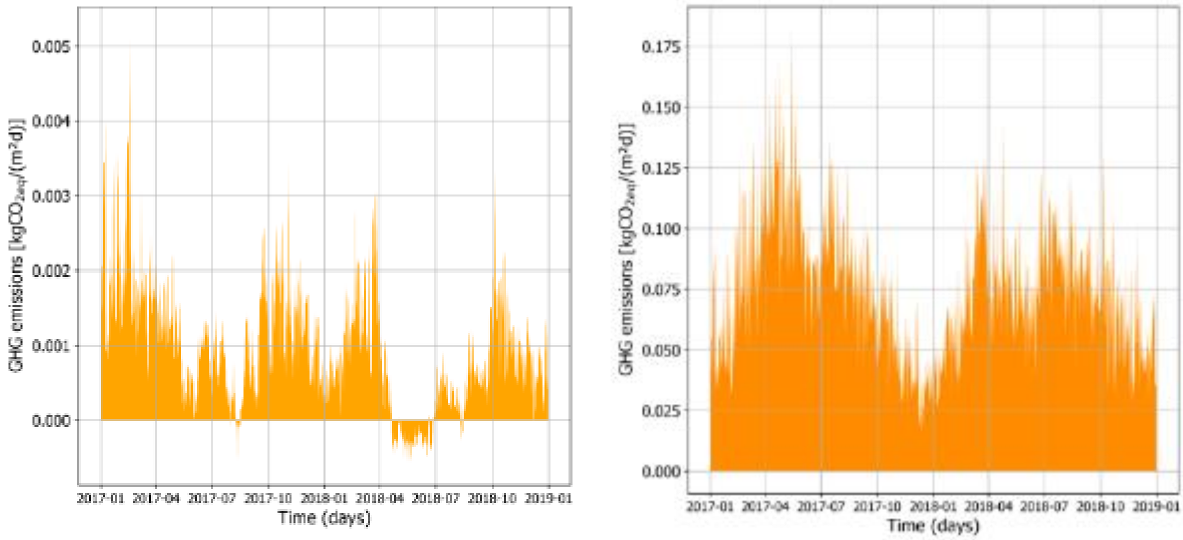

Figure 32: Environmental gain of the PV installation. Comparison between the reference scenario and the CS5B scenario for the GHG emissions (left) and NRE indicator (right).

Figure 33 presents the PV gain of the scenarios D and F, in terms of GHG emissions and NRE. It can be observed that the environmental gain of the PV installation is approximately 8% for the GHG emissions and 16% for the NRE. Thus, even if the PV gain is not significant for the different time steps, its overall performance is still better than the grid electricity, concerning both the climate change and NRE indicators. In terms of NRE, the gain with PV installations is important and during the full year. It. It has nevertheless to be noticed that optimized management of the PV electricity, including load management and eventually storage could improve the benefits related to such installations. This aspect will be covered within the next chapter.

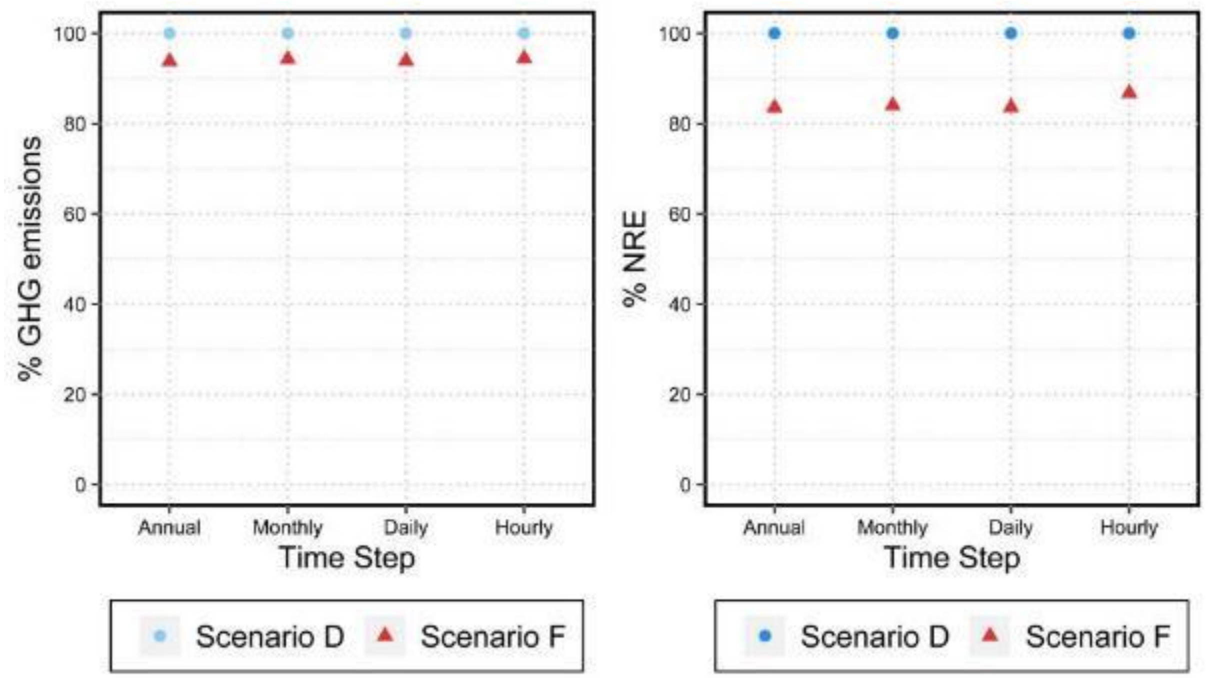

Figure 33: Environmental gain of the PV installation. Comparison of the scenarios D and F for the GHG emissions (left) and NRE indicator (right).

In this case study (CS-5), the environmental benefit of PV installation is found to be modest, especially for the climate change impact. This observation is related to several factors. First, the PV installation is small compared to the building size, i.e 21kWp for an Energy Reference Area of 2'663 m^2 (7.9 W/m^2). This implies that the self-generation rate is small, approx. 22%. Thus the substitution of the electricity from the grid is small and occurs mostly in late spring / summer when the building demand is low (no electricity used by the heat pump for space heating purposes) and when the Swiss consumed electricity environmental impact is low, implying a reduced gain from the PV electricity use. This observation does not mean that the PV installation is not interesting to mitigate the environmental impacts of the building electricity demand. It means that significant effort has to be put to have large PV installation that could contribute significantly to the overall building energy demand. It is also necessary to maximize the electricity production of decentralized system when the impact of the grid is important and when the building electricity demand is high. Finally, the observed results also confirm that the impact of the Swiss consumed electricity is generally low compared to the impact that can be observed in other countries. This situation implies that photovoltaic electricity in Switzerland need to be developed considering this situation therefore to consider dynamic environmental assessment when developing PV installation in buildings.

5. Conclusions

The first part of WP4 concerned the environmental impact assessment of the grid electricity. It was shown that the impacts fluctuate over time; intra- and inter – annually. The climate change and ecological scarcity indicators show a seasonal variability, rather than an intra-day fluctuation. The impacts are higher during the winter months than in the summer, since the imports mainly from Germany are higher during winter. Concerning the renewable and non-renewable primary energy indicators, they have higher intra-day variations than seasonal ones. The intra-day variations are related to the higher imports during specific hours of the day, i.e. early morning and late afternoon and occur all along the year. The observed seasonal variations, related to the imports from the neighboring countries, are less pronounced than for ES and GWP indicators. Thus the Swiss electricity mix is sensitive to the import shares and the production variability. In addition, an inter-annual variability has been observed, related to the production means availability. In 2017, the Swiss nuclear power plants produced less electricity, implying higher GWP impact, since the energy needs were covered by increasing the imports. The other indicators (NRE, RE, ES) were found to have less inter-annual sensitivity. It appears, thereby, that the impact of the Swiss electricity mix is sensitive to the nuclear national production, which influences the quantity of imports, in order to cover the national electricity demand. Hence, it would be interesting to apply the EcoDynBat calculation framework every year, so as to quantify and validate the inter-annual variation on a larger time scale.

The environmental impacts of the Swiss electricity mix calculated within the EcoDynBat project were also compared to other Swiss sources, namely ecoinvent and KBOB. The comparison has shown that the difference were mainly related to the calculation method for the imports. The EcoDynBat approach considers the physical flows of the electricity production means, in Switzerland and abroad, as well as the import flows. Conversely, the ecoinvent and KBOB database consider the certificate of origin on an annual basis. By doing so, the imports of both the ecoinvent and KBOB Swiss electricity mix have a smaller fossil-fuel share. This approach is valid on an annual basis, but it cannot be applied, so far, on an hourly basis, since there is a lack of the available information for the calculations and because certificate are sold on an annual basis.

It is not within the scope of the EcoDynBat project to argument on the most relevant approach for the impact assessment of the electricity mix. Each of them evaluates the impacts from different perspectives. The certificate of origin based approach represents an environmental accounting approach, on a yearly basis, while the physical flow approach presents the physical situation, at a specific time step. Nevertheless, it would be necessary to mention, that in the certificate of origin cannot be (so far) considered on an hourly basis and thus, with this approach there is no correlation between the time and the impact of the electricity consumption at a time t. In addition, it is worth to mention that, while the certificate of origin might be of interest when performing national environmental accounting, it can deserve the environmental optimization at the building level. Indeed, the environmental impacts of a building that would consume certified electricity are already found to be very low. Thus, performing energy efficiency and environmental impact optimization for such building configuration is hard to achieve and could be even counter-productive when aiming at implementing decentralized electricity production systems or storage solutions. Thereby, it seems relevant to account for the environmental impacts based on physical flows and traded electricity (by knowing exactly which energy is purchased at each time step, which requires to largely extend the access to the information for the environmental calculations) rather than relying on certificate of origin.

The dynamic environmental assessment of the Swiss electricity mix was further evaluated on the building level. Different case studies were evaluated and several conclusions could be drawn, regarding the electricity consumption impact assessment of the examined case studies. The impacts of the DHW and the other domestic uses, when covered by the grid electricity, show an insignificant sensitivity to the time step resolution. This trend is explained by the fact that the energy profiles of these energy uses are relatively stable throughout the year, and thus their impacts are not influenced by the fluctuations of electric grid impacts. Thus, considering an average annual impact for these energy uses is relevant, for all the different examined indicators.

On the contrary, as far as the heating needs are concerned, in case that they are covered by an electricity based production mean, their impacts are more sensitive to the time step. Indeed, the energy profile of the heating needs is highly seasonal, i.e. demand occurring mainly from mid-autumn to mid-spring, with a peak in the winter months. Thereby, the impact fluctuates more as a function of the time step resolution. For the SFHs, i.e. the CS1 to CS4 case studies, which correspond to renovated buildings, the relative difference between the hourly and annual time step is higher, compared to the other case studies, which correspond to recent and highly energy efficient buildings. At the building level, the time step influence is low. Although the time step influences the space heat demand, this trend is attenuated in relative by the other electricity needs (DHW and domestic uses) which have less sensitivity to the time step. Indeed, if a 15% sensitivity could be observed (for example) for space heating demand while this demand represent 50% of the total building electricity demand, the overall time step influence would fall at 7.5%.

Thus, at the building level, considering higher time step resolutions only shows limited variations in term of environmental impacts. Considering hourly time step does not seem to bring enough accuracy improvement to be used. It is necessary to state here that the case studies were selected based on data availability. It is therefore not possible to exclude that for other building energy demand profiles, the environmental impacts accuracy would not be affected by the time step consideration. The next chapter (focusing on sensitivity analysis) will illustrate the maximum theoretical influence of the time step resolution in order to identify if some building typologies could require to consider hourly time step.

As a conclusion, considering higher time step resolutions at the building level, for relatively stable profiles, is not relevant, however, for seasonal profiles it would be worthwhile to develop a simplified calculation impact model that encompasses the seasonality of the grid electricity impact. Developing a seasonal grid electricity impact model, using a simple approach, would improve the representativeness of environmental impact assessment for the buildings energy demand.

In addition, it has to be also noticed that considering higher time step resolution could become necessary in the near future. Indeed, when specific load management strategies will be set (for example in micro-grids, to maximize the self-consumption in buildings, etc.), the electricity consumption could fluctuate more significantly. These high fluctuations will induce a higher sensitivity to the energy sources, over time and, thus, their impacts.

Finally, the EcoDynBat project developed a calculation framework for the hourly environmental profile of the Swiss electricity mix that could be annually applied, in order to assess the evolution of the mix over the time, during the energy transition period. Furthermore, the EcoDynBat electricity impact profile could also serve for the environmental assessments of other domains, such as for mobility, in order to develop load strategies for the electric vehicles.

ECODYNBAT Project

Dynamic Life Cycle Assessment of Buildings

Chapter 4 – Part b: Case studies with micro-CHP (WP 4-b)

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3: SUPSI-DACD-ISAAC

Summary

This report deals with the environmental impacts of buildings equipped with micro-cogeneration units (micro-CHP). Two systems were studied, internal combustion micro-CHP systems and fuel cells. The environmental impacts were calculated, considering different levels of bio-methane (0%, 10%, 20% and 100%). The first three levels represent the current situation or that envisaged in the short term for gas networks in Switzerland, the last level being theoretical, provides the maximum potential, related to the use of biomethane.

The two objectives of this chapter are to study:

- The influence of the time step on the calculation of the environmental impacts of buildings, with micro-CHP units. Indeed, micro-CHP offers the potential interest of producing electricity concomitantly with heat, i.e. at the time when the environmental impacts of electricity on the Swiss grid are the highest (cf. chapter 4-a). The electricity produced and consumed in this way therefore substitutes the electricity from the grid.
- The comparison of the environmental impacts of a building, equipped with micro-CHP to a reference configuration, which includes a traditional gas boiler and consumes electricity from the Swiss grid. These results enable the classification of the micro-CHP to the Swiss energy strategy.

The results of the study showed three key elements:

- The environmental impacts of heat and electricity produced by micro-CHP are strongly dependent on the assumption made regarding the allocation of impacts for biogas production. In the case the biogas is considered as a product of waste treatment, its impact is zero making the use of micro-CHP profitable, in terms of environmental impacts. Conversely, if biogas is considered as a recyclable product, these impacts are very high. The EcoDynBat project does not aim to discuss which of these methodological assumptions is the most relevant. Therefore, it was decided to present both results.
- The influence of the time step for buildings, using micro-CHP is small to negligible (lower than in the chapter 4-a study cases). For fuel cells, according to the model used (i.e. chapter 2 model), the electrical demand of buildings is almost entirely covered by the micro-CHP and the influence of the time step is null. For internal combustion units, micro-CHP covers a significant part (71.6%) of the electricity demand, making the sensitivity to time step very low, as well. In fact, taking into account a high time resolution does not improve the accuracy of the calculation. Therefore, it does not seem important to consider this point in the case of an environmental study for a micro-CHP (and by extrapolation for all types of decentralized production, which would ensure a large part of the electrical demand of buildings).
- The environmental impacts of the energy demand of buildings (i.e. thermal and electrical) are strongly influenced by the hypothesis of the biogas impact allocation. If biogas is considered as a waste treatment, then micro-CHP offers an environmental benefit compared to the reference system (gas boiler + grid electricity). Conversely, if the biogas is considered as a recyclable product, then the use of micro-CHP increases the overall environmental impacts, compared to the reference situation. Therefore, it appears necessary to clarify the methodological choice, concerning the allocation of the environmental impacts of the biogas production.

Résumé

Ce rapport traite des impacts environnementaux de bâtiments équipés d'unité de micro-cogénération (micro-CHP). Deux systèmes ont été étudiés, les systèmes de micro-CHP à combustion interne et les piles à combustibles. Les impacts environnementaux ont été calculé en considérant différents niveaux de bio-méthane(0%, 10%, 20% et 100%). Les trois premiers niveaux représentent la situation actuelle ou celle envisagée à court terme pour les réseaux de gaz en Suisse, le dernier niveau présentant un caractère théorique et fournissant le potentiel théorique maximum lié à l'utilisation du bio-méthane.

Les deux objectifs de cette étude sont d'étudier :

- L'influence du pas de temps sur la précision du calcul des impacts environnementaux de bâtiments possédant des unités de micro-CHP. En effet, la micro-CHP offre l'intérêt potentiel de produire de l'électricité de manière concomittente avec de la chaleur, c'est-à-dire au moment où les impacts environnementaux de l'électricité sur le réseau Suisse sont le plus élevé (cf. chapitre 4-a). L'électricité ainsi produite et consommée se substituera donc à une électricité du réseau impactante.
- Les impacts environnementaux des bâtiments équipés de micro-CHP par rapport à une configuration de référence composé d'une chaudière à gaz traditionnelle et consommant de l'électricité du réseau Suisse. Ce résultats permettra de positionner l'intérêt de la micro-CHP dans la stratégie énergétique Suisse.

Les résultats de l'étude ont montré trois éléments clefs :

- Les impacts environnementaux de la chaleur et de l'électricité produite par de la micro-CHP sont fortement dépendant de l'hypothèse qui est faite concernant l'allocation des impacts pour la production de biogaz. Dans le cas où celui-ci est considérant comme un produit issue d'un traitement de déchet, son impact est nul rendant l'utilisation d'une micro-CHP pertinente. A l'inverse si le bigaz est considéré comme une produit recyclable, ces impacts sont très élevés. Le projet EcoDynBat n'avait pas pour objectif de discuter laquelle de ces hypothèses méthodologiques étaient pertinentes. Aussi, il a été décidé de présenter les résultats selon ces deux voies.
- L'influence du pas de temps pour des bâtiments utilisant des micro-CHP est très faible voir négligeable (plus faible que dans les cas d'étude du chapitre 4-a). Pour les piles à combustible, selon les modélisations réalisée, la demande électrique des bâtiments est presque intégralement couverte par la micro-CHP, de fait, l'influence du pas de temps est nulle. Pour les unités à combustion interne, la micro-CHP couvre une part significative (71.6%) de la demande d'électricité, rendant la sensibilité au pas de temps très faible également. De fait, la prise en compte d'une résolution temporelle fine n'améliore pas la précision du calcul. Il apparait donc comme inutile de considérer ce point dans le cas d'étude environnemental traitant de la micro-CHP (et par extension pour tous type de production décentralisé qui assurerait une grande part de la demande électrique de bâtiments).
- Les impacts environnementaux de la demande énergétique des bâtiments (i.e thermique et électrique) sont fortement influencés par l'hypothèse d'allocation des impacts du biogaz. Si le biogaz est considéré comme issue d'une procédé de traitement des déchêts, alors la micro-CHP offre un bénéfice environnemental par rapport au système de référence (chaudière à gaz + électricité du réseau). A l'inverse, si le biogaz est considéré comme un produit recyclable, alors l'utilisation de la micro-CHP augmente globalement les impacts environnementaux par rapport à la situation de référence. Il apparait donc nécessaire de clarifier les choix méthodologiques quant au calcul des impacts environnementaux de la production de biogaz.

Zusammenfassung

Der vorliegende Bericht behandelt die Umweltbelastungen von Gebäuden, die mit Mikro-Kraft-Wärme-Kopplungs-Anlagen (Mikro-KWK-Anlagen) ausgestattet sind. Zwei unterschiedliche Systeme werden hierbei untersucht, einmal die Mikro-KWK mit internem Verbrennungsmotor und die mit Brennstoffzellen. Die Umweltbelastungen wurden unter Berücksichtigung unterschiedlicher Konzentrationen von Biomethan (0%, 10%, 20% et 100%) berechnet. Die ersten drei Konzentrationen spiegeln die aktuelle Situation der Schweizer Gas-Netze dar bzw. die, die kurzfristig angestrebt werden soll, während die letzte ein theoretisches Maximal-Potential darstellt, das durch die Verwendung von Biomethan erreicht werden könnte.

Die zwei Hauptziele der vorliegenden Studie sind es, :

- den Einfluss des Zeitschrittes auf die Genauigkeit der Berechnungen der Umweltbelastungen bei Gebäuden mit Mikro-KWK-Anlage zu untersuchen. Mikro-KWK-Anlagen besitzen in der Tat das Potenzial, genau dann Strom mit Wärme zu produzieren, wenn die Umweltbelastungen der Elektrizität auf das Schweizer Netz am höchsten sind (siehe WP4-a). Der auf diese Weise erzeugte und verbrauchte Strom wird daher Strom aus dem betroffenen Netz ersetzen.
- die Umweltbelastungen von Gebäuden mit Mikro-KWK-Anlagen in Bezug auf eine Referenzkonfiguration bestehend aus einem traditionellen Gasheizkessel und Strom aus dem Schweizer Netz zu untersuchen. Dieses Ergebnis wird dazu beitragen, das Interesse an Mikro-KWK-Anlagen in der Schweizer Energiestrategie zu festigen.

Die Ergebnisse der Studie haben drei Schlüsselelemente aufgezeigt:

- Die Umweltbelastungen der von der Mikro-KWK-Anlage produzierten Wärme und Elektrizität hängen sehr stark von der Hypothese ab, wie die Einflüsse der Biogasproduktion zugeordnet werden. Wird das Biogas als Abfallprodukt angesehen, sind ihre Auswirkungen gleich null und machen den Gebrauch einer Mikro-KWK-Anlage relevant. Wird das Biogas jedoch als wiederverwertbares Produkt betrachtet, so werden seine Auswirkungen sehr stark. Das Projekt EcoDynBat hatte es sich jedoch nicht zum Ziel gesetzt zu beurteilen, welche dieser methodologischen Hypothesen relevant sind. Deshalb wurde entschieden, die Ergebnisse aus beiden Blickwinkeln darzustellen.
- Der Einfluss des Zeitschrittes für Gebäude mit Mikro-KWK-Anlage ist sehr gering und damit vernachlässigbar (geringer als in der Fallstudie des WP4-a). Nach dem durchgeführten Modell wird bei den Brennstoffzellen der Strombedarf der Gebäude fast vollständig durch die Mikro-KWK-Anlage gedeckt, de facto ist der Einfluss des Zeitschrittes gleich null. Für die Anlagen mit internem Verbrennungsmotor deckt die Mikro-KWK-Anlage einen signifikanten Teil des Strombedarfs (71.6%) und sind damit ebenfalls nur in sehr geringem Masse dem Einfluss des Zeitschrittes ausgesetzt. Somit erhöht auch eine höhere Zeitauflösung die Rechengenauigkeit nicht. Deshalb erscheint es unnötig, diesen Punkt in Umweltfallstudien zu Mikro-KWK-Anlagen zu behandeln (und im weiteren Sinne gilt dies für alle Arten der dezentralisierten Produktion, die einen großen Teil des Strombedarfs von Gebäuden decken würde).
- Die Umweltbelastungen des Energiebedarfs von Gebäuden (z.B. thermisch oder elektrisch) werden stark von der Hypothese beeinflusst, als was Biogas eingeordnet wird. Wird Biogas als Abfallprodukt betrachtet, besitzt die Mikro-KWK-Anlage einen Umweltvorteil in Bezug auf das Referenzsystem (Gasheizkessel + Strom aus dem Netz). Wird Biogas jedoch als ein wiederverwertbares Produkt angesehen, so erhöht der Einsatz einer Mikro-KWK-Anlage grundsätzlich den Einfluss auf die Umwelt in Bezug auf den Referenzzustand. Es erscheint daher notwendig, die methodologischen Optionen bezüglich der Berechnung der Umweltbelastungen der Biogasproduktion zu aufzuzeigen.

Table of content

Acronyms

A-W: Air-Water

CF: Characterization Factor

CHP : Combined Heat and Power

DHN: District Heating Network

DHW: Domestic Hot Water

DLCA: Dynamic Life Cycle Assessment

ES: Ecological Scarcity

FU: Functional Unit

GHG: Greenhouse Gas

GHGe: Greenhouse Gas emissions

GW: GigaWatt

GWh: Gigawatt hour

GWP: Global Warming Potential

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LHV: Lower Heating Value

MFH: multi-Family House

MW : MegaWatt

MWh : Megawatt hour

NRE: Non Renewable primary energy

RE: Renewable primary energy

SFH: Single Family house

UBP: Eco-Points

WP: Work Package

WP1: Work Package 1 – Review of methodologies

WP2: Work Package 2 – Input data with temporal variability considerations

WP3: Work Package 3 – Development of a DLCA framework for the project

WP4: Work Package 4 – Case studies

WP5: Work Package 5 – Sensitivity Analysis

WP6: Work Package 6 – Recommendations and dissemination of results

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1. Introduction

1.1 Objective

The EcoDynBat project aims at studying the influence of the time step on the environmental impact calculation for the building energy demand. The project uses a Dynamic Life Cycle Assessment (DLCA) approach for the environmental impact quantifications.

To do so, a state-of-the-art on DLCA has been performed (WP1) and set the necessary requirement for the project data collection phase and methodological framework. The necessary data have been collected, characterized and merged together into an “EcoDynBat dataset” (chapter 2). The methodological framework has been developed within WP3. The WP4 aims at applying the framework on real case studies to quantify effectively the influence of the time step choice on the environmental impacts of the building energy demand. Two sub-parts have been considered. First, in chapter 4-a, the impact of current building configurations were assessed. It corresponds to building with heat pumps, gas boiler and photovoltaic installations. The time step influence has been quantified for this typology of configuration, which is representative of the current building in Switzerland.

In the WP 4-b, the objective is to consider buildings that would be operated with micro-Combined Heat and Power (micro-CHP) units supplied with different shares of bio-methane. Indeed, within the Swiss energy turnaround, it is still expected that between 20 to 27% of the residential building will be heated by natural gas and biogas would cover between 3 to 10 PJ of the Swiss energy needs (forecast extracted from the Prognos report of the Swiss energy strategy 2050). Thus, assessing the environmental of biogas and micro-cogeneration is of interest.

To do so, different shares of bio-methane in the supply mix have been considered, as well as 100% natural gas (0% of bio-methane). Low shares, i.e. 10% and 20% correspond to the short-term objective of the gas providers or the current production configuration. The 100% supply scenario was chosen, in order to assess the maximum potential of using bio-methane. The micro-CHP technical system and configuration is rarely implemented in Switzerland for different reasons (policies, costs, etc.), but could gain in interest in the future. Indeed, it offers the possibility to use bio-methane (entirely , or as part of the gas supply mix) and has the capacity to produce both electricity and heat at the same time. This aspect is of interest especially in winter, when heat is needed, while the Swiss electricity grid is largely importing electricity from its neighboring countries to fulfil its national demand.

Thereby, a specific sub-chapter has been set in the EcoDynBat project, in order to cover the assessment of a building that would operate with a micro-CHP unit.

1.2 Report structure

Four buildings are considered within the chapter 4-b. For these buildings, two micro-CHP technologies were considered with 4 levels of bio-methane in their supply mix. Additionally to the four reference situations (i.e. the impact of the system with a traditional gas boiler and electricity from the grid), a total of 36 configurations have been assessed. For each of them, 4 environmental indicators have been employed. In addition, two possible choices for a key assumption regarding the environmental impact models have been made, one considering that biogas is issued from a waste treatment (i.e with no impact) and the other considering that biogas is a recyclable product for which some impacts can be allocated. Finally, for each configuration, 4 time steps (hourly, daily, monthly, yearly) have been considered.

This procedure leads to an overall set of 1’028 possibilities. It is therefore not possible to develop and discuss all the obtained results within a comprehensive report. It has been, thus, decided to present the main results, findings and conclusions in the chapter 4-b. The chapter 4-b annex presents the main findings per case study with more details. With this chapter, the key results, regarding the micro-CHP in the EcoDynBat project, are put forward.

2. System definition

The study of WP 4-b includes two micro-CHP technologies:

a. **Combustion-based micro-CHP**, which is widely used technology in many countries now (such as Germany or Japan). This technology has a high thermal efficiency (~70%) and a lower electrical one (~25%).
b. **Fuel cell micro-CHP**, which is already being used, but could gain in importance in the coming years. This technology has a high electrical efficiency (~55%) and a lower thermal one (~33%).

These two technologies have been considered, for four different buildings described in the Table 9:

		Construction period	Surface [m^2]	Electricity Demand [kWh/year]	Heat Demand [kWh/year]
CHP 1	a- Combustion-CHP	2013	2 663	37 332	136 534
	b- Fuel Cell				
CHP 2	a- Combustion-CHP	1919-1945	1 204	11 416	41 548
	b- Fuel Cell				
CHP 3	a- Combustion-CHP	1919-1945	890	17 771	77 059
	b- Fuel Cell				
CHP 4	a- Combustion-CHP	Before 1919	375	4 650	29 229
	b- Fuel Cell				

Table 9 Characteristics of the case studies

The building CHP 1, corresponds to the CS5 of the WP 4-a, i.e. an energy efficient and recently constructed multi-family house. The buildings CHP 2 to CHP 4 correspond to old buildings located in the canton of Neuchâtel. For these buildings, the hourly electricity consumption and thermal energy demand have been collected and provided by Viteos, i.e. the cantonal energy provider. The attributes (construction period and surface) have been extracted from the RegBL.

Based on the micro-CHP model presented in chapter 2, the heat and electricity shares covered by the micro-CHP units have been calculated (Table 10). The electricity from the grid covers the rest of the electricity needs (but not the heating needs). The remaining part of the heating needs are covered by a gas boiler fed with gas from the network with the same amount of biomethane as the micro-CHP units.

		Heat covered by the CHP	Electricity covered by the CHP
CHP 1	a- Combustion-CHP	77.1%	69.9%
	b- Fuel Cell	16.1%	100.0%
CHP 2	a- Combustion-CHP	78.0%	67.1%
	b- Fuel Cell	16.2%	99.3%
CHP 3	a- Combustion-CHP	69.0%	74.6%
	b- Fuel Cell	12.2%	99.9%
CHP 4	a- Combustion-CHP	50.7%	74.7%
	b- Fuel Cell	8.3%	99.0%

Table 10 Fraction of heat and electricity covered by the micro-CHP units for the various case studies

The energy demand profiles are provided in the annex of the chapter 4-b. As far as the electricity is concerned, intra-day peaks are observed, but there is no seasonality of the electricity demand profiles. For the heat demand, the CHP 1 exhibits higher seasonality, compared to the other three, because it concerns a low and energy efficient building, while the other three are older and less insulated. In addition, the climate conditions are different for CHP 1 (Classification “ouest du plateau” according to SIA 2028, average yearly temperature of the closest weather station = 10.4°C) and CHP 2-4 (Classification “Jura oriental” according to SIA 2028, average yearly temperature of the closest weather station = 9.1°C).

For the combustion-based micro-CHP, the units cover on average, 68.7% of the buildings’ heat demand and 71.6% of the buildings’ electricity demand. Conversely, for the fuel-cell units, the covered heat is low, i.e. 13.2% on average but the electrical coverage is 99.5%, because of their high electrical efficiencies. The backup for the heat is a gas boiler, since the building is already connected to the gas network for the micro-CHP and the back-up for the electricity is covered by the grid.

The buildings are connected to the gas network, in order for both the backup and the micro-CHP units to operate. For the micro-CHP study, within the EcoDynBat project, four supply mix have been considered, with no bio-methane in the gas network, 10%, 20% and 100%. With these four levels, it is expected to obtain a detailed assessment of the micro-CHP fed by bio-methane potential. The part of electricity not covered by the micro-CHP units is coming from the grid and its associated environmental impacts are taken from the results of the WP 4-a.

Such as for the WP 4-a, four time steps have been considered, hourly, daily, monthly and yearly calculations. The four environmental indicators (climate change, non-renewable primary energy, Renewable primary energy and ecological scarcity) have been computed for the case studies.

3. Environmental impact calculation framework

The considered processes and structure for the micro-CHP use in buildings is presented in Figure 34:

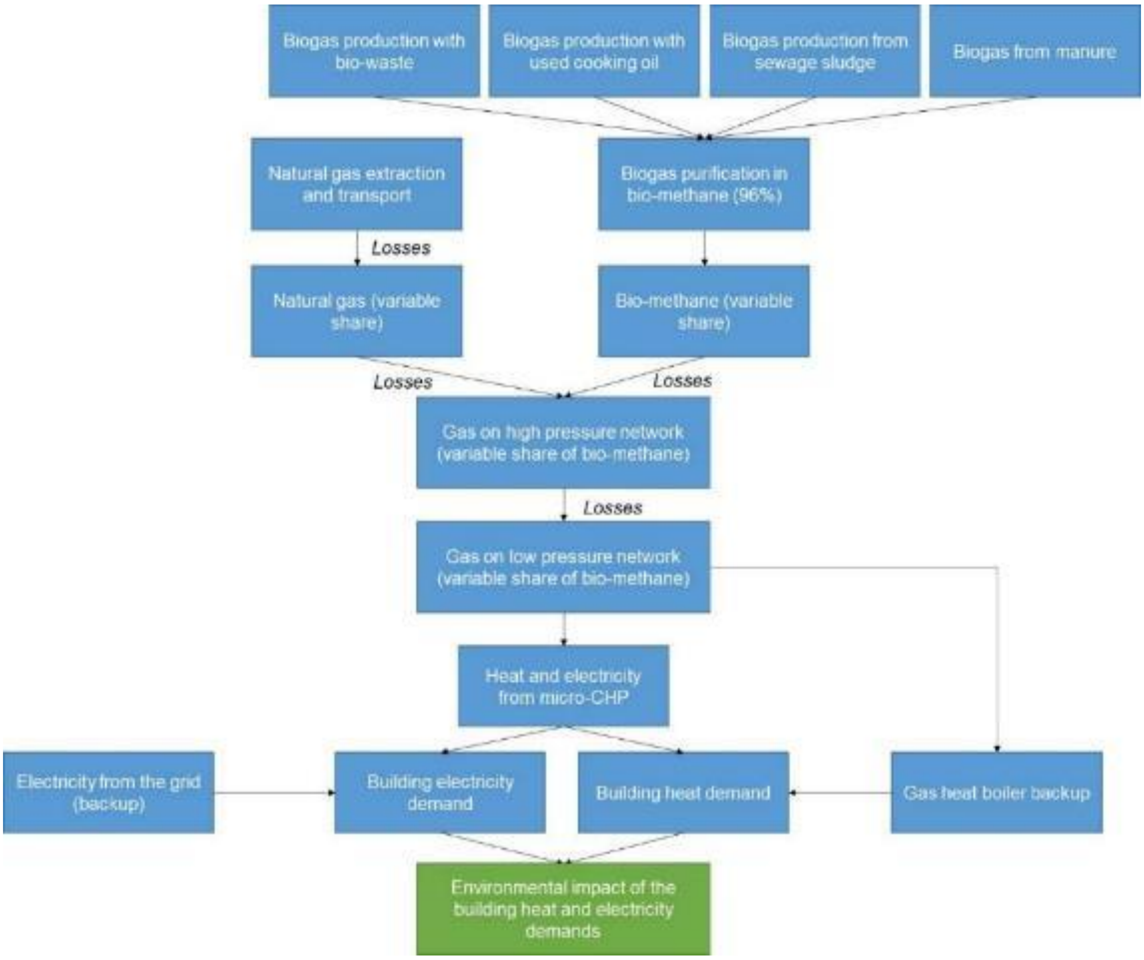

Figure 34 Model used to calculate the environmental impact of building's heat and electricity demands with micro-CHP

Regarding the environmental impacts, the electricity grid impact calculated in the EcoDynBat project has been used. The impact, related to the heat production relies on the ecoinvent v3.4 data, adapted to the specific EcoDynBat context. The details are given in the chapter 4-b annex and only the main aspects are introduced here.

The biogas can be produced using four different processes. Table 11 provides the environmental impact of 1 m^3 of biogas, produced by the four substrates available in ecoinvent. However, the most important assumption, regarding the biogas production, is whether the biogas comes from waste treatment (bio-waste or sewage sludge) or recycling (manure or vegetable cooking oil). In the first option, the impact of the biogas production is allocated to the product that has undergone the waste treatment and, therefore, the biogas has no environmental impacts. In the second case (recycled product), the biogas takes the environmental impacts of the recycling process. These two ways of considering the impacts of biogas imply important differences for the environmental indicators.

	Biogas from manure	Biogas from biowaste	Biogas from sewage sludge	Biogas from used vegetable cooking oil
Climate change [kg CO_2 eq/m^3]	1.92	0	0	0.36
NRE [MJp/ m^3]	5.47	0	0	5.25
RE [MJp/ m^3]	1.66	0	0	1.65
ES [UBP/ m^3]	11420	0	0	336

Table 11 Environmental impacts of biogas production according to ecoinvent, considering the four existing substrate for the production in Switzerland

From Table 11, it appears that the biogas source strongly influences the environmental impact results. It is not the purpose of the EcoDynBat project to define, which is the appropriate way to calculate the environmental impact of the biogas production. Thus, two options have been considered for the environmental impact calculations, i.e. the worst-case biogas production process (i.e from manure) and the best-case production process (from sewage sludge or bio-waste). These processes have been named “biogas as a recyclable product” and “biogas from waste treatment”.

The purified biogas, i.e. the bio-methane (transformed to bio-methane, via a pressure swing adsorption process) is injected to the gas network. The network has high and low pressure pipelines, with a specific loss rate, taken from ecoinvent (see annex of chapter 4-b for details). The bio-methane is mixed with natural gas according to the different shares considered in the EcoDynBat project (10%, 20%, 100% of bio-methane), while 0% of bio-methane corresponds to 100% of natural gas. This supply mix provides the necessary gas for the micro-CHP units and the backup boiler.

The ecoinvent database includes combustion-based and fuel cell micro-CHPs inventories, which serve as the basis for the calculation. In these inventories, the greenhouse gas emissions amount (CO_2 and CH_4 mostly) are characterized in quantity and characterized as having a fossil origin. For the EcoDynBat purpose, these inventories were used, nevertheless, their CO_2 and CH_4 emissions have been adjusted to the bio-methane shares considered in the EcoDynBat project (10%, 20%, 100% of bio-methane), by assuming that the overall emission was identical in absolute but split in two parts biogenic and fossil as a function of the bio-methane share .

In addition, for the micro-CHP unit, it is necessary to allocate the environmental impacts to the produced heat and electricity. Exergy factors have been considered for this, using the thermal and electrical efficiencies already employed for the micro-CHP performance calculation (see chapter 2 for the micro-CHP model description). These impacts are presented in Figure 35 and discussed in detail, in the annex of the chapter 4-b.

Regarding the backup gas boiler, the ecoinvent inventory has been adjusted to the various share of bio-methane, in the supply mix and the direct emissions. The assumptions and ecoinvent inventories used for this micro-CHP calculation are given in the annex of the chapter 4-b.

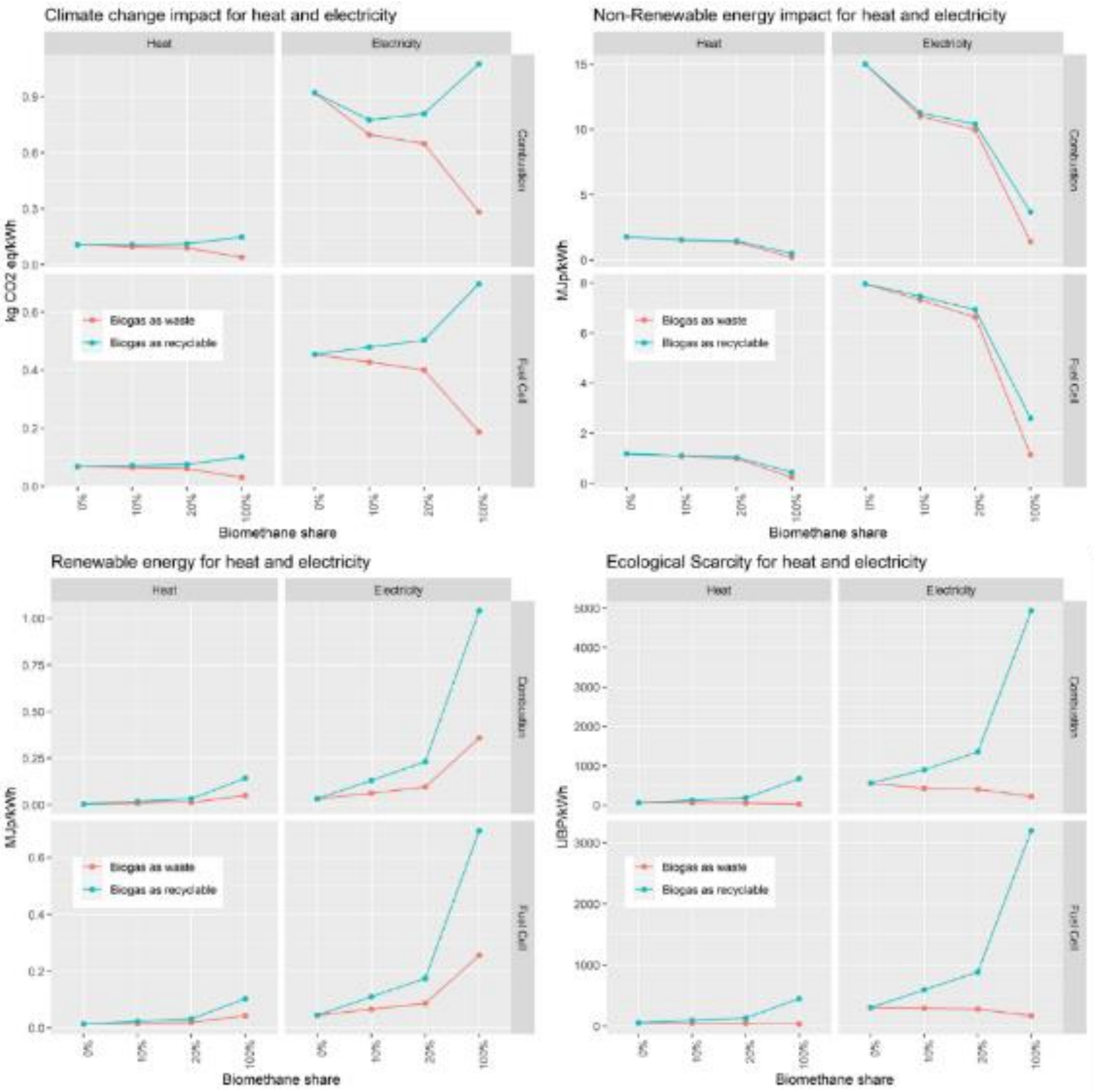

Figure 35 Environmental impacts for heat and electricity produced by micro-CHP (combustion and fuel-cell), according to the EcoDynBat assumptions

Figure 35 confirms that there is a clear relation between the share of the bio-methane and the impacts of the heat/electricity produced by the micro – CHP.

Considering that biogas comes from waste treatment, when increasing the share of bio-methane on the supply mix the environmental impacts of the produced heat and electricity for both combustion-based and fuel-cell micro-CHP are reduced, for all the indicators, apart from the RE. On the contrary, when biogas comes from recycling, the environmental impacts increase with the increase of the bio-methane share in the supply mix (except for the non-renewable primary energy indicator, since natural gas is substituted with the renewable source of bio-methane).

The modeling choice, regarding the biogas impact, is thus a key element that will influence the results of the micro-CHP potential in buildings. Nevertheless, as previously stated, it is not the purpose of the EcoDynBat project to solve this question and it might not be possible to give a unique answer. Thereby, within the project, it has been decided to use both modelling choice to present the results. It is necessary however to clarify this question especially because biogas should play a role in the Swiss 2050 energy strategy (between 3 to 10PJ covered by biogas in 2050 according to the Prognos report)

4. Results

The following chapter on the micro-CHP assessment:

- discusses the results, concerning the time step influence on the environmental impacts, for the combustion and fuel-cell micro – CHP, with different bio-methane shares;
- compares the environmental impacts of a case study with micro-CHP (with different bio-methane shares) to that with a traditional gas boiler, combined with electricity from grid (reference scenario).

The time step influence is presented in the main part of this report for all case studies (Figure 36 and Figure 37). Conversely, for the environmental impact assessment discussion regarding the micro-CHP, the results are presented on a monthly basis for the CHP 1 case study (including the profiles for impacts in the Figure 38 and Figure 40), while the results of the other case studies are summarized on a yearly basis (Figure 36 and Figure 37). The monthly results for all the other case studies are given in the annex of the chapter 4-b.

The first level of results (time step influence) aims at studying the effect of a decentralized production system that provides electricity, at the time the heat is needed. Indeed, for the WP 4-a case studies that combine a heat pump with a photovoltaic installations, the decentralized electricity production occurs mostly when there is no or minimum heating needs. On the contrary, with the micro-CHP, both heat and electricity are produced simultaneously, when it is needed.

The second level of results (comparison with reference scenario) is a secondary result of the EcoDynBat project. Nevertheless, it provides interesting information, regarding the environmental interest of the micro-CHP units in Switzerland, for buildings. This is the reason why this result is also presented here.

4.1 Time step influence

For each of the case studies and indicators, the heat and electricity impacts have been calculated, for the different times steps. The relative difference between the three time steps (hourly, daily and monthly) and the annual time step is then calculated, as a metric for quantifying the influence of the time step, on the environmental impacts.

4.1.1 Combustion-based units

The results of the four case studies and the four indicators are displayed in Figure 36. The results are provided for the two choices regarding the biogas impact consideration (waste treatment and recycling), as well as for the four bio-methane shares and the reference case scenario. For each of the case studies, the detailed results can also be found in the annex of the chapter 4-b.

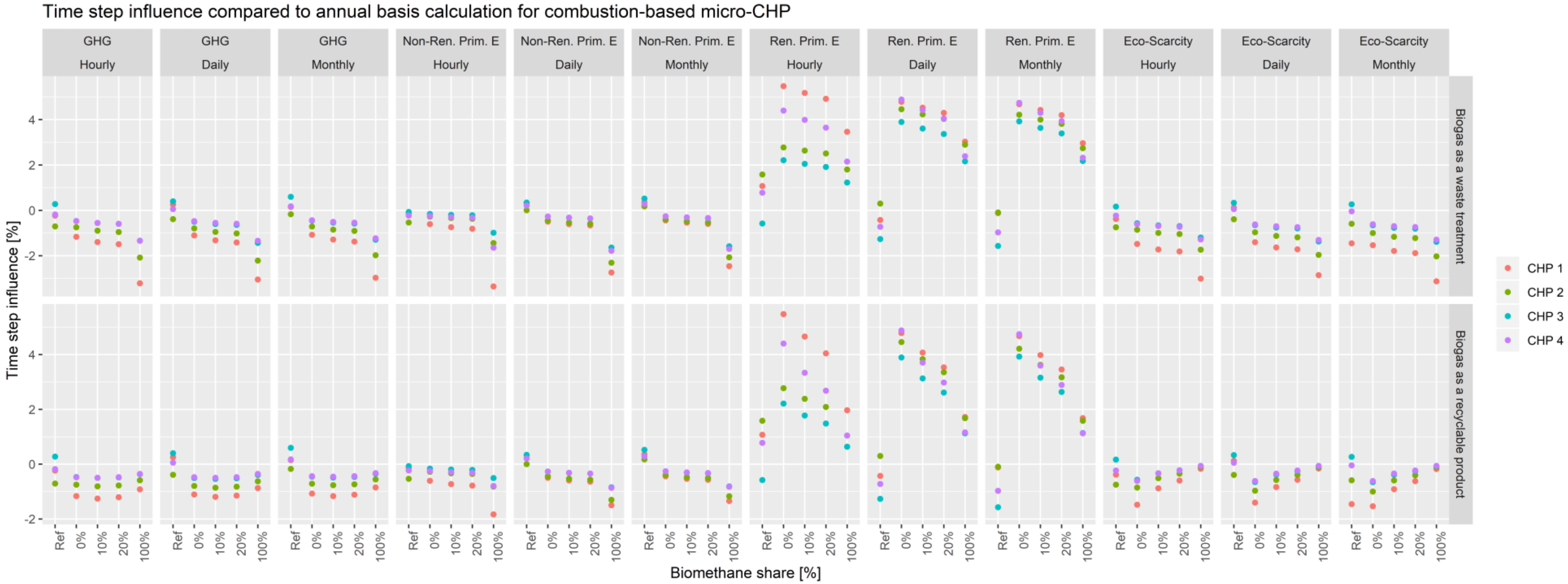

Figure 36 Time step influence considering the combustion-based micro-CHP units for the 4 case studies

From Figure 36, it appears that the time step influence is small. Except for the renewable primary energy indicator, the results among the different time step resolutions vary between -3 and 2%, at most (hourly VS annual calculations). The results for the RE indicator are slightly above (i.e. a maximum difference of 4.7% is observed from the annual calculation), which remains relatively low.

For the case where bio-methane comes from waste treatment, concerning the climate change indicator, the time step influence increases with the increase of the bio-methane share, for all case studies. Conversely, when the biogas is considered as a recyclable product, the higher the bio-methane share, the smaller the time step influence. This influence is generally smaller than for the biogas coming from waste treatment. This difference is explained, because of the higher unitary impact of the heat and electricity produced by the micro-CHP, for the biogas considered as a recyclable product. When comparing the results for the time step influence between the reference scenario and the micro-CHP (for the case of biogas as a recyclable product), for the latter the time step influence is smaller. This is explained by the fact that the electricity and heat produced by the micro-CHP have constant and high environmental impacts, unlike the electricity impacts of the reference scenario (electricity from grid) which has smaller impacts and a higher time sensitivity because 100% of the need is consumed from the grid.

The results of the eco-scarcity and non-renewable primary energy indicators lead to the same conclusions, as these of the climate change. For the case of biogas considered as waste treatment, the higher the bio-methane share the higher the time step influence, while the opposite trend is observed for the biogas, considered as a recyclable product. However, this time step influence remains insignificant (less than 3% in absolute term).

The renewable primary energy indicator is more sensitive to the time step choice. For all the case studies, the higher the bio-methane share, the smaller the time step influence, for both biogas scenarios. The lower the time step resolution, the less scattered are the results among the case studies, for both biogas scenarios. However, the overall magnitude and trend remain the same, among the different case studies. The relative differences, observed among the case studies, are related to their energy demand profiles. The time step influence is higher for the RE indicator, because of the high difference between the RE impact of the heat and electricity produced by the micro-CHP units compared to the impact for heat produced with a gas boiler fed with natural gas and electricity from the grid.

Thus, the time step influence for the RE indicator is higher than for other environmental indicators. This result can be explained by the high difference of the RE impacts of heat and electricity produced by the micro-CHP unit, among the different bio-methane shares and biogas origin scenarios. For example, the electricity coming from the grid has an average RE impact of 2.37 MJp/kWh, while the electricity produced by a micro-CHP has an impact ranging from 0.04 to 1 MJp/kWh (depending of the bio-methane shares and biogas origin scenario). Thereby, the difference between the impact from the grid and the impact from the micro-CHP is very large leading to a higher sensitivity of this indicator.

Nevertheless, the results of the four case studies show that the time step influence is insignificant, when considering combustion-based micro-CHP. The electricity produced by a micro-CHP has a constant environmental impact and thus it is not sensitive to the time step resolution. As a conclusion, it can be stated that it is not necessary to consider higher time resolutions, for the environmental impact assessment of the combustion-based micro-CHP.

4.1.2 Fuel-cells

The times step influence of the fuel-cell alternative is displayed in Figure 37.

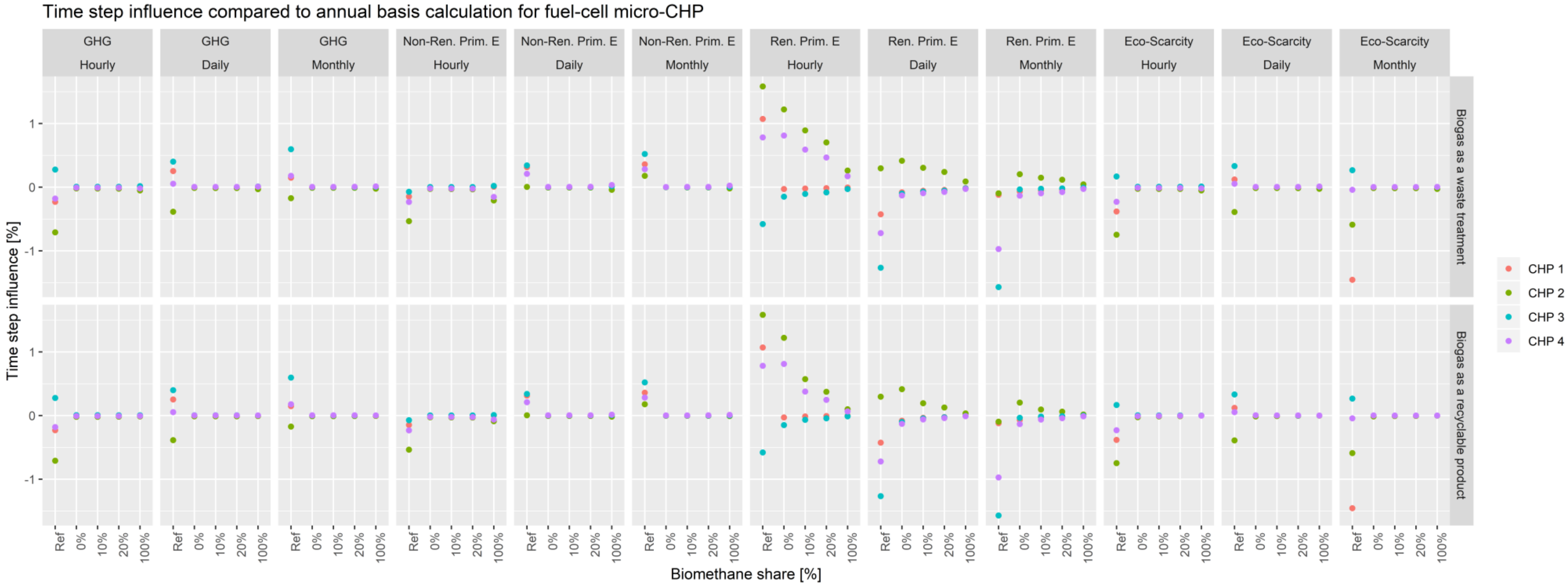

Figure 37 Time step influence considering the combustion-based fuel-cell unit for the 4 case studies

The time step influence is very small, when considering a fuel-cell micro-CHP. Indeed, as described in Table 10, the fuel-cell alternatives cover almost 100% of the building electricity demand. Thereby, the fluctuations related to the electricity from the grid are almost entirely trivialized given that the electricity impacts of the micro-CHP are constant.

The renewable primary energy indicator is the most influenced by the time step choice, for the cases that the fuel-cell units cover less than 100% of the electricity needs (i.e CHP 2 and CHP 4). The RE impacts of the grid electricity are higher than the electricity impacts of the fuel-cell units. Thereby, the small quantity of the electricity, coming from the grid, implies approx. 1% fluctuation, observed in Figure 37. By increasing the bio-methane share, the RE electricity impacts of the fuel-cell units increase and consequently the relative impacts of the grid electricity are trivialized. Thereby, the time step influence decreases, with the increasing share of bio-methane.

As a conclusion, it can be stated that the time step influence is negligible, for the fuel-cell micro-CHP. Therefore, it is not necessary to consider different time step resolutions.

4.2 Comparison of the micro-CHP performance with the reference case

In this section, the results of the comparison between the micro-CHP and the reference case scenario is presented. This comparison is performed for the hourly time step. This analysis provides interesting insights for possible future developments of micro-CHP in Switzerland. The figures for all the case studies and the different alternatives are given in the annex of the chapter 4-b. In the following sections, the results for representative case study CHP 1 are provided, as well as a summary of the main observations and findings for all the case studies.

4.2.1 Combustion-based units

The annual impact results for the CHP 1 case study with different indicators, scenarios and time steps are presented here. As an example, the monthly environmental profiles of the CHP 1 case study is given in Figure 38. The relative difference with the reference case is provided in

Table 12. The assessment and the results for the other case studies are displayed in annex of the chapter 4-b.

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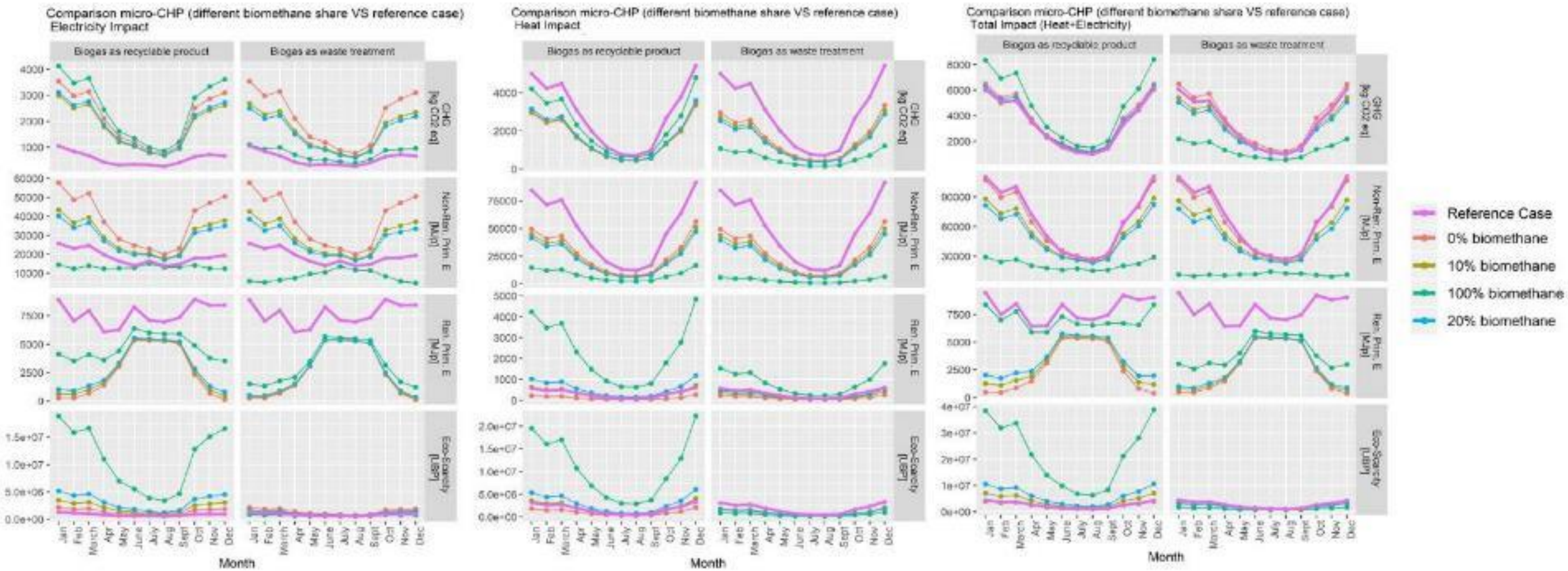

Figure 38 CHP1: Impacts of the reference case and the combustion based CHP for various bio-methane shares for 2018

		Impact of electricity use				Impact of heat production from micro-CHP				Total impacts of energy flows in the building			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	285%	197%	178%	34%	-44%	-48%	-52%	-79%	9%	-9%	-15%	-61%
	NRE	103%	57%	44%	-55%	-44%	-51%	-56%	-94%	-3%	-21%	-28%	-83%
	RE	-68%	-67%	-66%	-58%	-65%	-41%	-21%	160%	-67%	-66%	-64%	-49%
	ES	31%	6%	1%	-36%	-44%	-47%	-37%	-74%	-6%	-20%	-24%	-55%
Biogas as a recyclable product	Climate Change	285%	228%	241%	346%	-44%	-42%	-40%	-20%	9%	1%	5%	38%
	NRE	103%	59%	50%	-29%	-44%	-50%	-54%	-84%	-3%	-20%	-25%	-68%
	RE	-68%	-65%	-62%	-39%	-65%	4%	72%	622%	-67%	-62%	-56%	-12%
	ES	31%	99%	187%	893%	-44%	9%	63%	498%	-6%	58%	133%	728%

Table 12 Annual comparison of the reference case with the combustion based CHP option for various bio-methane shares (CHP1)

The environmental impacts are strongly influenced by the assumption, related to the biogas production, for all the indicators and the different energy uses. As far as the biogas as a recyclable product is concerned, the highest impacts are exhibited for the cases that the bio-methane covers 100%, for the climate change, the NRE and RE indicators and all the energy uses. On the contrary, in case that the biogas is considered as a product from waste treatment, the higher the bio-methane share is, the lower the impacts are. For the RE indicator, for both biogas models, the higher the bio-methane share, the higher the impacts. Thereby, the modeling choice regarding the biogas is a key issue. It is necessary to arrive at a consensus, concerning the way to model biogas.

Comparing the reference case to the two other biogas case scenarios (biogas as recyclable and as waste treatment) for the electricity, it can be shown that, independently of the bio-methane share, the impacts of the latter are higher than those of the reference scenario, for the climate change category. Indeed, the electricity from the grid has a smaller impact per kWh, than the electricity produced by the micro-CHP. When the biogas is considered as being issued from waste treatment, increasing the share of bio-methane, decreases the impact of the produced electricity for all indicators apart the RE. The contrary is observed when the bio-methane is considered as a recyclable product, i.e, the higher the bio-methane share, the higher the impacts of the electricity.

Regarding the non-renewable primary energy indicator, it is found that the higher the bio-methane share, the lower the electricity impacts. From 0% (in other words, 100% natural gas) to 20% of bio-methane share, the non-renewable primary energy indicator is higher than that of the reference scenario. However, with 100% of bio-methane, the scenario with a micro-CHP has lower impact than the reference scenario. As far as the renewable primary energy indicator is concerned, the impacts are found to be lower than the reference scenario, for both biogas models. Concerning the eco-scarcity and the biogas as waste treatment, the impacts decrease, by the increasing bio-methane share. The impact of the building electricity demand is lower than that of the reference scenario, for the case of a 100% bio-methane share. However, for a 0, 10 and 20% bio-methane share, the impacts are higher than those of the grid electricity. On the contrary, for the biogas as a recyclable product, the environmental impacts of the building electricity demand increase significantly with the bio-methane share. Thus, the micro-CHP should be avoided if this model assumption is made for the impacts of biogas.

Looking at the heat demand, the climate change impact is lower for the scenarios operated with micro-CHP, than the reference scenario. This result is related to the exergy allocation, used for apportioning the impact of the micro-CHP for the produced heat and electricity. Based on this allocation, most of the impacts, related to the use of a micro-CHP, are attributed to the electricity production and, thereby, the heat produced by the micro-CHP has a significantly smaller impact than the heat produced by a gas boiler operating with 100% natural gas (see annex of the chapter 4-b). In addition, with this exergy allocation even the scenario using a micro-CHP, but fueled with 100% natural gas (0% of bio-methane), has a smaller impact that the traditional gas boiler. As it was the case for the electricity impact, the heat impact is also significantly affected by the biogas model choice. When the biogas is considered to come from waste treatment, the impacts decrease with the increase of the bio-methane share, while the opposite trend is observed when the biogas is considered as a recyclable product. The results of the non-renewable primary energy indicator show that the scenarios with the micro-CHP have significantly lower impacts than the reference scenario, with the traditional gas boiler. This observation is valid for the different bio-methane shares (from 0% to 100%) and both biogas model choices. The lower NRE heat demand impacts, compared to the reference scenario, derive from the exergy allocation, as has already been described. In addition, it is found that by increasing the bio-methane share, the non-renewable primary energy impact diminishes, because of the decreasing non-renewable product.

The results, concerning the renewable primary energy indicator, show that by increasing the bio-methane share, the impacts gradually increase. For both biogas model choices, the highest impact occurs for a 100% bio-methane share. The main difference in the results for these two biogas modelling choices comes from the fact that, for the biogas as a recyclable product, the impacts of the scenarios with a 100% and 20% bio-methane share are higher than the reference scenario, while for the biogas as waste treatment, only the scenario of 100% bio-methane is higher. It can be also noticed that while the NRE indicator diminishes with the increasing bio-methane share, the opposite trend is exhibited by the renewable primary energy indicator. Regarding, the eco-scarcity indicator, the two model choices for biogas exhibit opposite trends. When the biogas is considered as a waste treatment, the higher the bio-methane share, the higher the impacts are, while the latter remain higher than the impacts of the reference scenario. On the contrary, when the biogas is considered as a recyclable product, the higher the bio-methane share, the lower the impacts are. In addition, these impacts are significantly higher than the reference scenario.

Looking at the total impacts and the climate change impact, for both biogas models, the impacts of the reference scenario are similar to those of the micro-CHP, for all the bio-methane shares (even for the expected bio-methane share in reality, i.e. approximately 20%), apart from that of 100%. When the biogas is considered as a recyclable product, the impacts of the micro – CHP are slightly higher (approximately 5%), than those of the reference scenario, while when it is considered as a waste treatment it is found to be slightly lower (approximately 15%). These differences are relatively small and this fact confirms that using a micro-CHP with a bio-methane share until 20% (for both choices of biogas modeling), does not imply a clear reduction of the climate change impact. However, for high bio-methane shares, i.e. 100%, the micro-CHP can significantly affect the climate change impact and the modelling choice of the biogas becomes critical. The climate change impact for the biogas coming from waste treatment is smaller than for the reference scenario and significantly smaller than for the impact for biogas when it is considered as a recyclable product. Thus, as it has already been mentioned, there is a clear need to refine the assumption concerning the biogas model choice, in order to reach a clear conclusion concerning the environmental impacts of biogas.

Regarding the two primary energy indicators, the impacts of micro-CHP scenarios are always smaller than the reference scenario. The micro-CHP with bio-methane, has a positive impact on the primary energies indicators by providing heat and electricity at the building level, compared to the reference situation (gas boiler + grid). For this indicator, both choices of biogas modeling present lower impacts than the reference scenario. Furthermore, the impacts of the eco-scarcity indicator are driven, again, by the biogas modelling choice. When biogas is assumed as being issued from waste treatment, the higher the bio-methane share, the lower are the impacts, while they are always smaller than the impacts of the reference scenarios. The results are the opposite for the biogas as a recyclable product. Thus, as it has already been mentioned, the biogas modelling choice can significantly influence the results.

The relative impacts of the four case studies compared to their respective reference scenarios are given in Figure 39. The detailed results are provided in the annex of the chapter 4-b.

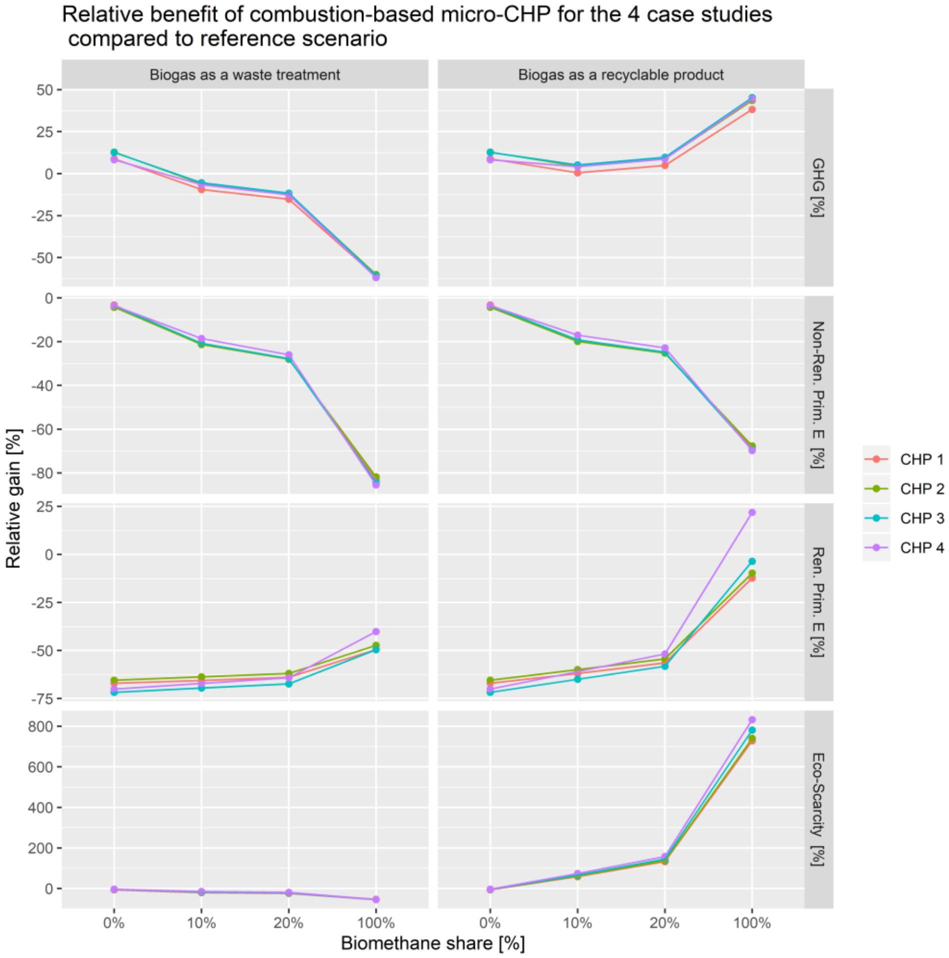

Figure 39 Relative benefits of the combustion-based micro-CHP units for the 4 case studies compared to the reference situation

Table 13 presents a summary of the results of the combustion-based micro-CHP environmental impacts, for all the case studies.

	Biogas from a waste treatment		Biogas as a recyclable product	
	Influence of the Bio-methane share increase	Impact compared to reference case	Influence of the Bio-methane share increase	Impact compared to reference case
Climate Change	↘	Higher than the reference case for approx. 5% bio-methane then lower	↗	Always higher than reference
NRE	↘	Always lower	↘	Always lower
RE	↗	Always lower	↗	Always lower for CHP 1 – 3, lower until a bio-methane share of 76% for CHP 4
ES	↘	Always lower	↗	Lower than the reference case for approx. 5% bio-methane then largely higher

Table 13 Summary of the observations & results regarding the combustion-based micro-CHP impact compared to the reference case

Looking to the Table 13 for the four case studies, the combustion-based micro-CHP alternatives present similar trends to the one described above for CHP 1. The biogas modelling choice remains a key parameter for the impacts and it is responsible for the opposite results of the climate change and the eco-scarcity indicators. The small differences, concerning the impacts among the four case studies, are related to their energy (heat and electricity) demand profiles.

The summary of the results for each case study is presented in the Table 14:

		Impact of combustion-based micro-CHP compared to reference case	
		Biogas from a waste treatment	Biogas as a recyclable product
CHP 1	Climate change	Always lower	Always above but until 20% max 5% above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Always lower
	Ecological scarcity	Always lower	Always above
CHP 2	Climate change	Always lower	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Always lower
	Ecological scarcity	Always lower	Always above
CHP 3	Climate change	Always lower	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Always lower
	Ecological scarcity	Always lower	Always above
CHP 4	Climate change	Always lower	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Lower until 76%
	Ecological scarcity	Always lower	Always above

Table 14 Summary of the main results regarding the four case studies

The results show that the micro-CHP impacts, for the biogas as a waste treatment, are systematically lower than the traditional reference scenario of the gas boiler and for different indicators, as well. In the case that the biogas is a recyclable product, the impacts of the ecological-scarcity and the climate change indicators are always above those of the reference scenario, while the primary energy indicators are always lower.

In general, the combustion-based micro-CHP should be promoted, instead of the traditional solution of the gas boiler, if the biogas is considered as a product of a waste treatment, but not if it is a recyclable product. However, this methodological question has to be further discussed by the LCA community.

4.2.2 Fuel-cells

The impact results for the CHP 1 case study, with a fuel cell, for the various indicators and alternatives are presented on a monthly environmental profiles in Figure 40. The relative differences with the reference case are given in Table 15.The assessment and the results for all the other case studies are displayed in the annex of the chapter 4-b.

As it was the case for the combustion-based micro-CHP, the environmental impacts are strongly influenced by the modeling assumption related to the biogas production. Indeed, the climate change and eco-scarcity indicators show the same trend as the combustion based micro-CHP, i.e. when the biogas is considered as a waste a treatment, the higher the bio-methane share, the lower are the impacts for both the heating and electricity needs (and therefore the total building energy demand). The opposite is observed, in the case that the biogas is considered as a recyclable product.

Regarding the primary energy indicators, their impacts are less sensitive to the biogas modelling choice. The fuel-cell micro-CHP NRE and RE total impacts (heat and electricity impacts) are lower than the impacts of the reference scenario. In both cases, by increasing the bio-methane share, the environmental impacts are reduced.

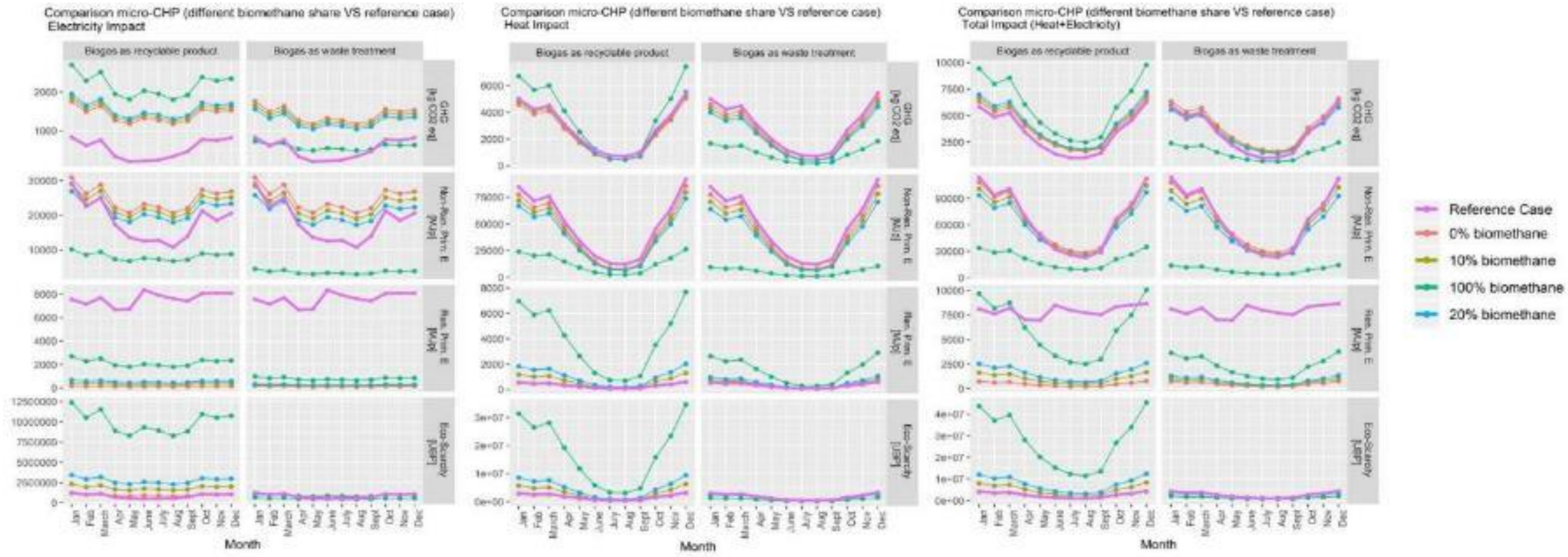

Figure 40 CHP1: Comparison reference case with a fuel cell unit for various bio-methane shares

		Impact of electricity use				Impact of the heat demand				Total impact of energy flows in the building			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	167%	152%	136%	11%	-12%	-17%	-23%	-68%	16%	9%	2%	-55%
	NRE	36%	25%	14%	-80%	-12%	-19%	-27%	-89%	1%	-7%	-16%	-87%
	RE	-98%	-97%	-96%	-90%	-7%	30%	66%	356%	-94%	-92%	-90%	-72%
	ES	14%	9%	4%	-36%	-10%	-15%	-20%	-57%	-2%	-7%	-12%	-50%
Biogas as a recyclable product	Climate Change	167%	182%	196%	310%	-12%	-8%	-4%	30%	16%	22%	28%	73%
	NRE	36%	28%	19%	-55%	-12%	-18%	-24%	-73%	1%	-5%	-12%	-68%
	RE	-98%	-95%	-93%	-72%	-7%	105%	217%	1110%	-94%	-87%	-80%	-24%
	ES	14%	122%	230%	1090%	-10%	79%	169%	888%	-2%	93%	189%	953%

Table 15 Annual comparison of the reference case with the fuel-cell CHP option for various bio-methane shares (CHP1)

The comparison between the fuel-cell scenario and the reference scenario shows, that the results are highly dependent to the allocation of the biogas impact, as it was the case for the combustion-based micro-CHP. Table 16 summarizes this comparison, for the electricity impact of the CHP 1 case study, while the results for the heat impact are presented in Table 17. The results for the other fuel cell micro-CHP case studies are displayed in Figure 41, while a summary of the combustion-based micro-CHP environmental impacts are given in Table 18.

Table 16 Key findings regarding the fuel-cell scenario compared to the reference case for the electricity demand for CHP 1

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Higher impact than the reference case. Significantly higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share - Increase of bio-methane share implies reduction of the impact - With 31% of bio-methane, the micro-CHP configuration implies an impact reduction compared to reference case
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies a small increase of the impact
	ES	- Impact higher than reference case until 20% of bio-methane but difference small - Increase of bio-methane share implies reduction of the impact - 28% of bio-methane implies an impact reduction compared to reference case
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend has the other allocation choice (but threshold at 39% of bio-methane share in the supply mix)
	RE	- Same trend has the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 17 Key findings regarding the fuel-cell scenario compared to the reference case for the heat demand for CHP 1

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact - Difference between all alternatives in summer is lower because is related to a small amount of energy demand for DHW
	NRE	- Same as climate change indicator
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Only the configuration with no bio-methane as a lower impact than the reference case
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower for fuel-cell than reference case until a bio-methane share of 28% then higher - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower for fuel-cell than reference case - Increase of bio-methane share implies a reduction of the impact
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Impact largely above the reference case
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

The building energy impact decreases by increasing the bio-methane share, for the NRE, RE, and ecological scarcity, for the biogas coming from waste treatment. For the climate change indicator, the impacts decrease for bio-methane shares higher than 22%. Thereby, for the assumption of the biogas from waste treatment, the fuel cell appears to be a promising solution to diminish the building energy demand environmental impact, when the bio-methane share in the supply mix is higher than 22%. In fact, the impact of the electricity coming from fuel cell is higher than the impact of the electricity from grid. However, the impact of the heat coming from fuel cell is by far lower than the heat coming from the gas boiler. Thus, the overall impact of the energy demand is thereby lower for the fuel cell alternatives.

When the biogas is considered as a recyclable product, the trend is not the same. For the climate change indicator, since the impacts of both heat and electricity increase with the increasing share of bio-methane, the overall impact of the building energy demand is also higher than the reference scenario. For the NRE indicator, the overall energy impact is lower for the fuel cell, compared to the reference case, and when increasing the bio-methane share, the impact diminishes. The RE indicator is also improved for fuel cells, compared to the reference scenario, but increasing the bio-methane share reduces the environmental gain. Finally, the ecological scarcity impact is significantly higher for the fuel cell scenarios, especially when the bio-methane share is 100%.

It becomes evident that for the fuel cell scenario, the allocation choice, regarding the biogas production, is again a key factor, especially for the ecological scarcity and climate change indicators. For the NRE and RE, it seems that in any case the fuel cell has lower impacts, when operated with bio-methane. The question regarding the biogas allocation has thereby to be solved. It is difficult for non-LCA practitioners, to understand why, for some bio-methane production chains, the impact is zero and thereby the electricity and heat obtained via a micro-CHP is low and, conversely, for other production process the impact would be drastically high and would lead to reject micro-CHP as a technical solution for heat and electricity at building level.

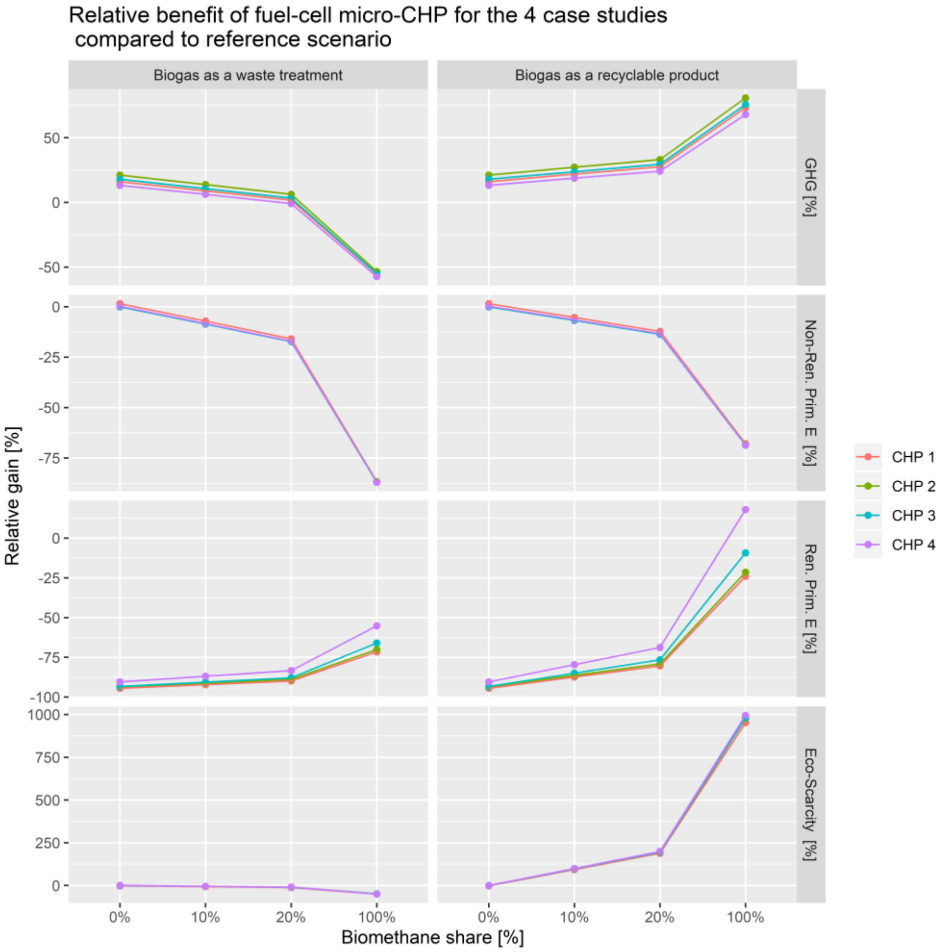

Figure 41 Relative benefits of the fuel-cell micro-CHP units for the 4 case studies compared to the reference situation

Table 18 Summary of the results regarding the fuel cell micro-CHP environmental impacts compared to the reference case

	Biogas from a waste treatment		Biogas as a recyclable product	
	Influence of the Bio-methane share increase	Impact compared to reference case	Influence of the Bio-methane share increase	Impact compared to reference case
Climate Change	↘	Higher than the reference case unitl approx. 23% bio-methane then higher	↗	Always higher than reference
NRE	↘	Always lower	↘	Always lower
RE	↗	Always lower	↗	Always lower for CHP 1 – 3, lower until a bio-methane share of 83% for CHP 4 then higher
ES	↘	Always lower	↗	Lower than the reference case for approx. 0.2% bio-methane then largely higher

The results of the four case studies, for the fuel-cell micro-CHP scenarios present similar results and trends, as these of the CHP 1. There are only very small differences regarding the four case studies that are related to the building energy (heat and electricity) demand profiles. These variations are summarized in Table 19.

Table 19 Summary of the results regarding the fuel cell micro-CHP environmental impacts compared to the reference case

		Impact of fuel-cell micro-CHP compared to reference case	
		Biogas from a waste treatment	Biogas as a recyclable product
CHP 1	Climate change	Higher until 23%	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Always lower
	Ecological scarcity	Always lower	Always above
CHP 2	Climate change	Higher until 28%	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Always lower
	Ecological scarcity	Always lower	Always above
CHP 3	Climate change	Higher until 25%	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Always lower
	Ecological scarcity	Always lower	Always above
CHP 4	Climate change	Higher until 19%	Always above
	Non-renew. E	Always lower	Always lower
	Renew-E	Always lower	Lower until 83%
	Ecological scarcity	Always lower	Always above

The results of the fuel cell micro-CHP are similar to those of the combustion-based micro-CHP, when biogas comes from waste treatment. A minimum of 30% bio-methane share in the gas network would ensure that the fuel-cell micro-CHP scenario would have lower impacts for any impact category and configuration. Regarding the other assumption (biogas as a recyclable product), the climate change and ecological scarcity indicators always are higher than the reference case and in this situation, a fuel-cell micro-CHP is not recommended.

5. Conclusion

The chapter 4-b studies the influence of the time-step for decentralized electricity production systems, other than photovoltaics. The micro-CHP has been chosen, because it is very different from the PV installation. Indeed, the former produces electricity at the time the heat is needed, mainly in winter. By assessing different micro-CHP configurations, a different very different decentralized electricity production system than PV installation is thus considered.

Different shares of bio-methane in the supply mix have been considered, as well as 100% natural gas (0% of bio-methane). Low shares, i.e. 10% and 20% correspond to the short-term objective of the gas industry or the current production configuration. The 100% supply scenario was chosen, in order to assess the maximum potential of using bio-methane. Two micro-CHP technologies were considered, the combustion-based units and the fuel-cell units. The latter was found to be a beneficial solution that could be applied in the near future in Switzerland. The EcoDynBat project covered 36 alternatives and 1’028 different results were assessed. Common trends were observed among the different studied scenarios. The influence of time step is found to be negligible for all the assessed configurations and all the environmental indicators. The micro-CHP units substitute the electricity from the grid, which has a variable impact with electricity directly produced that has a constant impact. Thus, the time step influence is smaller for the electricity, coming from a micro-CHP, than for the electricity taken from the grid. Thus, considering hourly, daily or monthly time step for the environmental impact calculations of buildings equipped with a micro-CHP unit is not necessary. From both 4-a and 4-b chapters, it appears that the taking into account different time steps is important only when a significant share of the building electricity demand is supplied from the grid and has a high seasonality.

Following this study, the results of the micro-CHP alternatives were compared to the reference scenario. This comparison showed that the assumptions concerning biogas impacts, are critical for the environmental impacts and led to important variations of the results. The biogas life cycle inventories are significantly heterogeneous. For two of the four inventories (biogas from sewage sludge and biogas from biowaste), the biogas is found to have zero impact per m^3 (see the annex of the chapter 4-b for details). While for the two other options, especially when biogas is produced from manure, the impacts are especially high compared to natural gas. However, it was not the purpose of the EcoDynBat project to verify the best modeling choice for the biogas impacts. Thus, it has been decided to provide the results for the two extreme cases, i.e. for biogas that has no impact (e.g. biogas produced, from sewage sludge in wastewater treatment plant, according to ecoinvent V3.4) and for biogas that has the maximum impact (i.e. biogas produced from manure). These results were computed, in order to provide a complete picture of the micro-CHP potential in the Swiss building.

If the biogas is considered as being impact free (i.e from a waste treatment), the micro-CHP units present an efficient solution of a low environmental impact system. This result is valid for all the studied indicators and for any bio-methane share for the combustion-based micro-CHP, while the fuel cell micro-CHP options is beneficial when the share of bio-methane goes above 30% in the Swiss mix. For this assumption, the higher the bio-methane share is, the lower the buildings overall impacts are. The mid-term objective of the gas supplier to achieve a 30% share of bio-methane would be, thus, a starting point.

When biogas is considered as a recyclable product, the climate change and ecological scarcity impacts of buildings are significantly higher than the impacts for the reference case. Indeed, using a micro-CHP with 100% natural gas is more beneficial than the micro-CHP, no matter what the bio-methane share is. Moreover, the impacts increase with the increasing bio-methane share in the gas supply mix. Thereby, for a 100% of bio-methane share, the produced electricity has a higher climate change impact than the electricity produced by a coal power plant. There can be a factor of 4 between the impacts of the electricity coming from bio-methane produced by sewage sludge and from bio-methane produced by manure.

With a micro-CHP unit, both heat and electricity are produced simultaneously. It is therefore necessary to allocate the impacts, separately. The exergy allocation approach has been used, according to which a large part of the impact is apportioned to the electricity production. Therefore, the produced electricity via the micro-CHP has higher impacts than that of the grid. Conversely, the heat produced by the micro-CHP units has significantly lower impacts than the heat produced by a traditional gas boiler. Within the four case studies, when biogas production is considered to have no impact, the low environmental impacts of the heat production counterbalances the high environmental impacts of the electricity.

ECODYNBAT Project

Dynamic Life Cycle Assessment of Buildings

Chapter 5: Sensitivity Analysis (WP5)

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Summary

This report presents several sensitivity analyses that have been carried out in relation to the dynamic considerations of the environmental impacts of the electricity demand of buildings in Switzerland. It aims to extend the results of the case studies that were carried out in previous EcoDynBat project reports.

In a first step, an analysis of the environmental impacts of a multi-family dwelling building including photovoltaic installations and batteries of various sizes was carried out. This study considers :

- variable sizes of installations,
- standard" battery discharge control approaches (i.e. to maximise self-consumption) or climate change oriented (i.e. allowing the building to go off the grid when its impact is high),
- the influence of the time step in calculating the environmental benefits of batteries (annual or hourly),
- a prospective scenario considering the phase out of Swiss nuclear production, replaced by imports from the neighboring countries,
- the calculation of environmental benefits in terms of non-renewable primary energy.

The results of these studies show that the environmental benefits of batteries in Switzerland exist but are currently limited, in particular due to the low environmental impact of grid electricity. The use of a control strategy to avoid consumption from the grid during peak times of its environmental impact improves the environmental benefit only slightly compared to traditional battery management. Taking an hourly time-step resolution of the GWP factor rather than an annual value, reduces the annual GHG emission savings, as the battery use can be disadvantageous when the hourly impacts of the Swiss electricity grid in summer have been identified as low.. In the case for which the Swiss nuclear production is replaced by imports (pessimistic prospective case), the environmental benefits of battery use are increased. In terms of non-renewable primary energy, the use of a photovoltaic system + battery implies a significant decrease in impacts. These results are valid for the case study that was used and cannot be generalized to the whole Swiss building stock. Further studies would be necessary to provide an overview of the environmental impacts of PV+battery systems.

In a second step, Global Sensitivity Analyses (GSA) were carried out to quantify in terms of variance the influence of time step in the calculations of the environmental impacts of buildings compared to other parameters. A first analysis at the scale of a single building and considering a variability on the size of the photovoltaic installation, its production and the interannual variation of the environmental impacts of Swiss electricity shows that the influence of the time step is the most important for the category of impact on climate change (for the other indicators, this influence is marginal). However, in the case of the climate change impact category, the influence of the interannual variability parameter (i.e., the variation in the environmental impact of the Swiss electricity grid between years) significantly outweighs the influence of the time step. It therefore appears that interannual variability is a key element to be taken into account in the calculation of the environmental impacts of buildings in the first place, followed by intra-annual considerations. A second GSA was carried out by considering several buildings of the same typology (single-family buildings) but with different load profiles. In this GSA, the variance of the environmental impacts is essentially explained by the choice of building and the interannual parameter of the impacts of grid electricity in Switzerland. The influence of the time step thus becomes marginal for all the environmental indicators.

Finally, a sensitivity analysis is carried out by varying the seasonal demand profile. For this purpose, a theoretical model of the building's electricity demand has been defined. This model makes it possible to vary the amplitude and duration of seasonal demand over a year. The relative difference between the environmental impact results on an hourly and annual basis was then calculated for several demand profiles. From this study, it appears that the hourly time step can present very different impact results from those obtained by a calculation on an annual basis, in the case of high seasonality (high amplitude of seasonal demand over a short duration), particularly for the impact category relating to climate change.

These results therefore confirm and extend the observations made on the case studies (see chapter 4 report). Further work appears necessary to define an approach to calculate the environmental impacts of the electricity demand of buildings in the long term. This approach should take into account the future major modification of the Swiss electricity supply mix, the interannual uncertainty and the emergence of solutions for the production, piloting and energy management of buildings, including in particular batteries, which could make the intra-annual considerations worth to consider.

Résumé

Ce rapport présente plusieurs analyses de sensibilité qui ont été réalisé en lien avec les considérations dynamiques des impacts environnementaux de la demande électrique des bâtiments en Suisse. Elle vise à étendre les résultats des cas d'études qui ont été réalisés dans les précédents rapport du projet EcoDynBat.

Dans un 1er temps, une analyse des impacts environnementaux d'un bâtiment d'habitations collectives incluants des installations photovoltaïques et des batteries de tailles variable a été réalisée. Cette étude considère :

- des tailles variables d'installations,
- des approches de pilotage de la décharge de la batterie « standard » (i.e pour maximiser l'autoconsommation) soit orienté changement climatique (c'est-à-dire en permettant au bâtiment de s'effacer du réseau lorsque son impact est élevé),
- l'influence du pas de temps pour le calcul des bénéfices environnementaux des batteries (annuel ou horaire),
- un scénario prospectif considérant la suppression de la production nucléaire Suisse, remplacée par des importations,
- le calcul des bénéfices environnementaux en terme d'énergie primaire non-renouvelable.

Les résultats de ces études montrent que les bénéfices environnementaux des batteries en Suisse existent mais sont restreints actuellement, en particulier du fait du faible impact environnemental de l'électricité du réseau. L'utilisation d'une stratégie de contrôle orienté vers un effacement du bâtiment sur le réseau en période de pointe des impacts environnementaux de celui-ci améliore faiblement le bénéfice environnemental par rapport à une gestion traditionnelle de la batterie. La prise en compte du pas de temps horaire pour le calcul des bénéfices environnementaux, sur la catégorie d'impact portant sur le changement climatique, des batteries réduit l'intérêt puisque la batterie sera très sollicitée en été, lorsque les impacts du réseau électrique Suisse ont été identifiés comme faible. Dans le cas où la production nucléaire Suisse serait remplacée par des importations (cas prospectif pessimiste), les bénéfices environnementaux liés à l'utilisation de la batterie sont augmentés. En terme d'énergie primaire non-renouvelable, l'utilisation d'un système photovoltaïque + batterie permet une baisse important des impacts. Ces résultats sont valides pour le cas d'étude qui a été utilisé et ne peuvent pas être généralisé à l'ensemble du parc de bâtiment Suisse. Des études supplémentaires seraient nécessaire pour fournir une vue d'ensemble des impacts environnementaux des systèmes PV+batterie.

Dans un 2ème temps, des Analyses Globales de Sensibilité (GSA) ont été réalisée pour quantifier en terme de variance l'influence du pas de temps dans les calculs des impacts environnementaux des bâtiments par rapport à d'autres paramètres. Une première analyse à l'échelle d'un seul bâtiment et en considérant une variabilité sur la taille de l'installation photovoltaïque, son productible et la variation interannuelle des impacts environnementaux de l'électricité suisse montre que l'influence du pas de temps est la plus importante pour la catégorie d'impact sur le changement climatique (pour les autres indicateurs, cette influence est marginale). Toutefois, même dans le cas de la catégorie d'impact sur le changement climatique, l'influence du paramètre de variabilité interannuel (i.e, la variation de l'impact environnemental du réseau électrique suisse entre les années) surpasse fortement l'influence du pas de temps. Il apparait donc que la variabilité interannuelle soit un élément clef à prendre en compte dans

le calcul des impacts environnementaux des bâtiments en premier lieu, puis ensuite les considérations intra-annuelles. Une deuxième GSA a été réalisé en considérant plusieurs bâtiments de même typologique (habitation individuelle) mais aux profils de charge différents. Dans cette GSA, la variance des impacts environnementaux est essentiellement expliquée par le choix du bâtiment ainsi que le paramètre interannuel de variabilité des impacts de l'électricité réseau en Suisse. L'influence du pas de temps devient alors marginale pour l'ensemble des indicateurs environnementaux.

Finalement, une analyse de sensibilité est réalisée en faisant varier le profil saisonnier de la demande. Pour ce faire, un modèle théorique de demande électrique du bâtiment a été défini. Ce modèle permet de faire varier l'amplitude et la durée de la demande saisonnière sur une année. La différence relative entre les résultats d'impact environnemental sur une base horaire et annuelle a ensuite été calculé pour plusieurs profil de demande. De cette étude, il apparait que le pas de temps horaire peut présenter des résultats d'impacts très différents de ceux obtenus par un calcul sur une base annuelle, dans le cas d'une forte saisonnalité (forte amplitude de la demande saisonnière sur une durée réduite) en particulier pour la catégorie d'impact portant sur le changement climatique.

Ces résultats confirment et étendent donc les observations réalisées sur les cas d'études (cf. rapport du WP4). Des travaux ultérieurs apparaissent comme nécessaire pour définir une approche de calcul des impacts environnementaux de la demande électrique des bâtiments sur le long terme en considérant la future modification majeure du mix d'approvisionnement électrique Suisse, l'incertitude interannuelle et l'émergence de solution de production, pilotage et gestion énergétique des bâtiments incluant en particulier des batteries qui pourraient rendre les considérations intra-annuelles prégnantes.

Zusammenfassung

Dieser Bericht beinhaltet mehrere Sensivitätsanalysen, die im Zusammenhang mit den dynamischen Aspekten zu den Umweltbelastungen des Strombedarfs von Gebäuden in der Schweiz durchgeführt wurden. Er zielt darauf ab, die schon erzielten Ergebnisse der vorhergehenden Berichte des EcoDynBat-Projektes zu erweitern.

In einem ersten Schritt wurde eine Analyse der Umweltbelastungen eines Mehrfamilienhauses mit Photovoltaikanlagen und Batterien unterschiedlicher Größe durchgeführt. Diese Studie untersucht :

- die unterschiedliche Grösse der Anlagen
- umweltfreundliche Ansätze zur Kontrolle der Entladung einer «Standard»-Batterie (z.B. um ihren Eigenverbrauch zu erhöhen bzw. es einem Gebäude zu ermöglichen, sich aus dem Netz auszuschalten, falls die Umweltabelastungen zu hoch werden)
- Den Einfluss des Zeitschrittes auf die Berechnung des Umweltnutzens von Batterien (jährlich oder stündlich)
- ein vorausschauendes Szenario, das den Atomausstieg der Schweiz in Betracht zieht und durch Stromimporte ersetzt
- die Berechnung des Umweltnutzens von nicht erneuerbarer Primärenergie.

Die Ergebnisse der Studien zeigen, dass der Umweltnutzen von Batterien in der Schweiz nur beschränkt vorhanden ist und dies wegen der geringen Umweltbelastung des Stromnetzes. Wird eine Kontrollstrategie angewendet, die das Gebäude in Zeiten hoher Umweltbelastung vom Netz nimmt, verbessert dies leicht den Umweltnutzen in Bezug auf eine traditionelle Steuerung der Batterie. Von geringem Interesse ist es, den stündlichen Zeitschritt bei der Berechnung des Umweltnutzens von Batterien in der Kategorie Klimaauswirkungen zu berücksichtigen, da die Batterie im Sommer, wenn die Belastungen des Schweizer Stromnetzes als gering eingestuft werden, stark nachgefragt wird. Für den Fall, dass die schweizerische Kernenergieerzeugung durch Importe ersetzt wird (pessimistischer Prognosefall), erhöht sich der Umweltnutzen der Batterienutzung. Was die nicht erneuerbare Primärenergie betrifft, so ermöglicht die Verwendung eines Photovoltaiksystems + Batterie eine erhebliche Verringerung der Belastungen. Diese Ergebnisse sind für die verwendete Fallstudie gültig und können nicht auf den gesamten Schweizer Gebäudebestand übertragen werden. Weitere Studien wären notwendig, um einen Überblick über die Umweltauswirkungen von PV+Batteriesystemen zu erhalten.

In einem zweiten Schritt wurde eine Global Sensitivity Analysis (GSA) durchgeführt, um den Einfluss des Zeitschrittes bei der Berechnung der Umweltbelastungen von Gebäuden im Verhältnis zu anderen Parametern in Bezug auf die Varianz zu quantifizieren. Eine erste Analyse an Hand eines einzelnen Gebäudes und unter Berücksichtigung der Variabilität der Grösse der Photovoltaikanlage, ihrer Stromerzeugung und der zwischenjährlichen Schwankung der Umweltbelastungen des Schweizer Stroms zeigt, dass der Einfluss des Zeitschrittes für die Wirkungskategorie Auswirkungen auf den Klimawandel am wichtigsten ist (für die anderen Indikatoren ist dieser Einfluss marginal). Bei der Wirkungskategorie Klimaänderung übertrifft allerdings ebenfalls der Einfluss des Parameters der zwischenjährlichen Schwankung (d.h. die Variation der Umweltbelastung des Schweizer Stromnetzes zwischen den Jahren) den Einfluss des Zeitschritts deutlich. Daher scheint es, dass die zwischenjährliche Schwankung ein Schlüsselelement ist, das bei der Berechnung der Umweltbelastung von Gebäuden zuerst berücksichtigt werden muss, gefolgt von interjährlichen Aspekten. Eine zweite GSA wurde unter Betrachtung mehrerer Gebäude des gleichen Typs (Einfamilienhaus) aber unterschiedlichen Lastprofilen durchgeführt. In dieser GSA wird die Schwankung der Umweltbelastungen im Wesentlichen durch die Wahl des Gebäudes und dem zwischenjährlichen Parameter der Variabilität der Auswirkungen von Netzstrom in der Schweiz erklärt. Der Einfluss des Zeitschrittes wird damit für alle Umweltindikatoren marginal.

Abschliessend wurde eine GSA durchgeführt, bei der das jahreszeitliche Bedarfsmuster variiert wurde. Dazu wurde ein theoretisches Modell zum Strombedarf eines Gebäudes erstellt. Dieses Modell erlaubt es, den Umfang und die jahreszeitliche Nachfrage über ein Jahr hinweg zu variieren. Die relative Abweichung zwischen den Ergebnissen der Umweltbelastung auf Stunden- und Jahresbasis wurde dann für mehrere Nachfrageprofile berechnet. Aus dieser Studie scheint hervorzugehen, dass der stündliche Zeitschritt bei starker Saisonabhängigkeit (hohe Schwankung der saisonalen Nachfrage über eine verkürzte Dauer) insbesondere für die Wirkungskategorie Klimawandel ganz andere Wirkungsergebnisse liefern kann als bei einer Berechnung auf Jahresbasis.

Diese Ergebnisse bestätigen und erweitern folglich die Beobachtungen der Fallstudien (siehe Bericht WP-4). Weitere Arbeiten erscheinen deshalb notwendig, um einen Ansatz für die langfristige Berechnung der Umweltbelastungen des Strombedarfs von Gebäuden zu definieren. Hierbei sollten künftige bedeutende Veränderung des schweizerischen Stromversorgungsmixes, die zwischenjährliche Unsicherheit und die Entstehung von Lösungen für die Produktion, die Steuerung und das Energiemanagement von Gebäuden, insbesondere auch von Batterien, berücksichtigt werden, die innerjährliche Aspekte zu einem Schlüsselfaktor machen könnten.

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1. Introduction

The present chapter on sensitivity analysis aims at broadening the scope of the EcoDynBat study by 1- considering the emergence of battery implementation within buildings and 2- evaluating how the variability and uncertainty of some parameters influence the environmental impacts of electricity demand in buildings. Different theoretical building configurations are taken into account, in order to proceed to a thorough sensitivity analysis of the impacts. For this reason, the following analysis have been performed:

1- The influence of the PV + battery installations in buildings is assessed in term of their environmental impacts (climate change and NRE) of the case study CS5 (multi-family house, see chapter 4-a) has been assessed. This study aims at providing some first insight regarding the interest of storage capacity within building in Switzerland considering the dynamic impacts of the Swiss consumed electricity. To do so, various configurations for storage size and energy management strategies are considered.

2- A Global Sensitivity Analysis (GSA) and variance base decomposition with Sobol Indices calculation has been performed, in order to evaluate how the time step resolution influences the impacts of the grid electricity, compared to the inter – annual variability of the grid electricity and the photovoltaic installation characteristics (peak power, specific production yield, etc.). This study is performed for the case study CS1 (single family house, see chapter 4-a)

3- A GSA has been performed by including (in addition of the above presented GSA) various specific building load profile in order to position the time step influence when comparing different building together

4- The influence of the time step resolution was then assessed by varying the seasonality of the building energy profile with scenario analysis performed via Monte Carlo simulations. This assessment provides information on the range of results variation that can be linked to the time step resolution as a function of the seasonality in the building energy demand.

2. Influence of PV size and storage

2.1 Objectives

In this study, the influence of the Self Generation System (SGS) including photovoltaic installation of various size and battery of various capacity is considered. It aims at quantifying how the environmental impacts of the building electricity demand can be affected by such SGS system encompassing the time step consideration and the dynamic aspect of the Swiss consumed electricity impacts.

To do so, the Multi-family House (MFH), described in WP4, will be used as the basis of comparison for the sensitivity assessment of technical and environmental factors. The relative difference in the environmental impact will be assessed while changing the:

- **time step** – this aspect was thoroughly analysed in WP4. Yet, as this study adds energy storage systems to the case study, it is deemed valuable to repeat the evaluation, but limiting it to the hourly and annual GWP factors (i.e. min-max temporal precision).
- **control approach** – an optimization control scheme that aims to reduce the sum of the daily GHG emissions will be applied, considering the hourly GWP[10] impact factor dataset developed in EcoDynBat.
- **grid supply mix** – as an LCA considers the building energy system over its full lifetime, and that the current Swiss Energy Strategy 2050 aims to achieve a phase-out of national nuclear energy sources within the lifetime of the current building stock. As such, an extremely pessimistic case of a future grid mix will be presented, where Switzerland has not developed any alternative local power generation sources, and the present portion of the national nuclear power in the grid mix is replaced by imports.
- **environmental impact factor** – both GWP and NRE impact indicators will be considered in order to quantify the potential of the energy storage for both aspects.

In addition, each scenario was simulated with twelve different PV and battery combinations to assess the sensitivity of the results to different designs of a Self Generation Systems[11] (SGS). The results will be evaluated in terms of the relative change within a scenario, and relative difference between the scenario results for each SGS and a reference scenario (Figure 42).

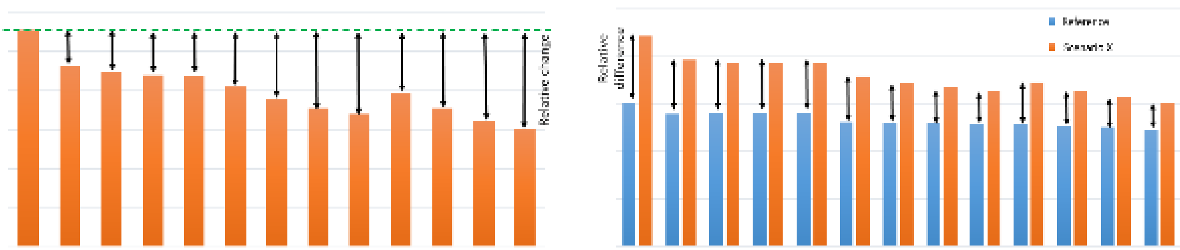

Figure 42: Sensitivity analysis in terms of relative change and relative difference in the results

[10] *In the following document the Global Warming Potential (GWP) indicator, the Climate Change indicator, and the GHGe indicator are interchangeable and all refer to the unit of kg CO_2-eq. per kWh.*

[11] *In the following document Self Generation Systems (SGS) refers to the entire system, which includes both the energy generation and storage equipment.*

2.2 Reference Case

The reference case is based on the energy consumption data of 2016-2017 of a Multi-Family House (MFH) in Gland (CS5 and CHP1 defined in WP4). For the sake of this study, the heating supply will be modeled for an Air to Water Heat Pump (AWHP), rather than the district heating system of the original building. This assumption follows the gaining popularity of HPs, which reached about 70% of the heating market share for buildings between 2001-2014 (Arpagaus, Vetsch, and Bertsch 2016) and therefore results might reflect a large portion of modern buildings heating systems. The general characteristics of the MFH are provide in Table 20.

Table 20: Building characteristics

Type	Multi-family house
ERA [m^2]	2663
Space heating and DHW system	Heat pump
Peak hourly average electricity consumption [kW_p]	46
Average annual electricity consumption [kWh/year]	88 592
Specific thermal demand [kWh/m^2]	35

From the case studies in WP4, it was deduced that there was no significant difference between the environmental impacts of a HP with a constant or variable Coefficient of Performance (COP). Therefore, a simplified approach using the average COP of 2.85 is used in this study to asses the electricity that is drawn by the HP. The resulting total hourly electric load distribution for the two years assessed is depicted in Figure 43. From the load curve it can be understood that the average hourly electrical demand remains below 10 kWh for about 60% of the time. It can be seen from the heat map that the average load tends to be higher in the winter, and that regardless of the month, on average the peak load occurs in the evening, approximately around 19:00, while a smaller peak is observed around 7:00 in the morning. The characteristics of the load can influence the effectiveness of a self-generation system, and, such as in this case, can support the use of a battery to meet the peak loads that occur during hours of low to null PV power generation.

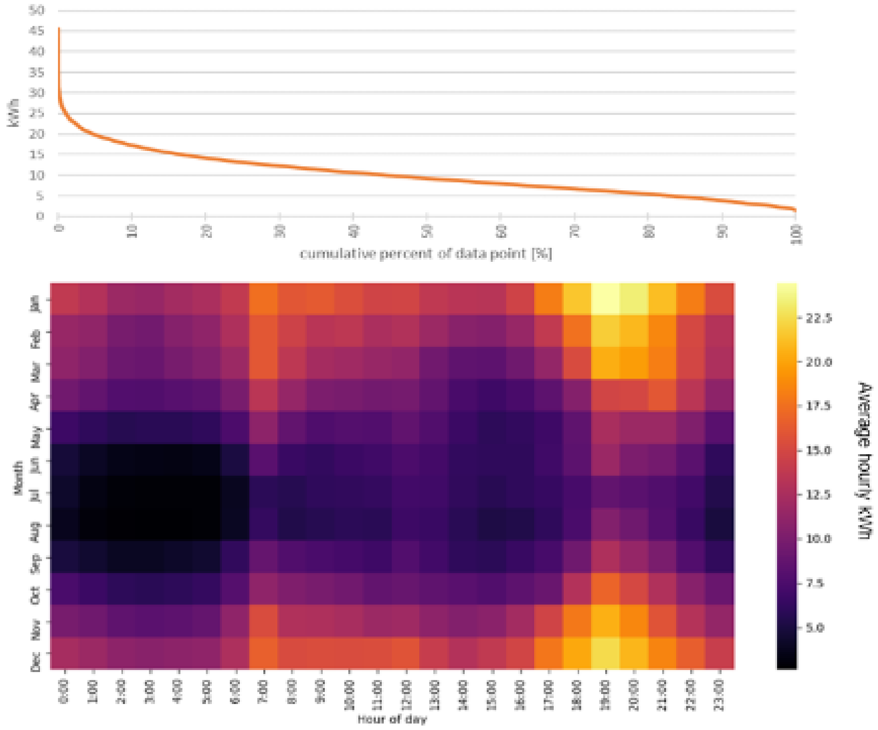

Figure 43: Profiling of the MFH total electric load – Cumulative load curve (top) and average hourly load map (bottom)

2.3 Key Performance Indicators

The analysis of the relative change in the results due to the SGS design is performed on two levels. The first focuses on the annual performance of the systems in terms of the energy sources used to meet the load, while the second focuses on the environmental repercussions from an LCA perspective.

2.3.1 Energy KPIs

Two KPIs relate to the PV energy that is used in the building and the resulting reduction in the consumed energy from the grid:

- The Self-Consumption (SC) factor represents the proportion of the on-site generation (G), which is utilised in the building. It is expressed, as $SC = G_{kWh\ used\ in\ building} / G_{kWh\ total\ produced}$

- The Self-Generation (SG) factor represents the percentage of the annual electrical load (L) that is covered by the on-site electricity generation (G) (Salom et al. 2014; Barzegar, Zhang, and Kummert 2018) and is defined as $SG = G_{kWh\ used\ in\ building}/L_{total\ kWh}$

2.3.2 Environmental KPIs

The environmental performance of the energy system is reviewed from a LCA perspective, taking into account the Life Cycle Inventory (LCI) of both the PV and the battery systems.

Building Energy System Emissions

In the model, the electricity consumed in the building comes from three possible sources, the grid (E_G), PV Directly Self Consumed (E_{PV-DSC}), and PV energy stored and discharged from the battery (E_{PV-BAT}). The annual emissions attributed to the electricity from each energy source is the product of the hourly energy and its corresponding GWP indicator:

$$GHG_i = \sum_0^{t=8760} E_i^t * GWP_i^t$$

In this study only accounts for the energy that was consumed by the building. As such, the total building emissions related to its electricity consumption are calculated as:

$$GHG_{building} = E_G * GWP_G + E_{PV-DSC} * GWP_{PV-DSC} + E_{PV-BAT} * GWP_{PV-BAT}$$

The GWP indicators for each source are as follows:

- **Grid energy** – this indicator changes for every time-step and is based on the EcoDynBat dataset.
- **PV energy Direct Self-Consumption (PV-DSC)** –The current study uses a constant GWP_{PV-DSC} of 0.083 kg CO_2-eq per kWh used in the building (see WP3 for more details). This value has been calculated by considering the environmental impact of the PV installation manufacturing (taken from ecoinvent) and the specific on site production based on the EcoDynBat simulation (see details in the WP2 chapter). This value is assumed to be constant in the following calculations since only the CS5 building has been considered. There is no size effects considered, i.e, the doubling the size for the PV installation implies a doubled electricity production (linear assumption).
- **PV energy discharge from battery (PV-BAT)** – the emissions of the solar energy that was first stored in the battery and later used in the building include the emissions attributed to both the PV and the battery energy. The environmental impact of the battery production in this study is 185 kg CO_2 eq. per kWh of storage capacity (kWh_c) and the battery life is 5000 cycles (B_L), as used in Stolz et al. (2018). In order to obtain an estimation of the GWP factor for each kWh stored and used in the building over its lifetime, the GHG emissions of the capacity is divided by the lifetime cycles, resulting in 0.037 kg CO_2 eq. per kWh discharged (kWh_d) in the building. The final sum of emissions of both the PV and of the battery is thus equal to a constant value of 0.12 kg CO2 eq. per kWh discharged.

Carbon Payback Time

To calculate the Carbon Payback Time (CPBT), the following general equation has been used:

$$CPBT = \frac{GHG_{System,total\ GHG\ emissions}\ [kg\ CO_2 eq.]}{System_{total\ GHG\ saved\ per\ year}\ \left[\frac{kg\ CO_2\ eq.}{year}\right]}$$

When calculating the CPBT for a building SGS that has only a Generation System (GS) and no Energy Storage (ES), then the calculation is rather straightforward where the numerator impact is obtained from ecoinvent when considering a PV as GS. Then, the denominator is calculated as:

$$System_{total\ GHG\ saved\ per\ year} = \sum_0^{t=8760}[E_{GS}^t * (GWP_G^t - GWP_{GS})]$$

However, when calculating the CPBT for a building SGS that includes a GS and a ES, the calculation is a bit more delicate, especially in terms of the environmental impact allocated to the stored energy used by the building. The calculation needs to consider both the environmental impact of the source of the stored energy and of the storage unit itself.

In this document we will present the CPBT of the battery:

$$CPBT_{BAT} = \frac{GHG_{BAT,total\ emissions}}{BAT_{total\ GHG\ saved\ per\ year}}$$

The numerator is calculated as the product of the GHG emissions per kWh nominal capacity (185 kg CO_2 eq./kWh_c) and the battery capacity installed in each case evaluated. The denominator, which accounts for the difference in the quality of the energy source, is:

$$BAT_{total\ GHG\ saved\ per\ year} = \sum_0^{t=8760}[E_{BAT}^t * (GWP_G^t - GWP_{PV})]$$

In other word, the CPBT of a battery is calculated by considering the environmental gain of the stored electricity compared to the electricity from the grid at the time the electricity is released. The impact of the stored electricity correspond to the impact of the PV electricity.

A simplified aging calculation method is applied to estimate the lifetime of the battery, in order to evaluate if the Carbon Payback Time (CPBT) occurs within this timeframe. Assuming that the battery capacity is 80% of its initial nominal capacity after 5000 cycles, then the aging due to cycling is simplified to a linear degradation of 0.004 % per Equivalent Full Cycle (EFC), while the calendar aging is assumed to be 0.07% per month (Segundo Sevilla et al. 2018). Generally, as the battery capacity decreases, so do the EFCs per year. However, this study used a simplified approach, which assumes a repetition of the charging and discharging that occurred during the first two years. As this implies a higher number for EFC throughout the years, it can be considered a slightly conservative approach as it will hasten the end of life of the battery. The battery capacity for each year is calculated as:

$$BAT_{capacity}^{y} = BAT_{capacity}^{y-1} * (1 - 0.00004 * EFC - 0.007 * 12)$$

2.4 Sensitivity Analysis Scenarios

The evaluation of the sensitivity to five technical and environmental elements, that could have an influence on the resulting LCA, is performed by evaluating the range of relative difference between the results of each scenario as compared to the reference case (ENERGY). A summary of the changing characteristics between each scenario is provided in Table 21.

Table 21: Scenario general characteristics

Scenario	Reference	Time step	Control	Grid Mix	Impact factor
Label	*ENERGY*	*TIME STEP*	*GHG*	*NO NUCLEAR*	*NRE*
Envrionmental indicator time step	hourly	Annual	hourly	hourly	hourly
Control approach/objective	rule based/ energy	rule based/ energy	optimized/ GHG	rule based/ energy	rule based/ energy
Grid mix	original	original	original	Nuclear substitution	original
Environmental impact factor	GWP	GWP	GWP	GWP	NRE

2.4.1 Reference

This scenario builds upon the characteristics of the MFH, and the technical limitations of the roof size and orientation are used to assess the PV array that could be fitted for it, and subsequently the adequate battery size according to standard practice. Further details of the SGS system sizing and the control approach are given in “Section 2.5: Energy Self Generation and Storage”.

It is interesting to note that in this case study, the characteristics of the load and of the GWP factor, which both vary on a daily and seasonal basis, such as described in the previous EcoDynBat chapters have a naturally environmentally advantageous relationship. It can be seen in Figure 44 that the evening peak load, coincidently occurs during a grid energy GWP factor valley. This happen because, at the national Swiss grid supply level, the pumping storage units are strategically controlled such as to produce electricity during peak demand periods.

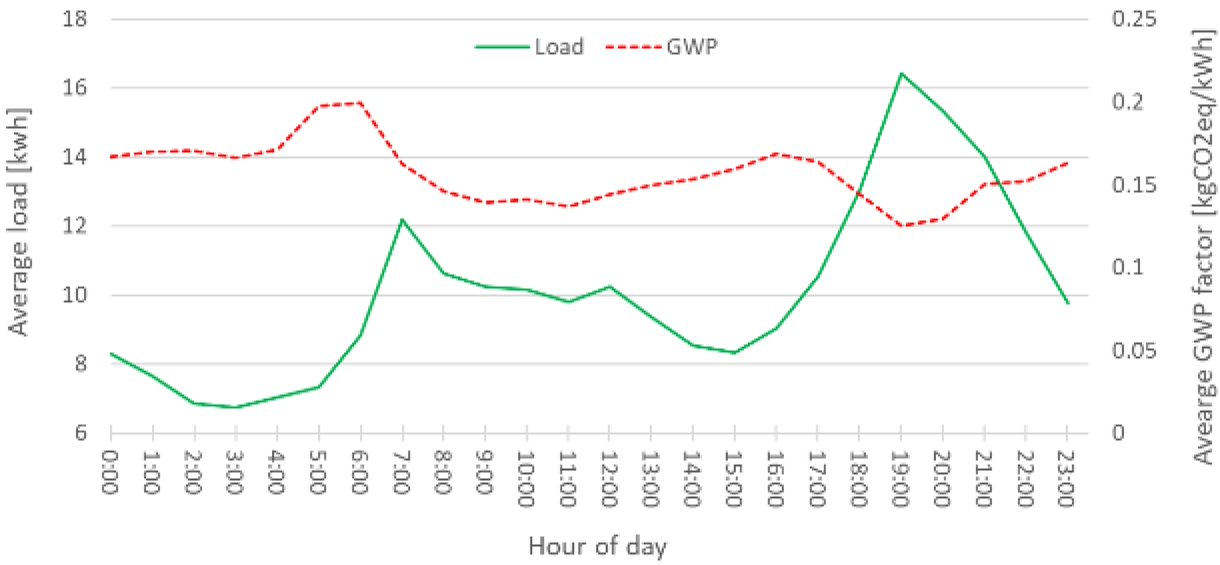

Figure 44: Average hourly load profile of the MFH and the average hourly grid GWP

2.4.2 Time Step

The main objective of the EcoDynBat project is to evaluate the influence of the time step on the environmental impact on the resulting DLCA. This aspect was extensively presented in the previous WPs. Since this WP evaluates the DLCA of additional building energy generation and storage systems that were not included in the previous WPs, the sensitivity to the time-step will be again evaluated, but only considering the hourly and annual time-steps of the GWP factor, as it presented the highest sensitivity to intra-annual fluctuations (see previous WPs).

This time-step aspect of the environmental impact factors gains significance when considering SGS control approaches, that would require high-resolution time steps in order to optimize the building energy consumption from an environmental perspective, rather than, or in addition to, the currently common economic and energy oriented approaches.

2.4.3 Control

Using an hourly impact factor allows for a more dynamics control of the battery, that performs a daily optimization cycle minimizing the GHG emissions related to the electricity consumed from the grid. In this case, the hourly GWP dataset from EcoDynBat will be used. The optimization objective of the battery (i.e. charging and discharging) is to minimize the sum of GHG emissions over the optimization cycle (ex: one day, one week, etc). The optimization is performed assuming perfect knowledge of hourly building electricity demand and the EcoDynBat grid GWP indicator throughout the optimization cycle, as such it provides the maximum potential for GHG savings. Further detailed information about the battery control strategy and boundaries can be found in "Section 2.5: Energy Self Generation and Storage".

A daily and a weekly optimization cycle horizon were run over the two years simulated, to verify the impact on the results. When optimizing on a daily basis, the battery tends to cycle every day, while on a weekly basis it might avoid discharging on a given day, in order to discharge only during weekly peak GWP indicator occurrences. It was found that even though the battery has a different discharging profile for the two time horizons, the total GHG emissions were not significantly different over a year, with differences between 0.2% and 1.9%,. The following study will thus present results for a daily optimization cycle, with hourly time steps.

2.4.4 Grid Mix

According to the Energy Strategy 2050, Switzerland plans to gradually phase out the locally produced nuclear energy. In 2017 and 2018, nuclear accounted for 26.4% and 30.5% of the production mix, respectively, of which 18% and 22.7% respectively (see WP 4 results) was generated in Switzerland. Since the PV system lifetime is normally considered between 20-30 years (Frischknecht et al. 2015), and that certain current battery technologies, under standard operation, could last over a decade(Peters et al. 2017; Pellow et al. 2020), it seems appropriate to investigate what would be the environmental impact of the building SGS in a future grid without a national nuclear energy source. This scenario will portray a pessimistic future, in which it is assumed that all the indigenous nuclear supply was not replaced by other national production sources or a large reduction of the electricity demand, and instead is entirely replaced by imports. It is also assumed that the reduction of nuclear production does not affect the quality of the imports.

The hourly GWP factor is calculated by the following procedure for each time-step:

1. Definition of the % of imports (%I), % of national production without nuclear (%SWI) and % of Swiss nuclear (%NUKE)
2. Climate change impact of the Swiss indigenous mix without nuclear (CO2SWI) and climate change impact of the imports (CO2IMP)
3. Impact Swiss mix without indigenous nuclear = %I x CO2IMP + %SWI x CO2SWI + %NUKE x CO2 IMP

2.4.5 Impact category

Just as were calculated the GHG emissions related to the building electricity consumption using the GWP indicator of the grid, PV, and battery, so is calculated the Cumulative Energy Demand (CED) from Non-Renewable Energy (NRE). The general form for each electricity source is :

$CED_i^t = E_i^t * NRE_i^t$ [MJp]

Where NRE_G^t varies on an hourly basis and is based on the hourly EcoDynBat grid mix dataset, and NRE_{PV-DSC}^t is 1.094 MJ/kWh. The impact factor NRE_{BAT}^t is assumed as 0.645 MJ per kWh_d, based on 3225.6 MJ per kWh capacity and a lifetime of 5000 cycles (Stolz, n.d.), resulting in a combined NRE_{PV-BAT}^t of 1.739 MJ/kWh_d.

The primary non-renewable energy demand is then computed as:

$$CED_{building} = E_{G,import} * NRE_G + E_{PV-DSC} * NRE_{PV-DSC} + E_{PV-BAT} * NRE_{PV-BAT}$$

2.5 Energy Self Generation and Storage

In addition to the five technical and environmental factors mentioned previously, a sensitivity analysis to the building's energy system will be evaluated. As a building SGS design is mostly influenced by technical and economic restrictions; equipment size, available space in/on/around the building, efficiency and price. As such, attention was given to indicators that characterize a generation and storage systems, and can be used as a basis of comparison:

- The Generation Multiple (GM), which relates the size of the generation system (G) with the design capacity load (L) (Salom et al. 2014). It can be calculated as $GM = G_{\max kW}/L_{\max kW}$
- The Battery-PV Ratio (BPR) expressed as $BPR = B_{kWh}/PV_{kWp}$, which relates between the nominal design capacity of the battery and the PV system.

A GM higher than 1 indicates that the peak load of a building could be met by the PV power produced, with no need for extra power from the grid or a battery, albeit only if the peak load and PV production occur at the same time. A value lower than 1, indicates that there is no possibility for the PV system alone to generate enough power to meet the peak load. As for the BPR, above a certain value, the incremental useful energy stored in the battery is insignificant, as there is not enough PV power produced to charge the additional battery capacity. The Swiss Federal Office of Energy SFOE (2018) recommends as a rule of thumb a value of 1.5. A study by Barzegar et al. (2018) found that the battery benefits above an BPR value of 4 kWh/kWp are insignificant, when simulating with low, average, and high residential consumption profiles. Thus, the BPR ratio can be used to asses if the battery is oversized, and in this study all cases evaluated will remain below this value.

These indicators can vary according to the objective of the system. For example, a PV and battery system can be used to reduce the energy consumed from the grid during peak-tariff hours (financial gains), or during peak GWP indicator hours (environmental gains), or a weighted version of both of these objectives. These objectives might require a different system design, as the load that is to be shifted might occur at different times, and have a different magnitude.

As a first step, a PV and battery system was designed according to standard practice, under the physical limitation of a rooftop PV on this MFH building. This base system will be described below, followed by the alternative designs that will be tested.

2.5.1 Photovoltaics

In chapter 2 was assessed the hourly irradiance provided by the HelioClim-3 model and the building architecture, based on which the expected PV production was estimated. The PV system characteristics are described in Table 22.

Table 22: PV system characteristics

PV module	Trina Solar poly TSM 240-PC05
Technology	Si polycrystalline
Number of cells	60
Efficiency [%]	15
Nominal power [W]	240 -0 /+3
Orientation	South-West
Azimuth [deg]	222.4
Number of modules	86
PV inverter model	ABB Micro 0.25
Nominal inverter power [W]	250
Peak electricity production 2017 [kW]	18
Annual AC electricity 2017 [kWh]	26 944

In this study, the PV energy generated that is not used on site, either directly or stored in the battery, is disregarded. At an aggregate level, the power injected to the grid from multiple building SGSs could alter the grid supply mix environmental impact indicator, and this aspect is out of the scope of EcoDynBat.

2.5.2 Electric Storage

The PV-Battery system is AC coupled and the initial battery sizing is based on the guidelines suggested by the Swiss Federal Office of Energy SFOE (2018), according to which the battery capacity is chosen as the minimum value between:

1. Bat kWh ≈ PV kW * 1.5
2. Bat kWh ≈ Annual electricity consumption kWh / (2*365)

Following these guidelines, two stackable Tesla Powerwall battery units were selected (Table 23).

Table 23: Battery characteristics (Tesla, 2018)

Battery model	Tesla Powerwall (includes battery inverter/charger)
Total energy [kWh]	14
Depth of Discharge [%]	100
Real power, max continuous [kW]	5
Round trip efficiency [%]	90
Maximum stackable units	10
Number of units	2

The battery operates under the following conditions:

1. $E_{Load}^{t} = E_{grid}^{t} + E_{dis}^{t} + E_{PV}^{t}$
2. $0 \leq P_{battery}^{t} \leq P_{battery,max}$
3. $E_{battery}^{0} = E_{battery,max}$
4. $E_{battery.min} \leq E_{battery}^{t} \leq E_{battery,max}$
5. $E_{battery}^{t} = E_{battery}^{t-1} + \eta_{cha} * E_{cha}^{t-1} - \left(\frac{1}{\eta_{dis}}\right) * E_{dis}^{t-1}$
6. $E_{cha}^{t}\ ,\ E_{PV}^{t}\ , E_{PV,dumped}^{t}\ ,\ E_{dis}^{t}\ , E_{battery}^{t}\ ,\ E_{grid}^{t}\ \geq\ 0$
7. $E_{cha}^{t} + E_{PV}^{t} + E_{PV,dumped}^{t} = E_{PV,tot}^{t}$

The first equation ensures that the sum of the energy drawn from the grid, the battery, and the PV is equivalent to the building load. The second equation keeps the charged/discharged power within the technical limits of the battery. The third equation assumes that the battery is fully charged when it starts operating at t=0. The fourth equation warrants that the battery will not go beyond or below the allowed state of charge. The fifth equation ensures that the stored energy in the battery is equivalent to its previous state with the addition/subtraction of the charged/discharged energy, accounting for the charge/discharge efficiencies. All variables are restricted to non-negative values (sixth equation), and, as such, the battery charging is limited to a value smaller or equal to the energy produced by the PV (seventh equation). It is assumed that the battery cannot be charged from the grid, as drawing power from the grid could essentially change the demand profile of the building, which at an aggregate level could have an impact on the grid GWP indicator.

The base case battery control approach is a simple rule-based mechanism focused on self-consumption and self-generation. Such a control aims at reducing the energy consumed from the grid, as a significant portion of standard electricity tariffs are based on energy consumption. This control has no predictive capacity, and the PV energy produced is directly fed to the building when possible. Any extra PV power is stored in the battery, to the extent of its capacity, to be used during sunless hours. This can represent both a control approach that is oblivious to the time-dependent environmental impact of building energy consumption, as well as a control approach that would be used when only an annual environmental impact factor is considered, since, in such case, shifting the time of energy consumption would have no effect on the final LCA.

2.5.3 Energy System Design Alternatives

The results of the PV and battery system described above would only reflect the performance of a specific MFH SGS and its particular conditions. In order to shine light on the sensitivity of the LCA results to the SGS system, twelve sizing alternatives were evaluated (Table 24). The results of these scenarios are then compared to the base case system with no PV and battery. These alternatives do not represent technically or economically realistic or optimized systems for this specific MFH, but rather a range of possible designs that could be found in the building sector.

Table 24: Generation and storage size variants

PV size [kW]	Battery size [kWh]
21	0
62	27
103	54
	81

All scenarios are presented in Table 25 in terms of the GM and BPR characteristics. The scenario nomenclature (“X_X”) indicates the PV nominal design capacity (kWp) and the battery nominal capacity (kWh). As an example, the original base case with a 21kWp rooftop PV design and no battery would be “21_0”, while the same case with an additional two battery units would be named “21_27”. The peak hourly consumption is registered at 46 kWh for the MFH building, and although on a higher resolution the actual peak during that hour could have been higher, the GM value calculated will be based on the this average value.

Table 25: KPIs of generated scenarios

Scenario	21_0	21_27	21_54	21_81	62_0	62_27	62_54	62_81	103_0	103_27	103_54	103_81
GM	0.5	0.5	0.5	0.5	1.3	1.3	1.3	1.3	2.2	2.2	2.2	2.2
BPR	0.0	1.3	2.6	3.9	0.0	0.4	0.9	1.3	0.0	0.3	0.5	0.8

2.6 Results

The following results present the energy performance, as well as the environmental impact of the MFH energy system for different scenarios and using alternative SGSs. The range of relative difference, between the results of the parallel SGSs of each scenario and the *ENERGY* base case, estimate the sensitivity of the results to these technical and environmental aspects. The range of relative change, between the twelve SGS results and the base case *0_0*, are used as a measure of the sensitivity of the LCA to the building energy system.

2.6.1 Energy Indicators

The resulting portion of the electric load provided by the grid and the PV, for the reference scenario *ENERGY,* with a simple battery control, and for the GWP optimized control *GHG* scenario*,* are shown in Figure 45. It can be seen that for this specific case study, the *ENERGY* and *GHG* controls provide similar results in terms of the portion of the load covered by the SGS. Aside from the GHG scenario, all other scenarios have the same control approach as the ENERGY scenario, and therefore the same Energy KPI results, while their enironmental KPIs will differ.

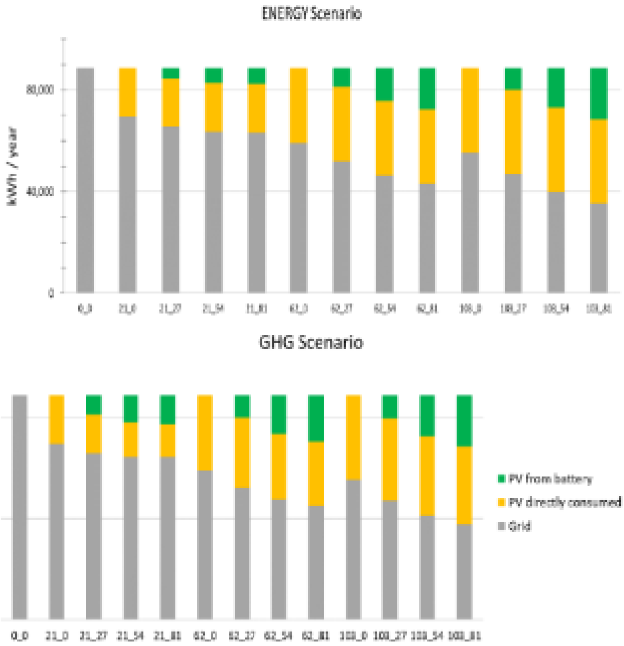

Figure 45: Electricity consumption source with a simple (ENERGY) and GWP optimized (GHG) battery control

The results for the *ENERGY* scenario, are further depicted in Figure 46. In the case of the 21 kW_p PV system, adding 2 battery units for a 27 kWh capacity increases the SC by 16%, from 72% to 88%. As this PV capacity is relatively low in comparison to the load, the energy produced is mostly consumed directly, and the SG does not increase significantly with the additional batteries as there is not much extra energy produced that can be stored in the battery. This is further demonstrated by the figures portraying incremental SC and SG benefits when increasing the battery capacity from 0 to 27 kWh, from 27 kWh to 54 kWh, and 54 kWh to 81 kWh. From this figure it can be seen that the slope is positive between 0 and 27kWh, and then start plummeting for each additional battery capacity. As can be expected, the larger 103 kWp PV system provides the highest SG, reaching a maximum of 60%.

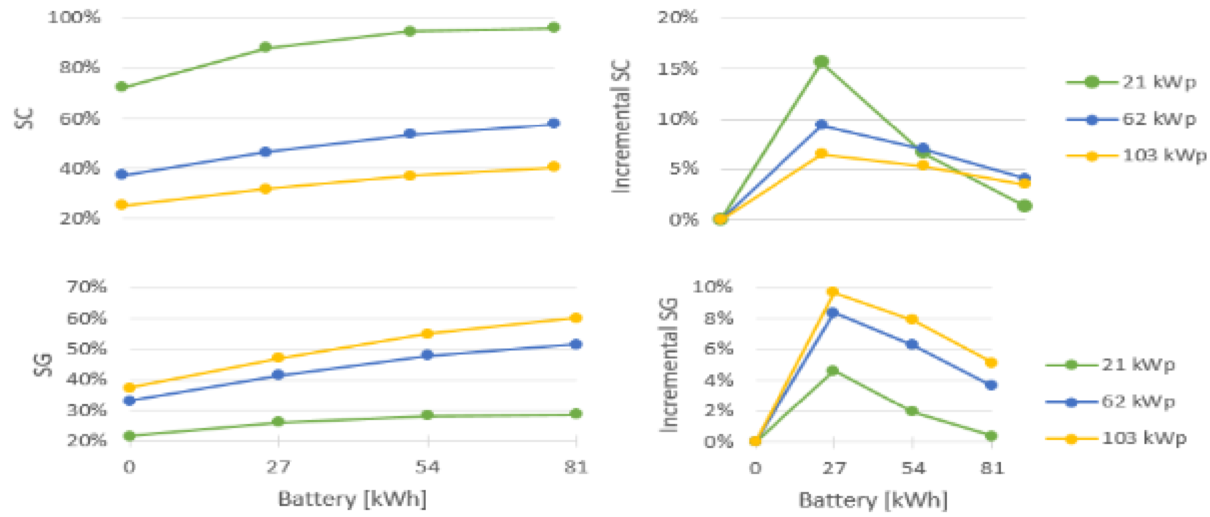

Figure 46: SC and incremental SC (top), and SG and incremental SG(bottom) for ENERGY SGS cases

In Figure 47 can be seen a tentative to co-relate between the characteristic GM and BPR of the system, with the resulting SC and SG of the ENERGY and GHG scenarios. In respect to the GM factor, a trend can be perceived, where higher GM systems tend to have lower SC but higher SG. This is explained by the reasoning that a higher GM implies that the SGS power capacity exceeds the load, and therefore more extra energy can be stored for later use in the building (otherwise it is either dumped or injected to the grid). Conversely, lower GMs result in the opposite trend, with higher SC ratios, as the load exceeds the PV capacity and therefore consumes the PV power more often instantaneously, without leaving any extras. For each GM modeled (0.5, 1.3, 2.2), a higher BPR achieves higher SC and SG values.

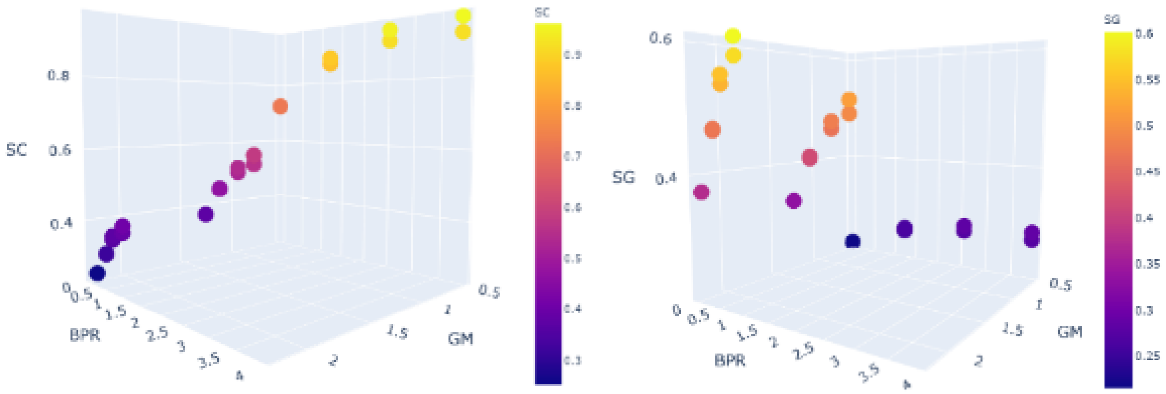

Figure 47: ENERGY and GHG scenarios - correlation between the characteristic GM and BPR of the system, and resulting SC and SG

2.6.2 Environmental Indicators

In Figure 48 can be seen the average difference between the hourly GWP impact factor of the energy drawn from the grid and from the battery. On the one hand, positive values (orange to blue in the color scale) represent periods where the grid GWP factor is higher that the battery discharge. On the other hand, the red areas indicate hours during which the average difference is zero or negative, which means that, from a GHG emissions perspective, there is no advantage in using energy from the battery. As described in WP4, there is a seasonality to the grid GWP factor, and as a result, during winter it is more advantageous to draw energy from the battery than from the grid. For the SGS modeled in this study, the combined PV and battery GWP impact factor is higher than the grid GWP in 35% of the time (between April and September).

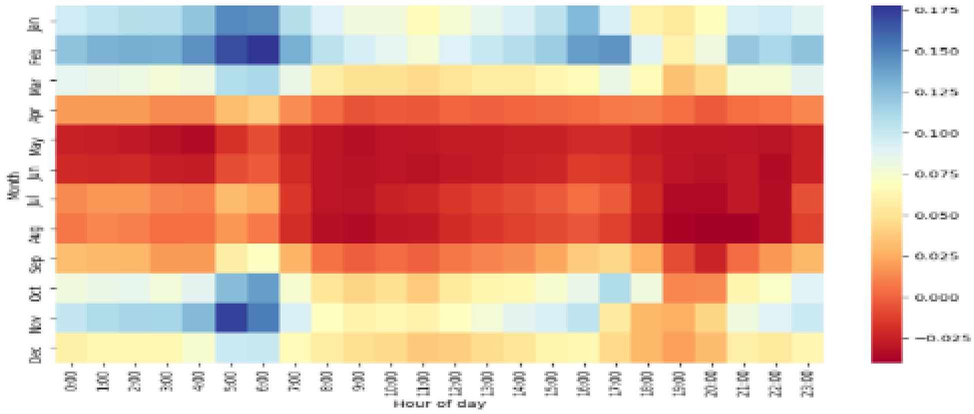

Figure 48: average difference between GWP factor of the grid and the battery discharge

This hourly difference reaches a maximum value of 0.46 kg CO_2eq/kWh, and a minimum value of -0.08 CO_2eq/kWh. The absolute values of the maximum and minimum point out that the potential hourly emissions savings with the SGS system (maximum value) are greater in magnitude than the potential drawbacks (minimum value).

In Figure 49 is given the building annual GHG emissions related to the electricity consumption for each SGS in the ENERGY scenario. These results are from an LCA perspective, which takes into account the emissions related to the energy from the PV and battery. It can be seen that most of the emissions related to the electricity consumption of the building are related to the grid consumption. In general, the SGS can improve the environmental performance of this MFH, and the total annual emissions savings can range between 975-2783 kg CO_2eq. The larger the SGS, the more the proportion of the emissions related to the energy sources (grid or PV) start converging, and in the largest case *103_81* the grid account for 58% of the climate change impact of the building electricity consumption, while the PV energy used on-site accounts for the remaining 42%.

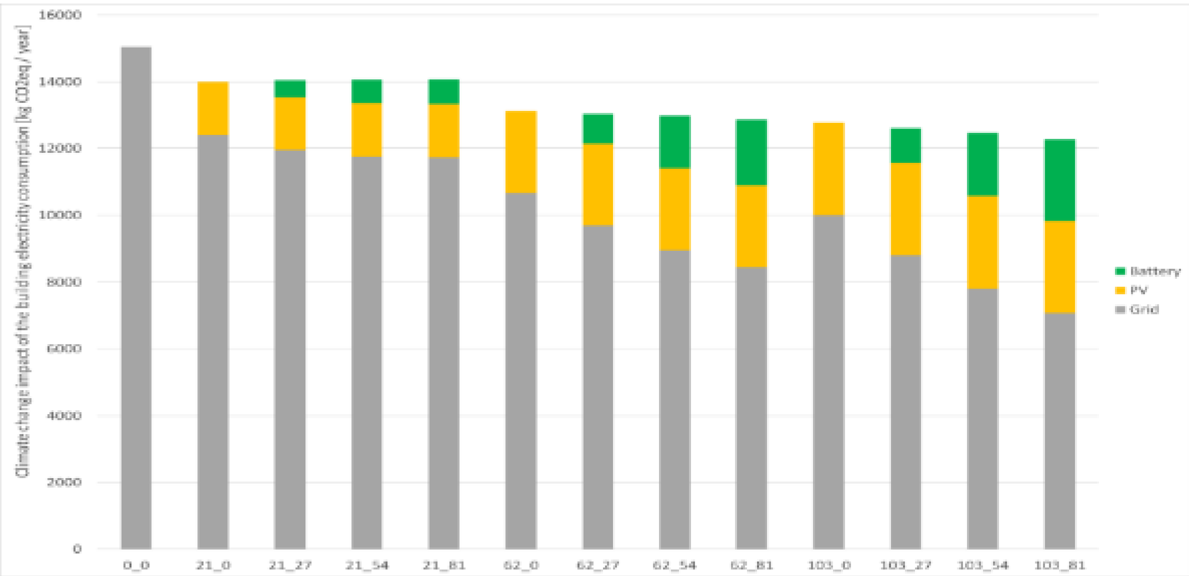

Figure 49: Climate change impact of the building electricity consumption of scenario ENERGY

2.6.3 Time step and control approach

In Figure 50 can be seen the comparison in the annual emissions of the SGSs for three scenarios:

- ENERGY – represents the simple battery control scenario. The grid emissions are calculated using the hourly GWP impact factor of EcoDynBat.
- GHG - represents the GHG optimized battery control scenario. The grid emissions are calculated using the hourly GWP impact factor of EcoDynBat.
- TIME STEP - represents the simple battery control scenario. The grid emissions are calculated using the constant annual GWP impact factor of EcoDynBat.

It seems interesting to compare these three scenarios since the GHG and TIME-STEP scenarios are not otherwise compatible, and a scenario using an annual GWP could not also use an hourly GHG optimized control. That is to say that the GHG optimization, which shifts the grid energy consumption to hours with low grid GWP factors, could no be performed in the TIME-STEP scenario, since the GWP factor is the same throughout the day. It can be seen that, for this case study, the time step of the GWP has a bigger influence on the LCA than the control approach.

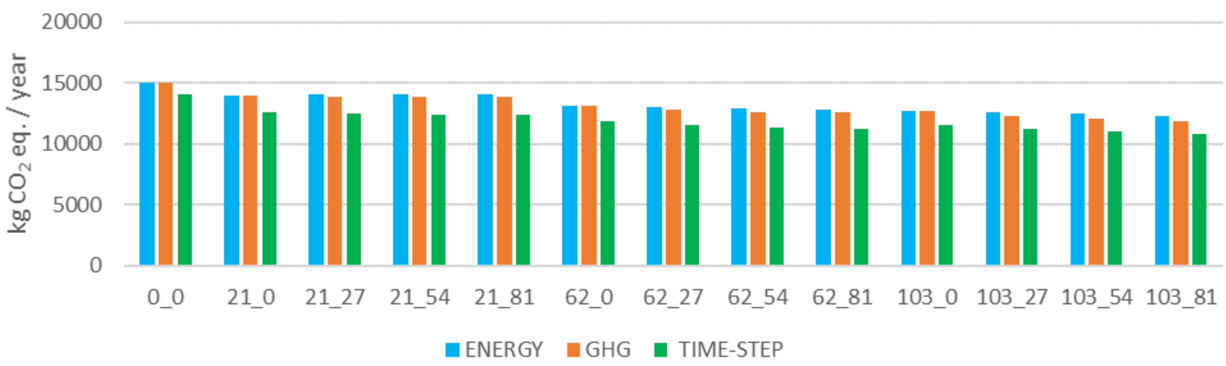

Figure 50: Annual GHG emissions of the ENERGY, GHG, and TIME-STEP scenarios

The median difference between the *ENERGY SGS* cases and their parallel in the *GHG* scenario is 287.0 kg CO_2eq/year. The median difference between the *ENERGY SGS* cases and their parallel in the TIME STEP scenario is 1465 kg CO_2eq/year. The relative difference between the *TIME STEP* and *ENERGY* for each parallel SGS ranges from 7% for the smaller SGS systems, to 23% for the largest SGS *103_81 case*. The relative difference with between *GHG* and *ENERGY* cases is below 4% for all parallel SGS systems.

As can be seen in Figure 51, the range of relative change in GHG emissions per year, from the reference case (0_0). Values in green indicate cases that achieve a value above 15%, yellow indicate the range of 10-15%, and in blue are SGSs with a value below 10%. In general the range of relative change is 7-19% and 7-21%, in the *ENERGY* a *GHG* control approaches, respectively. It can also be seen that for the smaller PV cases using the ENERGY approach, the additional battery actually reduces the relative difference of emissions, ergo reduces the environmental advantages. However this does not occur in the parallel scenarios using a GHG approach, where all cases with a battery have a higher relative difference than the case without battery. Additionally, another difference that can be seen in the results for the ENERGY and GHG approach is perceived from the comparison of relative difference in impact for the cases with a 62 kWp PV. In the ENERGY approach, albeit having a battery, the systems all have a lower relative difference than the case *103_0* with a larger PV and no battery. Yet, in the parallel cases with a GHG approach, the optimized use of the battery allows to increase the reduction in GHGs, and the 62kWp PV systems with a battery perform equally or better than the 103kWp PV system without a battery. In summary, some SGS installation with batteries can bring less environmental benefits than SGS with more PV and no battery, depending on the sizing of the system and the control approach.

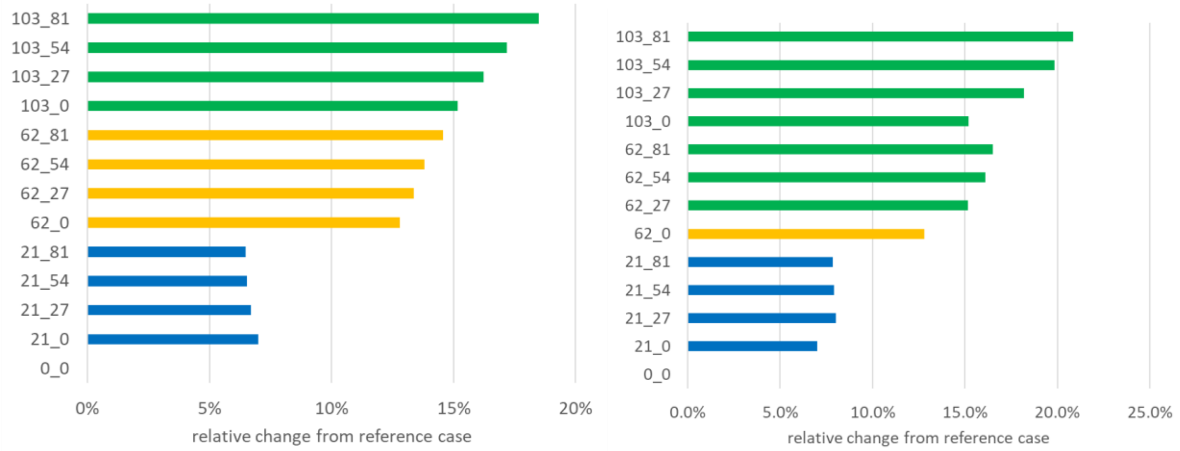

Figure 51: percent kg CO_2-eq. savings as compared to the base case (0_0) using ENERGY (left) and GHG (right) control

In literature about the LCA of PV and battery technologies (and the embedded emissions related to their manufacturing, operation, and disposal) a wide range of values is offered. One the one hand, the GHG of current SGS equipment might be higher than the one used in this study, and therefore it could be valuable to assess what would be the maximum value above which the SGS does not provide any savings. On the other hand some modern equipment might already have lower values, and therefore it could be interesting to evaluate what should be the kg CO_2eq per kWh discharged from the battery that would provide higher annual emissions savings. The latter case is especially relevant when considering that both PV and battery technologies are experiencing a period of increased diffusion, and are expected to improve in terms of performance (efficiency, energy density, lifetime, etc). Therefore, in order to provide an idea of the range of emissions within which the SGS system is either irrelevant or pertinent, from an environmental LCA point of view, three values were sought:

1. Zero percent GHG savings – the kg CO_2 eq. per kWh capacity related to the production of the PV and battery, above which the SGS would provide zero annual CO_2 emissions savings.
2. 15 percent annual GHG savings – this value provides an idea of the PV and battery emissions that would allow each of the SGS systems in this study to obtain 15% annual GHG savings.
3. 30 percent annual GHG savings – this value provides an idea of the PV and battery emissions that would allow each of the SGS systems in this study to obtain 30% annual GHG savings.

The results depicted in Figure 52 show a range of GWP factors for the energy discharged from the battery. These results were obtained by changing the GWP of both the PV and battery, but maintaining the current proportion of contribution of the PV and battery to the total GWP factor of the discharged energy, as well as the SGS energy performance, i.e. SG and SC. From the top figure it can be understood that if the combined GWP of the SGS equipment were to be above 0.22 kg CO_2eq/kWh$_d$ then none of the scenarios would achieve any GHG reduction, when compared to case *0_0*. In the middle figure can be seen values similar to the one used in this study, where scenarios 62_54 to 103_81 indicate a GWP of 0.12 kg CO_2eq/kWh$_d$ or below is required to achieve a relative change of 15%. From the same figure it can be seen that cases with a GM of 0.5 would require a GWP factor of 0.03-0.05 kg CO_2eq/kWh$_d$ to attain a relative difference of 15%. Finally, from the trend in the bottom figure it can be understood that, given the load of this MFH and the energy performance of the SGS equipment used in this study, it would not be possible for cases 21_0 to 62_0 to achieve a 30% relative difference, while case 103_81 would require a GWP of 0.08 kg CO_2eq/kWh$_d$ to achieve it.

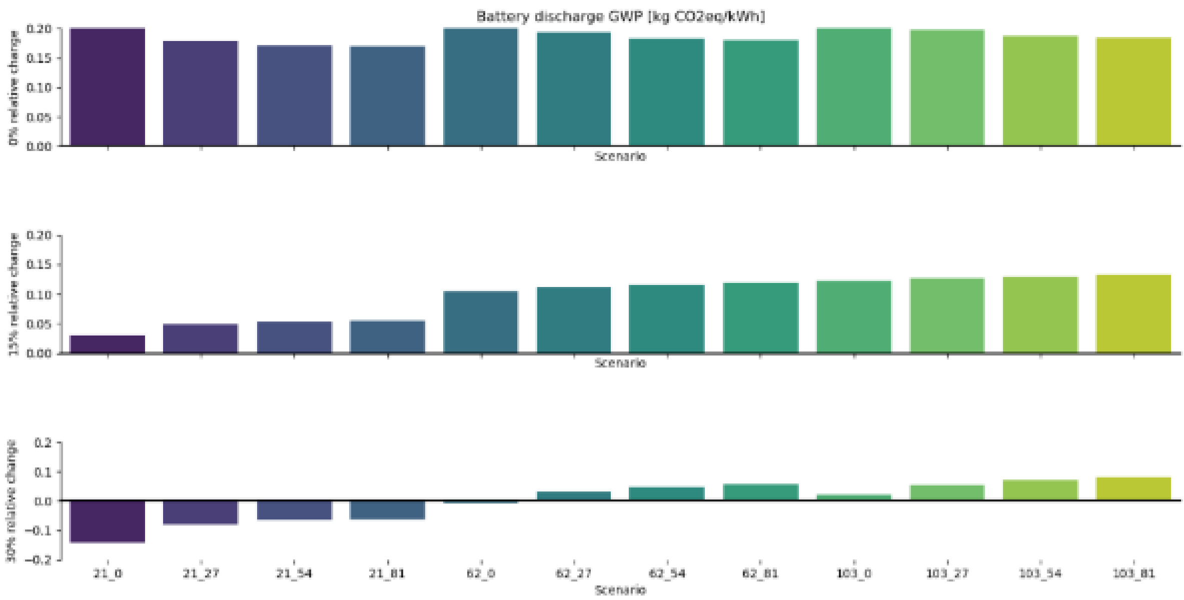

Figure 52: Range of battery discharge GHG impact factor and the annual emissions savings

Although not in the scope of EcoDynBat, it was deemed of interest to offer, as well, an estimate of the Carbon Payback Time of the battery, as a complementary perspective on its contribution to lower *GHG* emissions of buildings. To do so, the lifetime of the battery was estimated by using a simplified aging equations. This was applied both to the *ENERGY* and *GHG* cases, where the latter tends to cycle more during the year as its objective it to store energy and use it during peak grid GHG emission. In the case of *GHG*, the resulting degradation of the battery capacity leads to an end-of-life between 10-16 years (Figure 53). These results concord with the current standard lifetime for lithium-ion batteries of approximately 10-15 years.

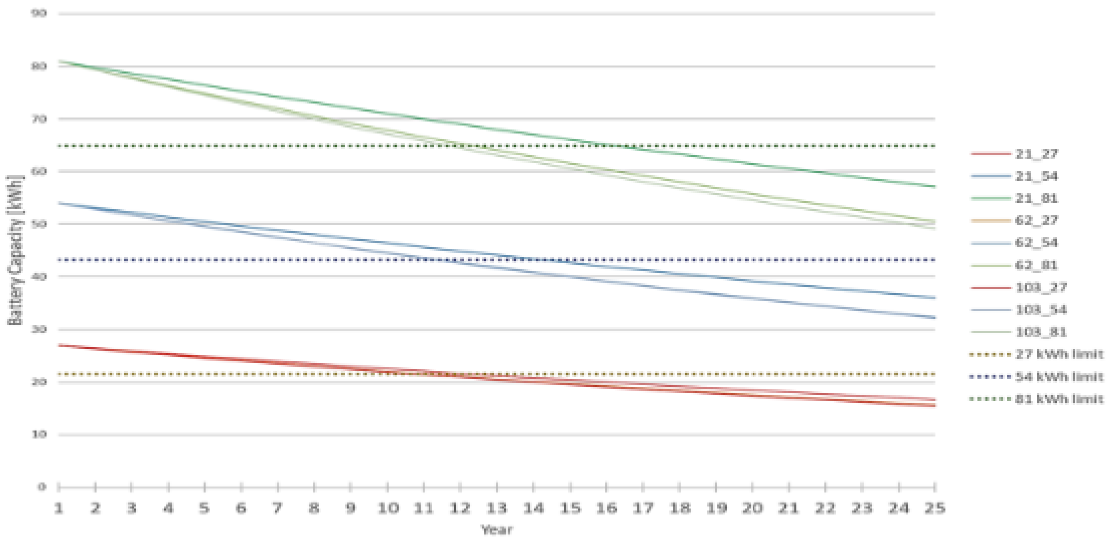

Figure 53: Battery lifetime

The Carbon Payback Time (CPBT) of the different scenarios, as well as the saved GHG emissions for the different scenarios, are presented in Figure 54. The results show a wide range of CPBT, where in the ENERGY approach, the designs with a PV of 21 kW do not provide sufficient annual savings to compensate for their embodied GHG emissions. The difference in the control approach emerges from this analysis, where it is apparent that in the GHG case, more of the PV energy is stored and discharged from the battery, as its objective is to use it when the grid GWP factor is high. Due to the more frequent charging and subsequent discharging of the battery, its lifetime is shorter, yet it provides higher annual emissions savings. Therefore in all GHG scenarios the battery achieves a CBPT before the cycling and aging degradation bring upon a 20% reduction in nominal capacity.

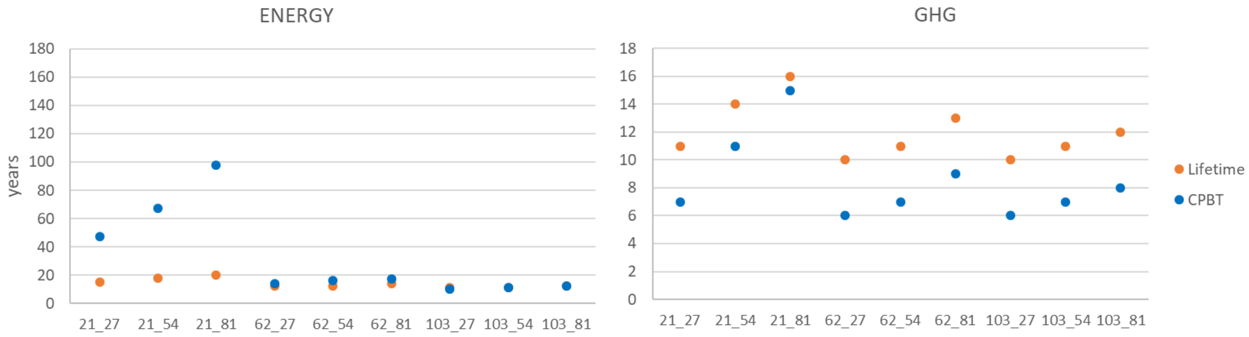

Figure 54: Carbon payback time

The difference in the CPBT of the ENERGY and GHG scenarios highlights the inherent change in the daily behavior of the battery in these two approaches. In Figure 55 can be seen the average hourly distribution of the energy discharged from the battery for the *ENERGY 62_54* case. It can be perceived that both battery control approaches tend to discharge most energy during the evening between 19:00-22:00. However the GHG optimized battery will discharge during peak grid energy GWP factors. Yet, as the *ENERGY* approach send more PV energy directly to the building, it has a slightly higher SG ratio which balances, to a certain extent, the lack of PV energy stored and available during non-PV hours.

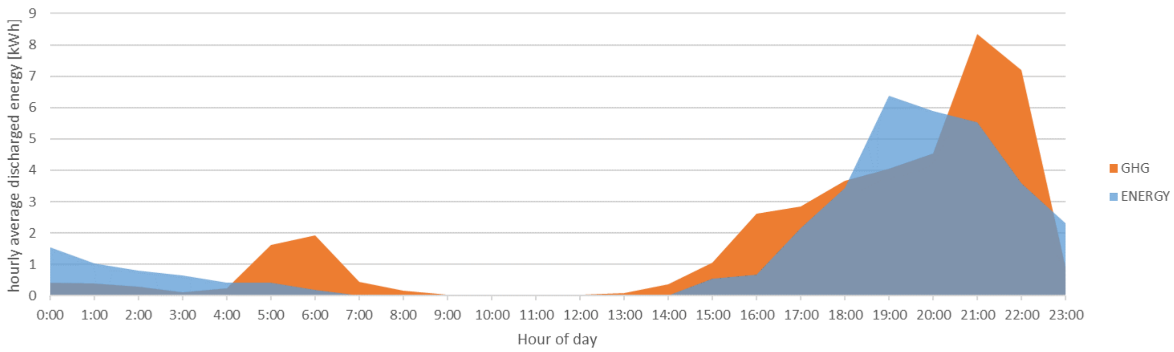

Figure 55: Average houly distribution of the of discharged battery energy over the two years analyzed

The difference in the approaches is most significant in winter (Figure 56) during which there is less PV energy produced and the *ENERGY* battery control charges and discharges less energy, as compared to the *GHG* approach. This is because the first approach prioritizes sending the PV energy directly to the load, and consequently less energy is charged in the battery. The second approach has perfect knowledge of both the hourly load and the GWP factor of the Swiss grid, and therefore will charge the battery more often, rather than send the energy directly to the load, and use this stored energy when the grid GWP factor is highest.

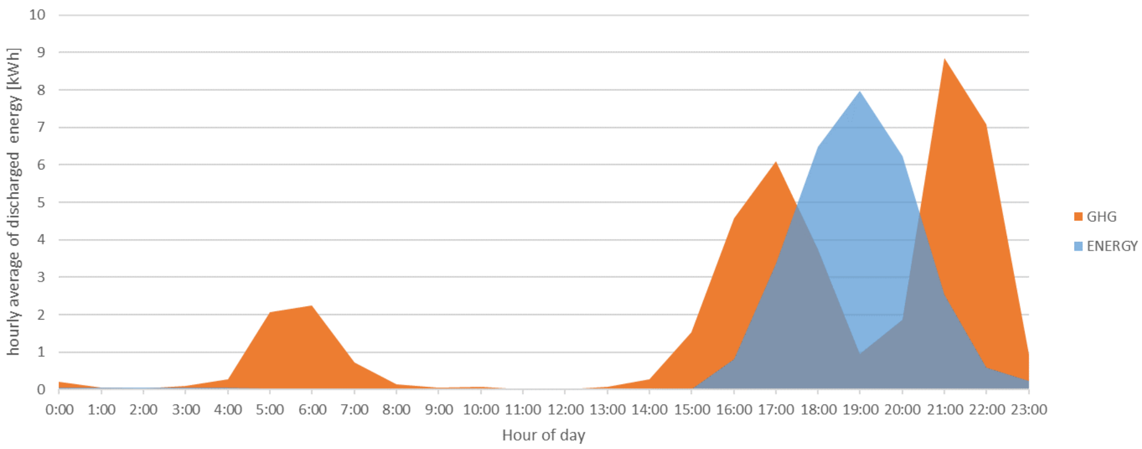

Figure 56: Average hourly distribution of the battery energy discharged during winter

This highlights that the battery discharge timing, optimized for an hourly time-step GWP impact factor, does play a strategic role, albeit it could bring more significant benefits on the annual system emissions in grids if the GWP factor of the Swiss mix would have a lower share of nuclear and hydro power sources.

2.6.4 Future grid content

Since within year 2050 the Swiss grid mix might change, the following results depict an extreme scenario where all national nuclear energy is substituted by imports. A first review of the hourly GHG impact factor, as seen in Figure 57 , shows that the hourly GWP impact factor in both the present and future grid scenarios is most often higher than the content of the current PV energy stored in the battery. While the present hourly grid GWP impact factor is higher than the SGS impact factor 65% of the time, the Nuclear-substitution hourly grid GWP impact factor surpasses the SGS emissions 95% of the times. This means that in 95% of the hours of the year, it would be advantageous, from an environmental LCA stand-point, to use energy from the SGS rather than from the grid.

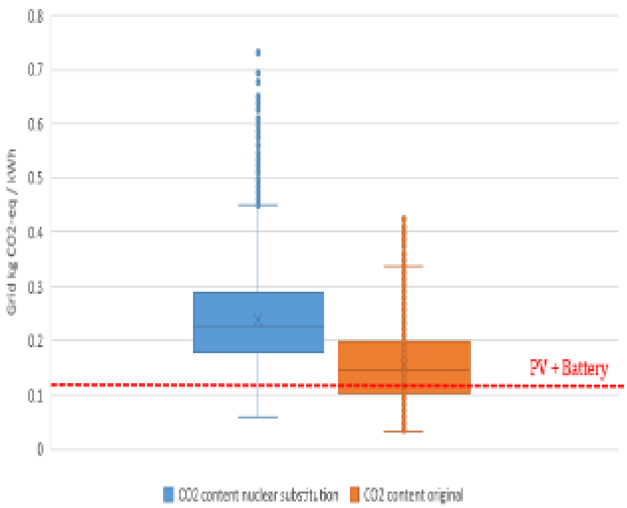

Figure 57: GWP hourly impact factor comparison for different energy sources.

The median GWP hourly impact factor of the building SGS unit, the original mix, and the future grid mix are 0.12, 0.15, and 0.23 kg CO_2-eq./kWh, respectively. In Figure 58 can be seen that when using the ENERGY control approach (which is oblivious to the grid GWP indicator and therefore maintains the same daily operation) the GHG emissions emanated from the energy consumed from the grid have a relative difference between 12-14% in the 0.5 GM cases, 21-30% in the 1.3 GM cases, and 25-38% in the 2.2 GM cases.

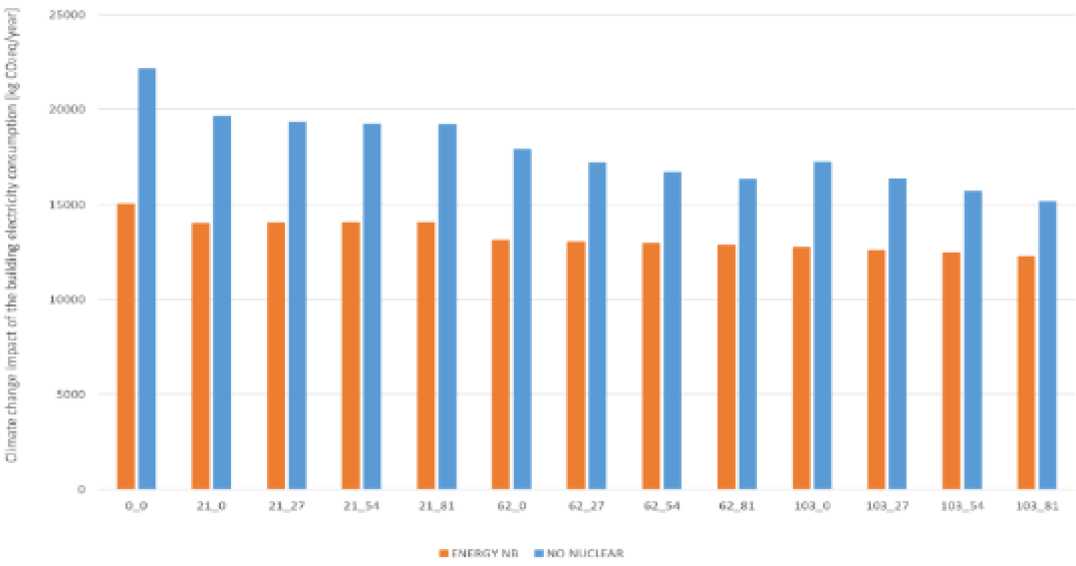

Figure 58: GHG emissions related to the building electricity consumption – original vs. nuclear-substitution scenarios

Since the substitution of national nuclear energy sources by imports increases the GWP factor of the grid, there is a large difference in the results of each scenario, with respect to the original grid case. The highest relative difference, between scenario results for the original grid and the nuclear substation, occurs for the case without SGS and amounts to 38%. The *103_81* SGS case, which the highest SG, has the lowest relative difference between the two grid mix scenarios (21%) as it relies less on the grid and more of its energy is self-generated.

2.6.5 Non Renewable primary energy indicator

A first glance at the range of difference between the hourly NRE impact factor of the energy from the grid and from the battery for each month (Figure 59) shows that, over the two years analysed, the grid NRE impact factor is consistently higher. More precisely, the energy from the grid is 0.9 to 7.1 MJp/kWh higher than energy from the battery, with a median value of 4.4 MJp/kWh.

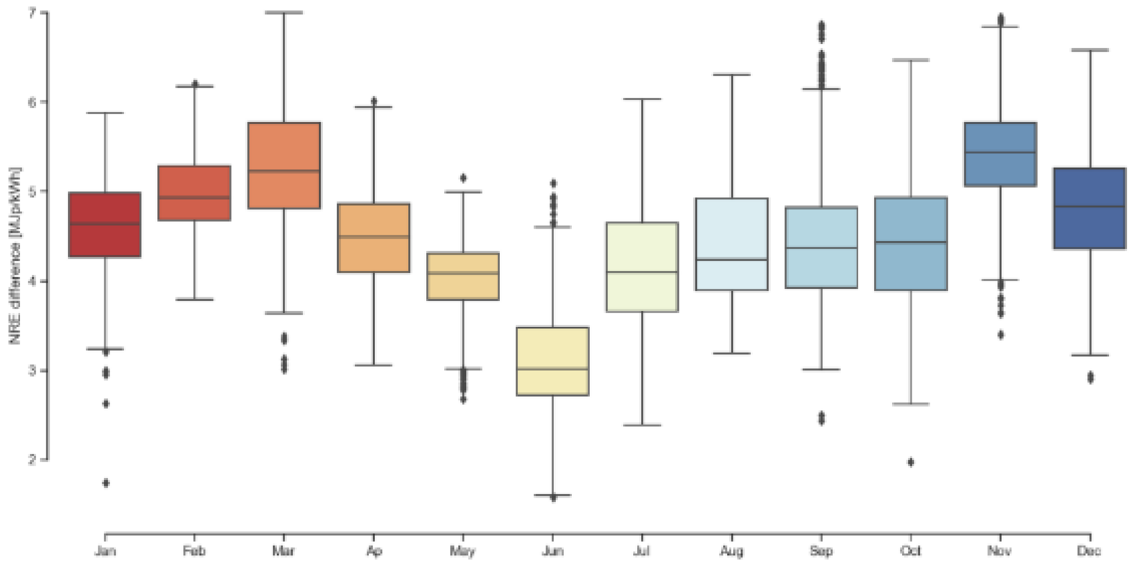

Figure 59: difference between NRE impact factor of the energy from the grid and from the battery

As such, at any given instant, using energy directly from the PV or from the battery would results in reducing the NRE impact of the building electricity consumption at that time. In Figure 60 can be found the resulting annual electricity consumption equivalent in NRE primary energy, where it is clear that the grid energy accounts for most of the NRE impact.

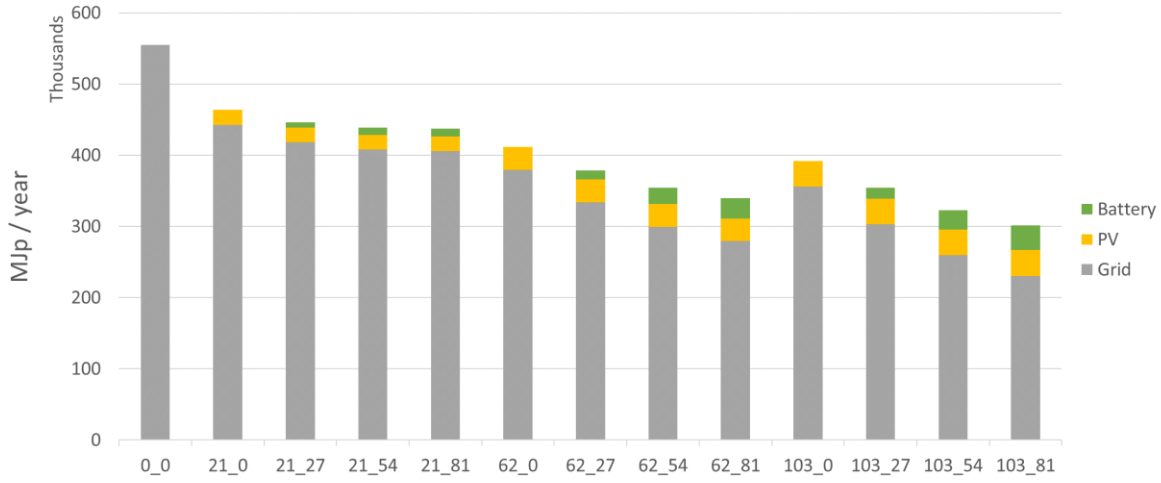

Figure 60: Building energy consumption NRE primary energy per year

The relative change in the results for each SGS implies as well the environmental benefits/drawbacks brought by the various building energy systems. When using the NRE indicator, the LCA assessment of the environmental impact of the building electricity consumption demonstrates that there are higher benefits to using SGSs, than when using the GWP factor. The maximum GHG emissions savings amounted to 18.5%, in the *ENERGY* scenario in the biggest SGS *103_81* scenario, the same system and control approach provides 2.5 time more savings, with a primary energy reduction of 45.6%. The control approach is oblivious to the grid environmental impact factor, and therefore the savings presented could be considered a conservative estimate, as no timely environmental optimization was performed. When compared to the GWP factor, using the NRE impact factor increases the range of difference between the various SGSs and the *0_0* case. This is due to the characteristics and time-dependent variability of the impact factor, which were discussed in the previous WPs of EcoDynBat. It should also be noted that using the NRE factor can influence the perception of drawbacks and benefits of the building SGS. That is to say that SGS seem to offer higher potential environmental gains when considering the NRE rather than the GWP factor.

2.7 Discussion

This study evaluated the sensitivity of the environmental impact of the electricity consumed by a MFH to technical and environmental factors. To this end five scenarios (see Table 21) were developed:

- **ENERGY** – maintained the characteristics of the reference building and grid
- **TIME-STEP** – use annual grid GWP factors
- **GHG** – replaced the simple control approach by an optimization approach that aims to reduce the daily GHG emissions related to electricity consumed from the grid.
- **NO NUCLEAR** – developed an hourly grid GWP indicator time-series in which the national nuclear energy source is replaced by imports.
- **NRE** – used the NRE factor instead of the GWP factor.

In addition, each scenario was simulated with twelve different PV and battery combinations. Then the resulting annual environmental impacts were evaluated in terms of the relative change from case 0_0 due to the SGS, and the relative difference between the parallel SGSs results of each scenario and the reference ENERGY scenario (see Figure 42).

In Figure 61 can be seen the relative difference of each SGS in each scenario, as compared to the reference SGS of the ENERGY scenario. Only the results for the GWP assessment are compared, as the NRE scenario analysis has a different unit and the magnitude is therefore not comparable. It can be seen that this difference, between the parallel SGS cases for each scenario and the base case scenario (ENERGY) is rather constant. The influence of the time-step on the environmental impact of the building electricity consumption was thoroughly analysed in WP4, and therefore in this study was only evaluated for the reference ENERGY scenario. It was estimated that the SGS could alter the results for a relative difference between the annual and hourly values of 7-13%. As for the additional scenarios evaluated in this study, the ranges are between 0-3% for GHG, 21-38%, and for NO NUCLEAR.

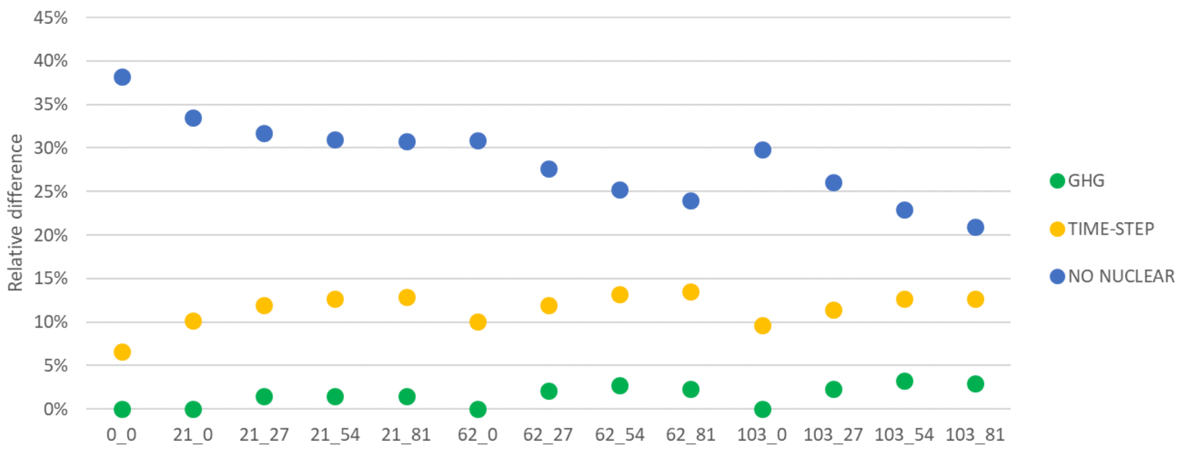

Figure 61: relative difference between the SGS results of the scenarios and the base scenario ENERGY

From these relative difference trends it can be understood that, for the MFH studied in this project, the grid GWP indicators can have a significant influence on the LCA results and therefore careful attention is required for the time-step choice, as well as in the process quantifying the energy sources in the grid mix. The control approach did not influence the results much, but this might be partially due to the natural characteristic daily variation of the load of this MFH and the grid GWP factor. Another added reason could be that since the Swiss grid supply mix has a relatively low GWP, then the shifting of energy to periods of peak GWP does not, overall, significantly reduce the annual sum the GHG emissions.

The characteristics of the SGSs, their resulting energy performance, and annual GHG savings are summarized in Figure 62. As a reminder, these characteristics are:

- GM – unitless ratio of the annual peak PV power to the peak load of the MFH case study
- BPR – ratio between the capacity of the battery and the PV
- SC – unitless ratio between annual the amount of PV energy consumed in the building and the total PV enrgy produced by the array
- SG – unitless ratio between the annual amount of PV energy consumed in the building and the total load of the building

In terms of the GHG emissions for the electricity consumption of the building, even the smaller PV systems (GM 0.5) without a battery can provide some annual savings. Yet the advantages of an addition of a battery in these cases could be detrimental and reduce the annual GHG savings, depending on the control approach. This is because the PV production is often consumed directly by the building, and therefore, even if in most periods the energy discharged from the battery has a lower GWP than the grid, the battery does not provide enough energy to the building to compensate for its embodied GHG. However, larger SGSs with higher GM ratios can provide reasonable environmental benefits, even when considering the relatively low GWP factor of the current Swiss grid and the embodied GHG of contemporary SGS technologies.

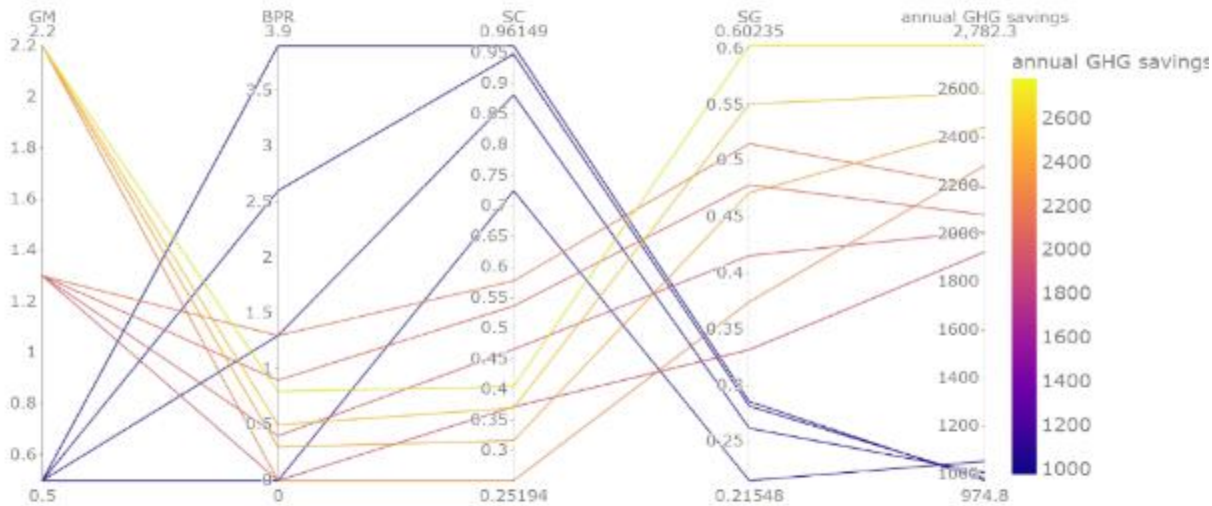

Figure 62: Summary of results with the ENERGY control approach using an hourly grid GWP impact factor

It can be concluded that SGS systems with relatively low GM ratios, where the PV capacity is less than the peak load, can achieve high self consumption ratios, taking full advantage of the solar energy they produce. However, these tend to have lower self-generation (SG) ratios, as the load can be higher than the energy produced, and therefore less energy is stored in the battery. As can be expected, SGSs with higher GM reach higher levels of autarky, but the natural mismatch between residential load profiles and PV production result in lower SC ratios, as a higher amount of PV energy is produced that cannot be directly used in the building or stored in the battery. Lower SC imply larger amounts of extra PV power that is not consumed on-site, and which, if injected in the grid without a coordinated control system with distribution grid operators, could challenge local grid stability. It is not within the scope of EcoDynBat to weigh these conflicting advantages and drawbacks, and therefore this study does not attempt to identify an optimal SGS, which depends on the multiple and sometimes diverging objectives of the customer, Transmission System Operator (TSO), and public authority. The objective of this study is rather to present a range of results that indicate the sensitivity of the environmental DLCA to the various SGS designs that can be found in the modern building stock.

In terms of the sensitivity of the environmental LCA to the SGS for the different scenarios, the ranges in Figure 63 allow to discern the relative change in the results, as compared to the base case without any SGS (case *0_0* in each scenario). The relative change for the different SGSs can vary between 3.7% to 45.6%, depending on the controls (GHG), the time-step of the impact facor (TIME-STEP), the grid mix (NO NUCLEAR), and the impact factor (NRE) used.

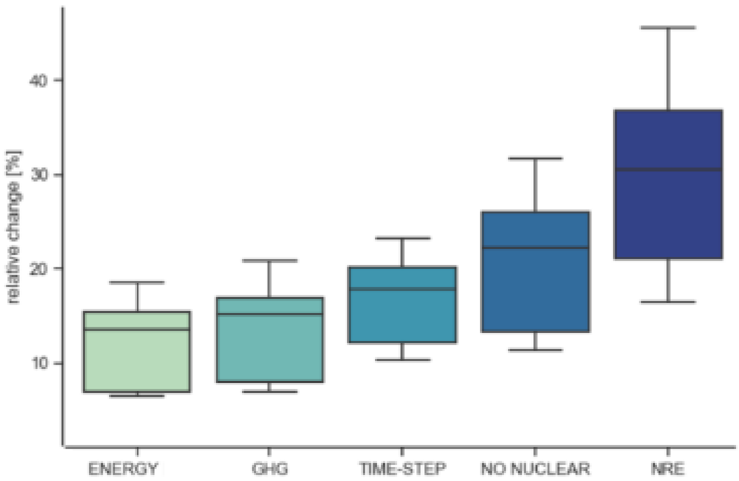

Figure 63: influence of electricity supply system on the environmental impact

From the previous figure, it can be noted that in this specific study case, the ENERGY and GHG control approach reach similar ranges. This could be due to the characteristic hourly variation of this MFH demand profile and of the GWP impact factor for the Swiss grid, which have coincidently inverse peaks and valleys. Using an annual GWP factor could potentially increase the difference between the resulting LCA of a building with SGSs that rely less on the grid. This could be because the annual grid GWP factors in this case are 0.18 CO_2eq./kWh and 0.14 kg CO_2eq./kWh (taken from WP4 results for the year 2017 and 2018), and therefore they are constantly higher than the GWP impact factor of the PV energy directly consumed (0.08 CO_2eq./kWh) and of the PV energy stored and discharged from the battery (0.12 CO_2eq./kWh). As such, when using annual values, it is always beneficial to use energy from the SGS rather than from the grid. This is not the case when using an hourly grid GWP factor, where the benefits of using the SGS are apparent in winter when Switzerland imports more energy with higher GWP intensities, but less clear during the warmer season when a higher portion of the supply mix is supplied with indigenous hydropower and lower GWP intensities. The evaluation of the extreme scenario of nuclear substitution by imports increased the maximum percent difference of environmental impact outcomes when using different SGSs from 12%, in the ENERGY scenario, to 22%. Finally when considering the range of the NRE impact factor, the sensitivity to the technical SGS characteristics is highest, reaching up to 33% difference between resulting DLCAs.

It is important to note that the following results use real energy consumption data from an MFH, and aim to capture the variability of the LCA of the electricity consumed in this case-study reference building. The resulting energy and environmental performance of the SGSs, albeit built upon sound and reasonable assumptions, could vary for different reasons, such as:

- building typologies – single-family house, office, school, etc. which will have different load profiles, energy needs and building compacity (high compacity restrict the available surface for PV installation for example)
- consumption characteristics – thermal performances, habitant behavior, etc
- control approach and objective - rule-based or model predictive control aimed at energy/economic/environmental savings.
- Technical and environmental assumptions – technologies and their general characteristic in terms of efficiencies, lifetime, LCIs, etc. Indeed, there is currently an important uncertainty related to the environmental impacts of stationary battery.

Therefore, the results of this study are valuable for the insight they provide in terms of the sensitivity of the LCA result to certain technical and environmental factors, yet they should not be interpreted as a general and all encompassing evaluation of the advantages and disadvantages of PV and batteries systems, which is outside the scope of the EcoDynBat project.

It should be kept in mind that an LCA considers the entire lifetime of the building, which normally can span over more than three decades. This report addressed some uncertainties regarding the range of the GWP impact factor of the SGS, as well as the impact of a change to the Swiss grid mix, however a full exploration of possible technological improvements and policy driven grid mix changes, was outside the scope of the current study and could be potentially investigated in future work. Such scenario investigation could be relevant when contemplating the energy transition bound to occur over the lifetime of the current building stock. In such context, although the current individual building SGSs, with a simplified control mechanism, might provide only 3-13% reductions in GHG emissions, these still represent a stepping stone that, given the likelihood of improvements in SGS technologies, will provide higher environmental benefits in the not so distant future. Moreover, given the increasing diffusion of electrified thermal loads and mobility, and the need for a renewable and sustainable substitution of the non-renewable energy sources, albeit their current shortcomings in terms of LCA environmental impact, building SGSs might become an integral component of the upcoming Swiss energy system.

3. Global Sensitivity Analysis

3.1 Method

Sensitivity analyses (SA) can be used to estimate how the variability of input parameters might influence the variability of response for models (Saltelli, 2004). However, the current practice within the LCA community is to perform sensitivity analyses, in a simplified way. Indeed, two different methods are mostly used, i.e. the scenario analysis and the one-at-a time sensitivity analysis. Scenario analysis includes the study of different scenarios, e.g. pessimistic, average and optimistic scenarios, while according to the second method the modelling parameters are varied, one by one around their reference values and thus no interactions are taken into account. These sensitivity analyses do not provide a complete picture of the results variability because, among others, they do not consider the full possible range of the variations of the parameters, and they do not consider the possible combined effect between the parameters.

Thus, in the EcoDynBat project, a Global Sensitivity Analysis (GSA) was preferred. GSA offers the possibility to vary all the model parameters simultaneously in order to capture the overall variability and the possible interactions. In addition, contrary to the local methods, the global methods use the whole range of the possible variations of the parameters. Hence, the parameters are varied, according to their variation intervals and distributions. The GSA method used for the evaluation of the environmental impacts is a variance based GSA called the Sobol' method. According to this method, the total variance of results is decomposed into the variances of the input parameters and their interactions, (Sobol′, 2001). It is, thus, possible to quantify the influence of each input parameter on the results and rank their contributions on the variability of outputs (i.e. quantified impacts). The use of distributions then allows for the account of preferential configurations (i.e. more probable) that the modelled systems may take.

The detailed mathematical model of Sobol' method is presented in Saltelli (2004), Saltelli et al. (2006) and Sobol (2001).

The calculations have been performed, using the free and open source R software, which contains the necessary libraries to compute the Sobol indices. It will therefore be possible to characterize how the variance of environmental impacts for an indicator can be linked to the variance of different input parameters. By doing so, it will be possible to compare the influence of the different parameters.

3.2 Model Determination

Within this study, it was decided first to consider the variability for one single building (GSA-1) and then to enhance the GSA by adding multiple building (GSA-2). This later assessment provides information on the time step influence when comparing different building together. Both models are of interest since they provide information at the building level (for example when aiming at developing renovation or environmentally oriented energy management optimization) and at the building comparison level (for example when aiming a developing microgrid or for district environmental characterization).

It has been decided arbitrarily to use the CS1 case study for the GSA-1. Then, in the GSA-2, CS1-4 were considered since they are all single-family buildings with similar technical systems (photovoltaic and air-water heat-pump). Their characteristics are presented in Table 26.

Table 26: Technical characteristics of the case studies, energy consumption and PV production, used for the two GSA studies

	Case study 1 - CS1 (GSA-1 and 2)		Case study 2 - CS2 (GSA-2)		Case study 3 - CS2 (GSA-2)		Case study 4 - CS2 (GSA-2)	
	2017	2018	2017	2018	2017	2018	2017	2018
Building type	SFH							
ERA [m2]	247		273		149		130	
Construction year	1975		2000		2000		1987	
Heating system and DHW production	Air-Water Heat-pump							
PV peak power [kWp]	10 (installed in 2012)		10.7 (installed in 2013)		7.4 (installed in 2013)		6.6 (installed in 2014)	
Annual energy consumption [kWh]	14160	14833	16875	18888	15326	15538	8522	7789
HP electricity consumption [kWh]	5408 (38%)	5581 (38%)	4484 (27%)	4382 (23%)	3610 (24%)	3886 (24%)	3924 (46%)	4383 (56%)
DHW electricity consumption [kWh]	1934 (14%)	1890 (12%)	7300 (43%)	8678 (46%)	2342 (15%)	2428 (16%)	1987 (23%)	1961 (25%)
Domestic appliances electricity consumption [kWh]	6817 (48%)	7361 (50%)	5130 (30%)	5828 (31%)	9373 (61%)	9281 (60%)	2611 (31%)	1434 (19%)
Photovoltaic production [kWh]	11160	10777	10993	11365	8426	8208	7489	7032
Share of produced electricity sent to the grid [%]	64.8	58.2	74.5	71.2	56.3	50.6	69	75
Share of produced electricity self-consumed [%]	35.2	41.8	25.5	28.8	43.7	49.4	31	25
Independency ratio [%]	27.8	30.4	16.6	17.3	24	26	27	23

The chosen input parameters for the GSA-1 and GSA-2 are the years (2017 or 2018), the time step resolutions (annual, monthly, daily or hourly time step), the photovoltaic production in kWh/kW$_p$ and the photovoltaic peak power in [kW$_p$]. The first parameter represents the inter-annual variability, and it affects the energy demand profile for the building, the PV production profile, as well as the environmental impacts of the grid electricity. As far as the PV production is concerned, it is defined using two parameters, i.e. the specific PV production profile and the PV peak power. For the first parameter, the four production profiles were used, i.e. the PV profiles of the four SFH case studies. This specific production is independent of the energy demand profile for the building and thus these profiles can be used, in combination to the building energy demand profiles. They correspond to different PV orientations, inclinations and installation characteristics. The second parameter defines the size of the PV installation and the total PV electricity profile is calculated by multiplying it with specific production curves. The range of the possible peak power has been set from 0 to $20kW_p$, which corresponds to a building with no PV installation to a highly-equipped, respectively. Using these PV powers, both low and high auto-consumption levels are covered. Indeed, this values cover a high self-consumption rate of up to 100%, which implies a low autarky rate, below 0.1% for very small installations and a low auto-consumption rate (below 13%), which implies a high autarky rate, up to 41.5%. It should be noted that there is an asymptote above $20kW_p$ and it is not possible to increase the autarky rate higher without storing the electricity since there is a mismatch between the PV production and the building electricity demand. For the GSA-2 model, the building choice parameter has been added. The four building from CS1-4 are considered and sampled equiprobably. Then, once the building choice is made, it is coupled with the inter-annual variability parameter described above to define the specific building load profile (expressed in kWh/m^2 ERA for a given year). A summary of the parameters is given in Table 27.

The sensitivity of the output can be quantified for to the different time step resolutions, the inter-annual variability, as well as the PV production. 20'000 different configurations have been made leading to 20'000 simulations, for each environmental indicator.

Table 27 Parameters' description and characterization for the two GSA

GSA model	Parameter	Description	Sampling choice
GSA-1 and 2	Inter-annual variability	Choice between the two available years, for the building load profile, the PV production profile and the grid electricity impacts.	[2017;2018]; equally likely
		It corresponds thus to the inter-annual variability.	
	Time-step choice	Choice between the four considered time steps of the project	[Annual, Monthly, Daily, Hourly]; equally likely
	Photovoltaic electricity production profile	Four production curves are considered for four different installations, this enables to test the sensitivity to the PV installation configuration (orientation and inclination)	Four specific PV generation profiles [kWh/kWp]; equally likely
	Photovoltaic peak power	Various PV installation sizes are considered and thus the sensitivity of the PV installation size is evaluated	[0;20] kWp; uniform distribution
GSA-2	Building load profile	The four SHF buildings CS1-4 of WP4 are considered. Thus the influence of the building choice is characterized within GSA2	CS1- CS4 equally likely

3.3 Results

3.3.1 GSA-1 - Sobol indices

Figure 64 presents the Sobol indices for the four indicators and the four studied parameters.

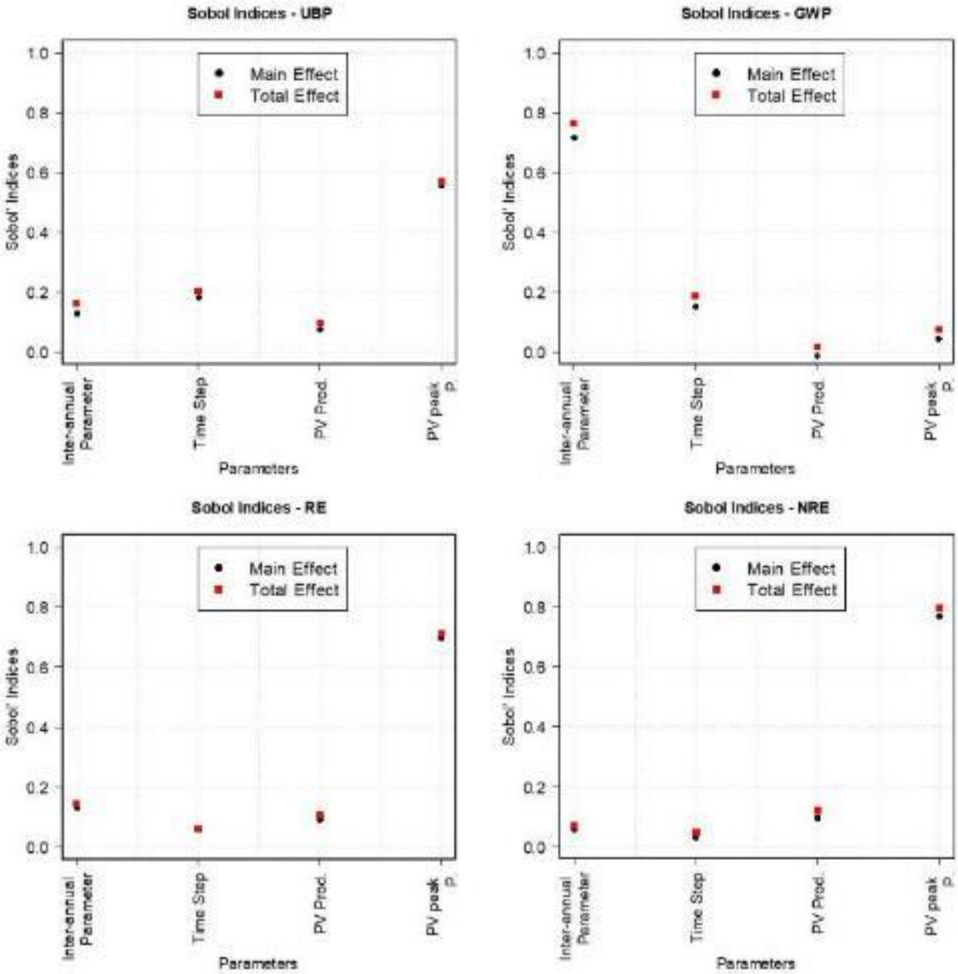

Figure 64 Sobol Indices for GSA-1

From the Figure 64, for GSA-1, It has to be mentioned that only small joint contribution has been detected between the parameters for all indicators, since no important differences are observed, between the first and total order Sobol indices (a maximum 0.05 difference is observed).

Climate change indicator

For the climate change impact category, the inter-annual parameter has the highest influence (first order Sobol index = 0.71) on the environmental impact variability. This result derives from the fact that the imports (mainly from Germany, rich in CO_2 content) diminished significantly from 2017 to 2018, because of an increase on the autogenous Swiss energy capacity. There is an approximately 22% impact variation between 2017 and 2018, which causes this increased influence on the impacts variability. The time step resolution is the second parameter that affects the climate change variability, but its first order

Sobol index is still modest, i.e. 0.14. This result confirms the observations of the chapter 4-a according to which the time step has an insignificant influence on the climate change variability, which is below to the inter-annual variability.

The photovoltaic peak power and the variability related to the PV specific production (kWh/kWp have a minor influence, on the uncertainty of the building climate change impact (0.01 and 0.04 for their 1st order Sobol indices, respectively). This result can be explained by the fact that PV electricity emits between 75 to 95 g CO_2 eq per kWh, mainly from spring to autumn, when the grid electricity has a similar climate change impact.

Primary energy indicators

For the NRE indicator, the photovoltaic peak power is the most influential parameter on the NRE variability, with a first order Sobol index = 0.77. Indeed, the electricity produced by the PV installation and consumed on site has a much lower NRE impact (1.09 MJp/kWh), than the electricity coming from the grid (6 MJp /kWh). Thus, varying the PV power and consequently the percentage of the self-consumption rate and level of autarchy strongly influences the building's environmental impact variability. The photovoltaic specific production is the second most influential parameter i.e. first order Sobol index = 0.1, on the NRE variability which remain modest. This is related to the unitary impact of the consumed photovoltaic electricity, which is lower than the impact of the kWh consumed from the grid. Thus, avoiding the consumption of electricity from the grid will affect the NRE environmental impacts for the building.

The inter-annual parameter has low influence on the NRE variability, i.e. first order Sobol index = 0.05. As it has already been shown in chapter 4-a, the NRE of the grid electricity does not present high variability between the years 2017 and 2018, since the unitary impacts of nuclear electricity and fossil fuel based electricity are similar.

Finally, the time step resolution has the lowest influence of the NRE variability i.e. first order Sobol index = 0.03. This observation confirms the results presented in chapter 4-a, according to which the time step does not influence substantially the variability of NRE impact under the current sampling choices.

As far as the RE indicator is concerned, the PV peak power is the most influential parameter, with a first order Sobol index = 0.69. Thus, varying the PV peak power affects significantly the RE variability. The second influential parameter is the inter-annual one, with a first order Sobol index=0.13, while the third one is the specific PV production, with a Sobol index=0.09. The ranking of these two parameters are reversed, comparing the NRE and RE indicators. This is because the RE indicator is slightly more sensitive to the variability of the grid electricity, expressed by the inter-annual parameter. Finally, the time step parameter presents the lowest first order Sobol index, i.e. 0.06, confirming the results of the WP4, on the time step influence.

Ecological scarcity indicator

For the ES factor, the most influential parameter is the PV peak power i.e. first order Sobol index = 0.56. As it was the case for the RE and NRE, there is a large difference between the unitary impact of the PV electricity produced and consumed on site when compared to the grid electricity impact. Indeed, the PV electricity has an impact of 120 UBP/kWh while the grid, over the two considered years, has an average impact of 270 UBP/kWh. Thus, varying the quantity of the produced on-site electricity and substituting it to the grid electricity, has a significant influence on the ES variability.

The second most influential parameter is the time step, with a 1^{st} order Sobol index of 0.18, as it was the case for the climate change indicator. This observation confirms the results, presented in chapter 4-a, according to which the ecological scarcity indicator, like the climate change indicator, was more influenced by the time step choice than the primary energies indicators.

The inter-annual parameter is the third contributor on the ES variability, with a first order Sobol index of 0.13. As it was the case for the energy indicators, the unitary impacts of the nuclear electricity and fossil fuel based electricity are similar, for the ES indicator, as well. The ES impact of the grid electricity is 277 UBP/kWh in 2017 and 258 UBP/kWh in 2018. Thus, this relatively small difference between the two years does not influence significantly the ES variability. Finally, the specific PV production curve is the last contributor, with a first order Sobol index of 0.07.

3.3.2 Time step variability range

Using the GSA results, the range of the time step influence has been calculated for the 20'000 simulations; taking the annual time step as a reference, see Figure 65.

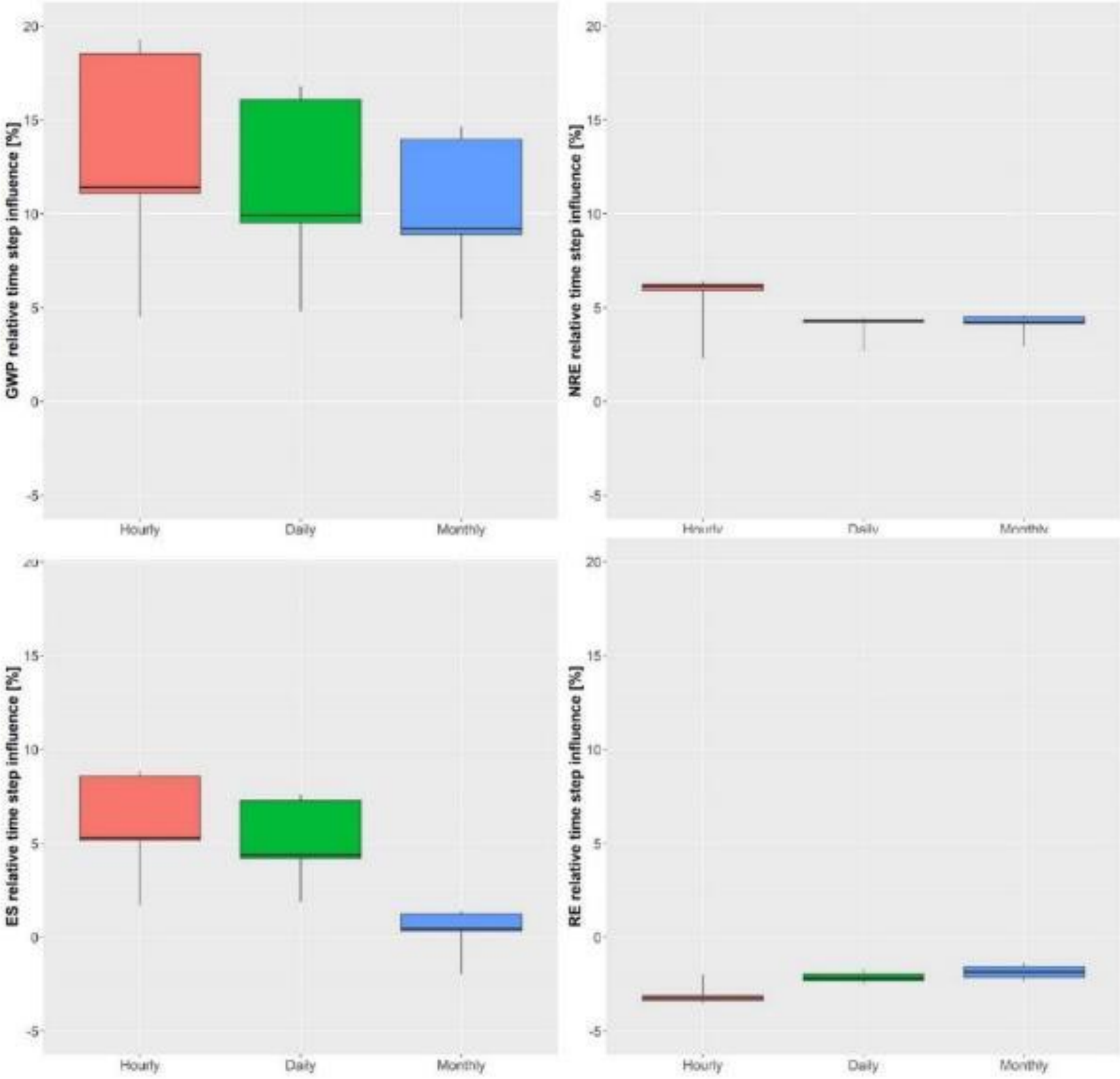

Figure 65 Relative time step difference per indicator

The relative difference between the hourly and annual time step, for the climate change indicator ranges from 4.4% to 19.3% and it has the highest median and interquartile range among all indicators, i.e. 11.4% and 6.3%, respectively. Thus, the climate change indicator is the most sensitive impact category to the time step resolution. The ecological scarcity is the second most sensitive environmental indicator to the time step resolution, with a relative difference between the hourly and annual time steps, ranging from -2% to 8.8 %, while the median value is 4.4% relatively small, independently of the fact that the time step resolution influences the variability of the results. The NRE indicator has a smaller min/max range from 2.3 to 6.4 % and the median is 4.4%. Thus, the time step influence is low for this indicator. The same trend is observed for the RE indicator, which ranges from -3.5% to -1.3% with a median value of -2.3%. For this indicator, the time step influence is negative, which means that higher time step resolutions imply to obtain a smaller impact result, compared to the annual time step resolution.

The results of the 20'000 simulations, confirm the general trends that have been observed in the chapter 4-a, regarding the time step influence on the environmental impacts. The highest difference of the results can be observed, between the hourly and the annual time step, for all the indicators, except for the RE indicator. For the climate change indicator, considering a monthly time step could be an intermediate solution, between the annual calculation and the hourly one, by increasing the results accuracy without increasing much the complexity of the calculations. Performing daily or hourly calculations would increase the accuracy disproportionally to the complexity.

For the NRE and RE, it is recommended to keep the annual calculation, as it is already the case, since the time step influence is insignificant. For the ecological scarcity, the gain in accuracy for the monthly calculation is negligible, compared to the annual calculation. It would be necessary to consider daily calculations at least to see an increase in accuracy.

3.3.3 GSA-2 - Sobol indices

The results of the GSA-2 (i.e including the building variability) are presented in the Figure 66:

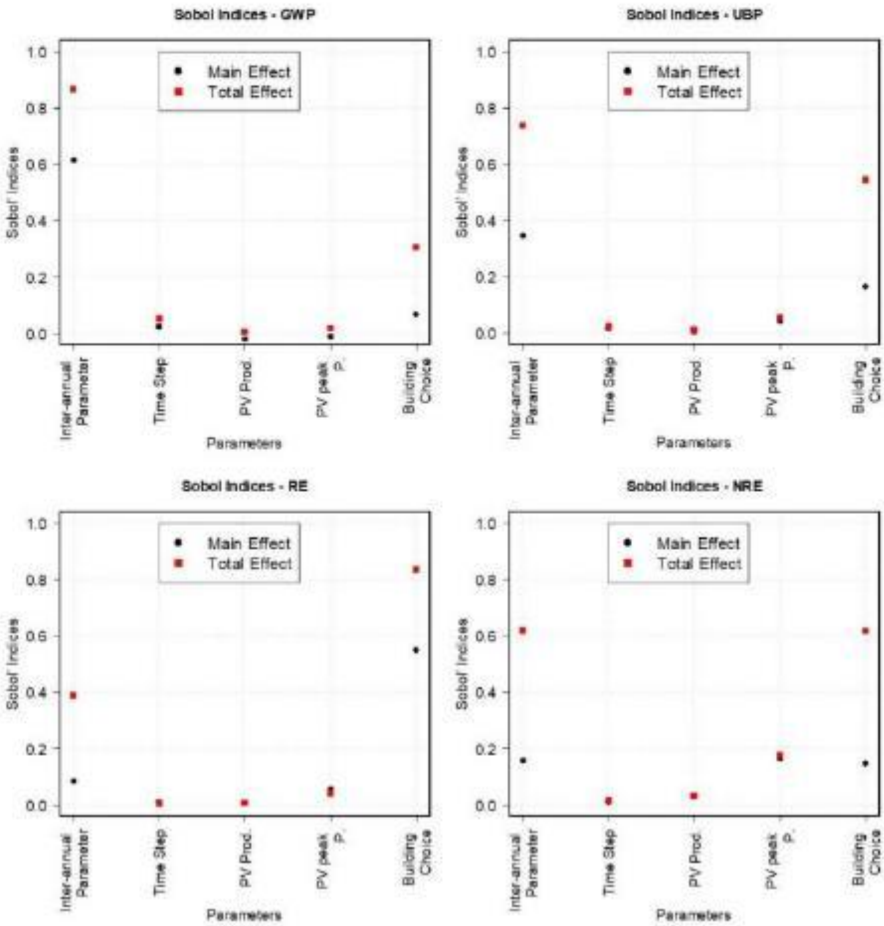

Figure 66 Sobol Indices for GSA-2

When considering the building choice variability, two main observations can be made. First, for all indicators, the building choice and the inter-annual parameters are the most contributing parameters. Second, the joint contribution between the inter-annual parameter and the building choice is important since there is a large difference in their first order and total order Sobol indices. These observations highlights the strong interaction between both parameters. Thus, both inter-annual parameters and building choice should be considered when performing the environmental assessment of a group of building for example.

With GSA-2, the time step parameter is not significant for any of the environmental impact category. Indeed, its biggest influence is for the climate change indicator (such as GSA-1) but is 4.5% at maximum. By generalizing the results of GSA-2, it is possible to notice that the inter-annual and building choice parameters largely overcome and flatten the relative influence of all other parameters.

3.3.4 Discussion on the results of variance decomposition

GSA-1

The variance decomposition and the Sobol indices generalize and confirm the observations, already, made for the case studies in chapter 4-a. Indeed, the time step influence is generally insignificant, but higher for the climate change and ecological scarcity indicators, for which it represents the second most influential parameter on their variability. In addition, the results confirmed that the climate change indicator is the most sensitive to the time step choice resolution, i.e. median = 11.4% for the relative time step difference, between the annual and the hourly time step. Thus, considering a monthly time step resolution, only for the climate change indicator, appears to be the most relevant choice, since it improves the calculation representativeness, while keeping the calculation procedure simple.

For the primary energy and ecological scarcity indicators, the photovoltaic peak power is the most influential input parameter within the considered scope of variability. Indeed, the environmental impacts of the PV electricity for these indicators are significantly different from the electricity from the grid and thus, varying the PV self-consumption induces important variability on the environmental impacts.

As far as the inter-annual variability is concerned, it is the most influential parameter on the climate change variability. In 2017, the limited Swiss nuclear production, compared to 2018, caused an increase of the imports, mostly from Germany, and thus energy, mainly coming from fossil fuels. The inter-annual variability is less important for the primary energy and ecological scarcity indicators, since the unitary impacts of the nuclear electricity and fossil fuel based electricity are similar. Thus, it becomes clear that the inter-annual variation is an important parameter that should be included, in the assessment of the climate change impact for buildings. The inter-annual fluctuations and uncertainty of the Swiss electricity mix could then be considered. This is particularly necessary, in the future, since the Swiss electricity mix will evolve, significantly, because of the 2050 Energy Strategy. In addition, it would be necessary to include an uncertainty factor related to the availability of production means. As it was the case between 2017 and 2018, similar trends could occur the coming years, for various reasons, e.g. less hydro availability because of water shortage for example. Developing uncertainty model for the near future considering the data from the past year would thus be of interest.

GSA-2

The model GSA-2 is similar of GSA-1 but add different building profile, with the same affectation, i.e SFH. It aims at identifying how the environmental impact variability is affected when broadening the scope of the study. This could be useful when environmental assessment of a group of building would be considered.

When considering different buildings, the time step influence becomes, in term of variance contribution, non-significant. The main influences are related to the building choice and the inter-annual parameter. It confirms that considering the inter-annual uncertainty would be necessary when performing environmental assessment of long-term objects (such as buildings in particular). It has to be noticed that this study was relying on ex-post data, i.e, for which both grid impact and load curves profiles were know jointly for various buildings. For prospective assessment enabling to anticipate and mitigate the future environmental impact, it would be more challenging to consider this aspect. Indeed, it would be necessary to define uncertainty profiles or scenarios for the electricity grid impacts and the building load profile as a function of external forecasted parameters (external temperature, population, development of productions means, etc.). Nevertheless, from the observed results, considering only deterministic values for long-term assessment could lead to mistake when considering the environmental impacts of buildings.

Summary on GSA

It is important to notice, that the Sobol indices give information on how the environmental impact variability is affected by the input model variability (variance-oriented approach). The indices present the relative influence of one parameter, given the influence of the other selected parameters of the model. Thus, a relative high Sobol index could also mean that the absolute variation of the output is modest. For example, looking at the ES indicator in GSA-1, 20% of the variability of the ES impacts are explained by the time step parameter. However, the difference of the ES impacts, between the annual and the hourly time step is small, i.e. median=5%. Thus, both aspects should be presented, in order to assess the importance of a parameter of the variability of the output.

Within the model defined for the GSA (1 or 2), the time step influence appears to have a very moderate or even non significant influence. However, the results of the GSA are obviously dependent of the model used for the calculations. Here, the models were developed without considering possible energy management strategies that would be developed in order to mitigate the environmental impacts of the building (such as the battery example of the previous chapter). However, when energy management strategies are aimed, the hourly time step information become crucial since it will be one of the element considered to manage the building electrical flows. Thus, it is possible to expect that for future smart buildings, the hourly time consideration would be of interest and would contribute in mitigating the environmental impact of the building sector energy demand.

4. Seasonality assessment: Theoretical study

In this chapter, the seasonality of the building electricity demand is addressed. This theoretical study aims at exploring how the environmental impact evolves, as a function of the seasonality of the building demand, given an hourly time step. Based on the results, the types of the electricity demand profiles, that are sensitive to the time step choice for their environmental impact calculations, can be identified.

4.1 Model description

The developed model refers to the total electricity needs of the building and no distinction is done for the type of the energy needs, i.e. space heating or domestic hot water, etc. It includes two aspects: 1) the duration and 2) the amplitude of the seasonal demand, taking the constant demand as a basis. The theoretical model for the seasonality assessment is described in Figure 67, for a one-year period. The model includes three parts, i.e. the two parts of the seasonal demand, which are always symmetric and the constant demand. The seasonal symmetric parts correspond to the demand that occurs during the first and the last part of the year, as for example the electricity demand necessary to run a heat pump, for the space heating needs.

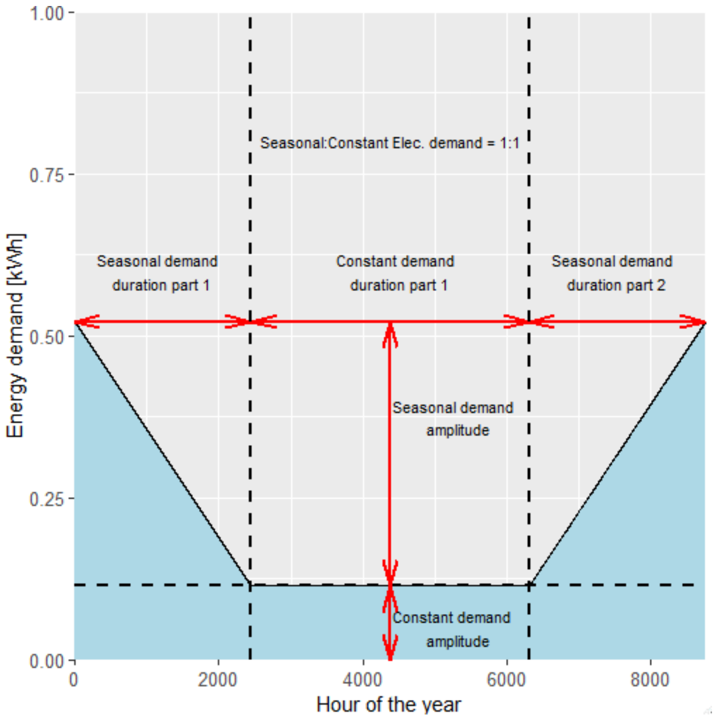

Figure 67 Theoretical model for the seasonal assessment

Both the amplitude and the duration determine the magnitude of the seasonality. The amplitude of the seasonal demand is defined as a ratio over the constant demand, based on which the duration of the seasonality is calculated. This ratio is defined in the following analysis, as the seasonality ratio. The annual constant demand was set at 2’000 kWh, while the sum of the constant and seasonal demand is always equal to this value. This threshold was set arbitrarily, since any other value would give the same results, taking into account that the results derive from the relative difference, between the annual and the hourly impact calculation. In the initial scenario, the demand is equally apportioned at each hour of the year; i.e. the building consumes 0.23 kWh every hour, as seen in the top-left plot of Figure 68. For this situation, the seasonality ratio is 0:1. Then for the second scenario, the seasonality ratio is set at 1:10. This means that one tenth of the 2’000 kWh is a seasonal demand, while the remaining is a constant demand. The duration of the seasonal demand is long, i.e. 4’350 hours. Thus, small seasonal amplitude and long seasonal duration means low seasonality ratio. Another example can be seen, by looking at last bottom right plot of Figure 68. In this plot, the seasonal demand occurs for 1’900 hours (950 hours at the beginning and the end of the year) and the ratio is 1:1, which means that the seasonal demand is 1’000 kWh, while the constant demand is also 1’000 kWh. Hence, high seasonal amplitude and short seasonal duration correspond to high seasonality ratio.

For the theoretical model assessment proposed here, the duration and amplitude of the seasonality is varied (in the continuous domain) and sampled, by Monte Carlo simulations. For each sampled scenario, a ratio and a duration of the seasonality are sampled. The environmental impacts are calculated on the hourly and annual basis and the relative difference is then calculated. This model is simple, since it does not account for any daily variability, as it is observed in reality (see WP4). However, it provides information on how the time step choice is influenced by the seasonality.

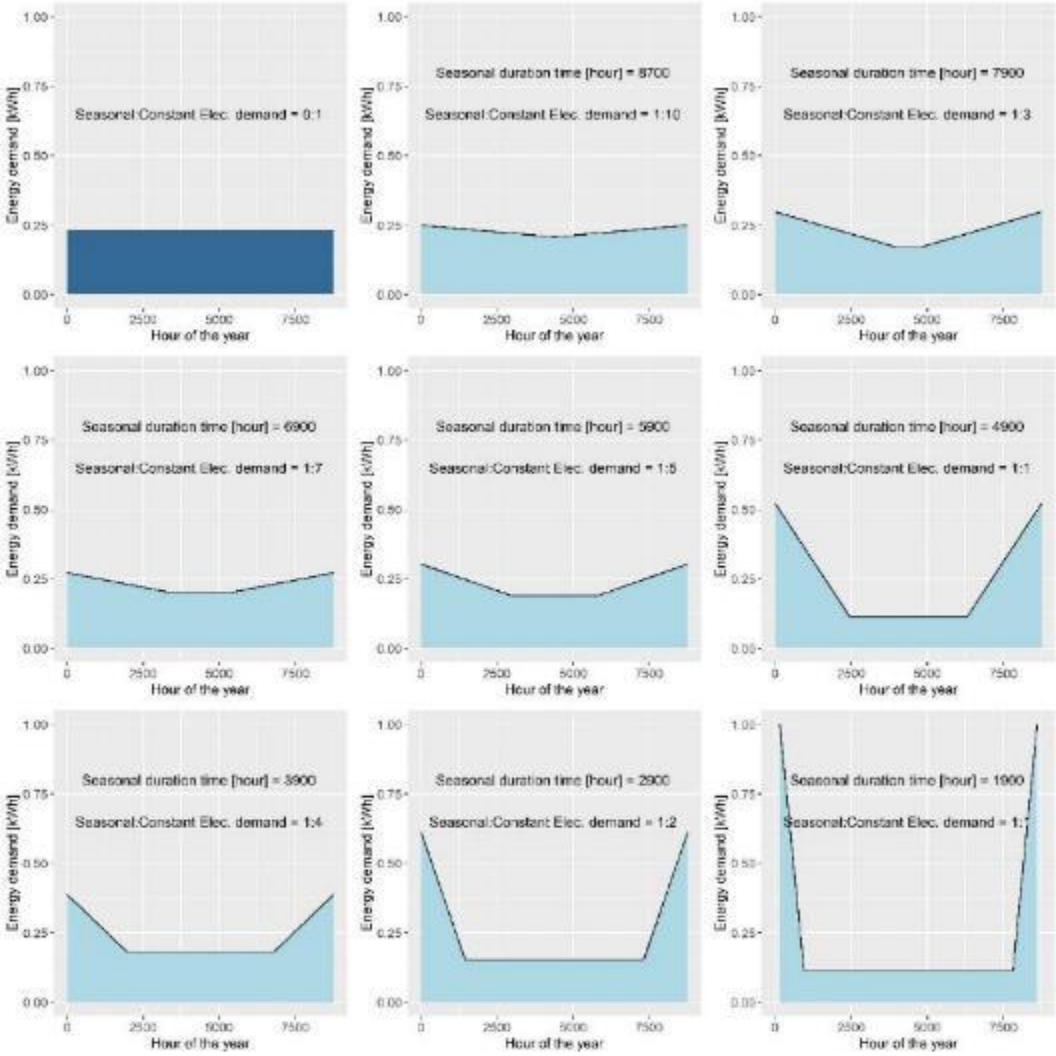

Figure 68 Theoretical model representation to assess the influence of the seasonality

4.2 Results

2’000 calculations have been simulated and the relative time step difference has been calculated, as a function of the number of hours, during which the seasonal demand occurs, see Figure 69. For the sake of simplicity, only four seasonal ratios have be plotted, from 1:0 (only seasonal demand to 1:10, mainly constant electricity demand).

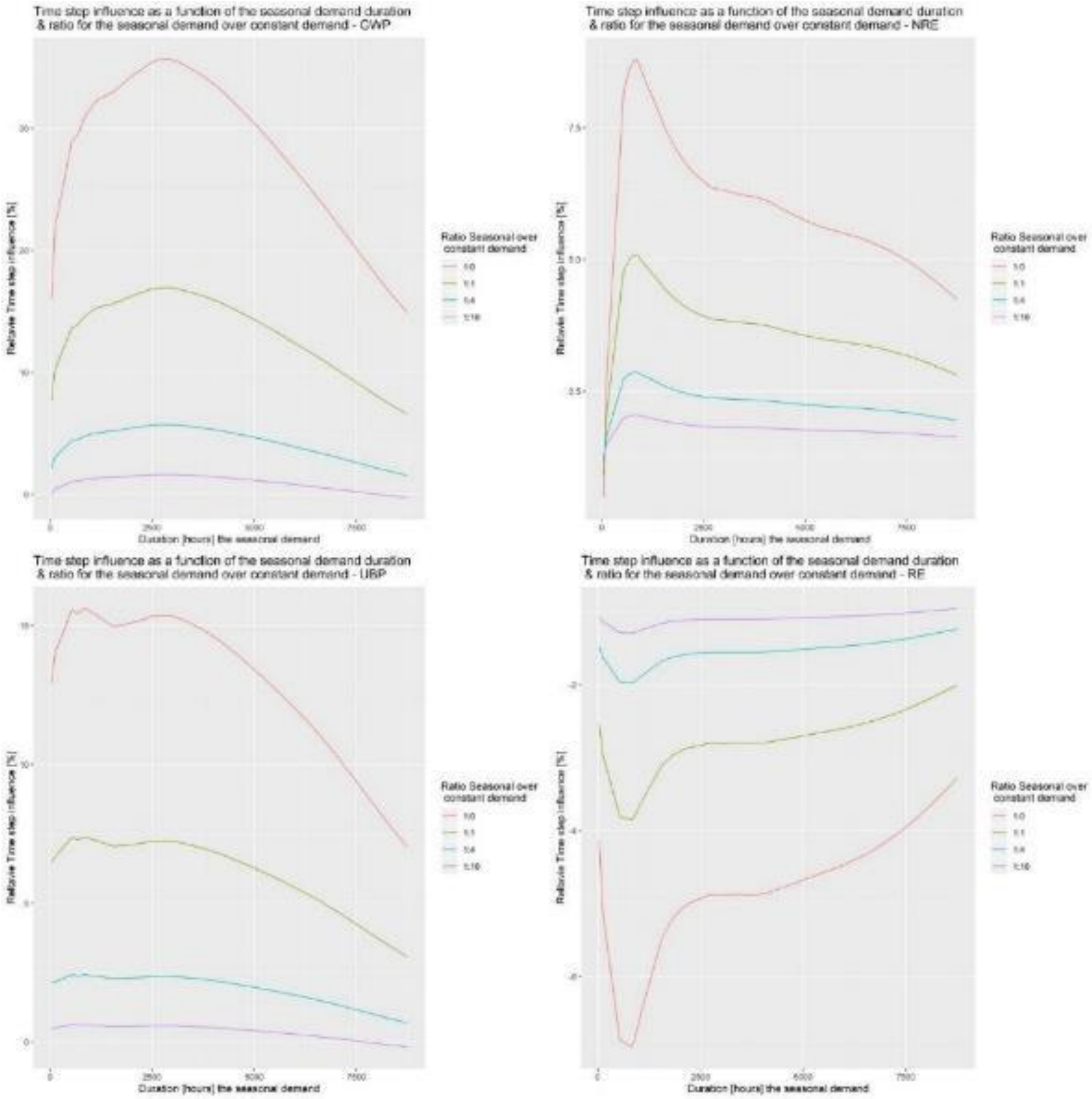

Figure 69 Results of the seasonal influence

Figure 69 shows the influence of the seasonality, on the time step choice. The highest difference of the results, between the annual and the hourly time step is observed for demands with a high seasonality ratio (1:0, which mean high amplitude and short duration of the seasonality), while, the smallest time step influence, is observed, when the demand is mainly constant (ratio 1:10, which mean small amplitude and long duration of the seasonality). Thus, the time step resolution influence increases with the increasing seasonal amplitude. On the contrary, the time step influence decreases with the increasing seasonal duration. For example, the time step influence, between the hourly and the annual time step is lower for seasonal durations of 8’000 hours, than for durations of 2’500 hours.

Furthermore, it is important to notice that the higher the amplitude of the seasonality, the higher the peaks of the curves, for all the indicators. Higher peaks mean higher deviation from the average annual impacts. Thus, scenarios that exhibit high seasonality in terms of amplitude, but relatively low seasonal duration, tend to have high variations between the results of the annual and the hourly time step.

For the climate change indicator, the relative time step influence can reach 35.5% at most for a seasonal demand duration of 2’860 hours and a seasonality ratio of 1:0 The relative time step difference peak falls to 17% for a ratio 1:1, to 5.7% for a ratio 1:4 and finally to 1.6% for a ratio 1:10. This observation is on agreement with the WP4 results for which, when the seasonal demand was considered separately (electricity demand for the space heating with heat pump), the time step influence was higher compared to when the overall building electricity demand was considered. Taking into consideration that for a building, the heating season lasts approx. from the 1st of November to 31st of March, which corresponds approximatively to 3624 hours, the relative time step difference ranges from 0.3% (ratio 1:10) to 26% (ratio 1:0).

For the NRE indicator, the relative time step influence is much lower than for the climate change indicator. This is consistent to the WP4 results. For a seasonality ratio of 1:1, the maximum relative time step difference is 5%, 2.9% for 1:4 ratio and 2% for a 1:1 ratio. Considering that the heating season has 3624 hours, the relative time step difference ranges from 1.8% to 6.2%.Thus, for this indicator, the relative time step influence is relatively low. It should be also noticed that the NRE indicator is more influenced by the intra-day fluctuations, as already explained in chapter 4-a, aspect that it is not covered by this simplified model.

For the RE indicator, the relative time step influence is lower than the NRE indicator and negative, as well. It means that the higher the time step resolution, the lower the impacts. For a seasonality ratio of 1:1, the maximum time step difference is 3.8%, 2% for a 1:4 ratio and 1.3% for a 1:10 ratio. Considering the heating season of 3624 hours, the relative time step difference ranges from minimum 1.1% to maximum 4.9 %. Thereby, as it was the case for the NRE indicator, the RE indicator is not significantly influenced, by the seasonality, as it was accounted with this simplified model. The RE is influenced by the intra-day fluctuations, which are not accounted with this model.

For the ecological scarcity indicator, the relative time step influence lies between those of the climate change and the NRE indicators. For a seasonality ratio of 1:1 the maximum time step difference is 7.4%, 2.4% for a 1:4 ratio and 0.6% for a 1:10 ratio. Considering the heating season of 3624 hours, the relative time step influence ranges from 0.5% to 14.9%.Thus, for this indicator, the relative time step influence is moderate, result that is consistent to the WP4 observations.

4.3 Discussion

Both the amplitude and the duration of the seasonality can significantly influence the results, between the annual and the hourly time step calculations. The developed model is relatively simple; however, it provides information on how the relative influence evolves, as a function of these two parameters. The results confirm the observations, made in the WP4, regarding the time step.

It appears that for low seasonality ratio (low amplitude and long duration), the time step influence is low and there is probably no need to perform calculations with higher time resolutions. However, for high seasonality ratios (high amplitude and short duration), the time step influence could be critical and probably higher time step resolutions could be necessary. Thus, this theoretical evaluation could be a way to define if an annual or a higher time resolution calculation is needed. When aiming at calculating the environmental impact based on a electricity load curve, the decision procedure could start with examining both the amplitude and the duration of the seasonality. If the former is high, then the seasonal duration should be examined. If the seasonal duration is small, then an hourly basis calculation should be performed, otherwise annual calculation, for simplicity reasons.

The NRE and RE indicators are not sensitive to the considered seasonality, so impact calculations, with a time step higher, than the annual step is not relevant. It should be noticed though, that including intra-day fluctuations in the model, could change this conclusion.

The ES indicator is more sensitive to the seasonality. However, the relative time step influence for a seasonal demand ratio that could be observed in reality is relatively low (5% on average). Thus considering higher time resolution for this limited gain is questionable. In addition, including intraday variations could change the results, as for the NRE and RE indicators.

The climate change indicator is influenced more by seasonality than other impact categories. This element is key when considering the high share of heat pumps for space heating in the building sector. In the WP4, few buildings were considered and it has been found that for this specific configuration of building with heat pump, the climate change impact could be sensitive to the time step choice. However, in the WP4, the obtained ranges for relative time step influence were moderate because of the seasonality ratio, ranging between 1:2.5 to 1:6 and the duration of the seasonal demand that was important. Thus, considering the WP4 results and the above presented assessment, it can be expected that for some building configurations, the time step choice could be significant for the results.

The developed model for the evaluation of seasonality identified possible building load profiles that could induce important relative time step influence. Based on this model, it is possible to identify mainly two types of buildings, for which the time step influence could be significant:

- The renovated buildings, for which the space heating demand is still high, for the case that a heat pump is used. In this situation, the seasonal ratio is small and the seasonal duration could be high. The results have shown that this configuration could be critical, concerning the time step influence on the results. The CS1- CS4 buildings of the WP4 fulfill this criterion and they exhibited the highest sensitivity to the time step resolution. While for CSa – CS4, the influence was limited (see chapter 4-a), it tends to confirm, with the above presented results, that this category of building should be more deeply assessed regarding the time step resolution aspect.
- The case of an energy-efficient building that exhibits a high seasonality in the space heating demand. This case corresponds to a low seasonal duration and a moderate seasonal magnitude. The CS5 of WP4 seems to correspond to this profile, since it has small energy consumption for the space heating and small seasonal duration, since it uses efficiently the solar gains. However, it seasonal ratio is relatively low 1:3, which limits the time step influence.

From this sensitivity analysis, two additional points need to be highlighted:

- It would be necessary to develop a specific metric, characterizing the seasonal demand ratio. In the assessment developed above, the ratio was calculated, taking into account a theoretical model, with a constant demand over the year and a simple seasonal demand. Nevertheless, in practice, the building load profiles are more complex and the used model would not be sufficient for the assessments. Using time-series decomposition model (additive or multiplicative) could be a way to quantify the seasonal fluctuation, versus the intraday fluctuations and the constant demand. Then, based on this proper metric to characterize the building electricity profile, it could be possible to define if a higher time resolution (other than the annual time step) should be used for the environmental impact calculations.
- The intra-day fluctuations have not been accounted with this model. These fluctuations could imply higher sensitivity for the NRE and RE indicators, as already identified via the WP4 case studies. It would therefore be necessary to address this point more.

5. Conclusions

This sensitivity analysis chapter had as objective to enhance and broaden the scope of the EcoDynBat study regarding the time step influence when considering the environmental impacts of the building electricity demand.

The first results described in this report dealt with the time step implication when considering photovoltaic + storage Self Generation Systems (SGS). Several configurations of SGS (including low to large PV peak power and battery capacity) were considered on a low energy consumption Multi-Family building. The environmental impacts were calculated considering 1- both energy and GHG oriented control strategies for the battery management, 2- the GHG impact of SGS when using the dynamic LCA results or the annual constant value, 3- the GHG impact with a scenario on which the Swiss nuclear production is replaced by imports from the neighboring countries and finally 4- the Non-Renewable primary energy impact of SGS systems.

The energy and GHG control strategies appear to provide similar impact ranges. This could be due to the characteristic hourly variation of the considered MFH demand profile and of the GWP impact factor for the Swiss grid, which have coincidently inverse peaks and valleys. Thus, the GHG impacts of the grid is low when the demand is high during the days (because the grid peaks are mostly covered by pumping storage units). When considering an annual GWP factor the environmental benefits of SGS is increased especially with large systems. This results is observed because when considering the annual grid GWP factors it is always higher than the environmental impacts of the electricity stored and delivered by the SGS. Conversely, when using an hourly grid GWP factor, the benefits of using the SGS are apparent in winter when Switzerland imports more energy with higher GWP intensities, but less clear during the warmer season when a higher portion of the supply mix is supplied with indigenous hydropower and lower GWP intensities. The evaluation of the extreme scenario of nuclear substitution by imports increased the environmental impact benefits of SGS from 12%, in the ENERGY scenario, to 22%. Finally when considering the range of the NRE impact factor, the sensitivity to the technical SGS characteristics is highest, reaching up to 33% difference between resulting DLCAs.

Therefore, the results of this study are valuable for the insight they provide in terms of the sensitivity of the LCA result to certain technical and environmental factors, yet they should not be interpreted as a general and all encompassing evaluation of the advantages and disadvantages of PV and batteries systems, which were outside the scope of the EcoDynBat project. Further work regarding the SGS system in Switzerland should be promoted in order to provide a clear overview of the environmental interest of such systems.

Then, two Global Sensitivity Analysis (GSA) have been performed. These GSA aim at quantifying the share of environmental impact variance induced by the time step consideration compared to other parameters (photovoltaic production, inter-annual variability, building load profile). The first assessment consider only the variability induced for a model that consider only one building while the second GSA considers different buildings choices. These assessments have shown that the time step choice has a limited influence on the environmental impact variability.

Considering only one building, the time step parameter has the biggest influence on the climate change impact category but remains limited (max 11%). For this impact category, its influence remains lower than the inter-annual variability of the consumed electricity impact. The ecological scarcity and primary energy indicators are mostly influenced by the photovoltaic peak power. For these three indicators, the inter-annual variability of the consumed electricity impact has a low influence because has shown in the chapter 4, the impacts of the Swiss consumed electricity is less fluctuating over the time and between the years. The main reason of this difference has to be found in the unitary impact of the nuclear electricity and the fluctuation in term of nuclear production over the two considered year (which influence the imports levels). Thus, from this assessment, it appears that the high time step resolution could be considered (even if its influence is modest) for the climate change indicator but does not seem relevant for the other indicators. In addition, this assessment has shown that the inter-annual uncertainty should be considered when calculating the environmental impacts of a product or service that would occur over a long time period (several years).

The second GSA has been performed in order to broaden the scope by considering the influence of various building load profile. When including this additional parameter, both the inter-annual and the building choice parameters influences overcome the others. In addition, there is a large joint influence with these two parameters (high total Sobol indices). For this model, the time step influence becomes marginal.

Finally, as a sensitivity assessment, a theoretical model considering the load profile seasonality has been developed. This model has been set in order to estimate the maximum range and profile related to the time step influence as a function of the seasonal demand profile (including its duration and amplitude). This sensitivity assessment has confirmed that the relative difference between hourly and annual calculations is the biggest on the climate change indicator when the seasonal demand profile is important (i.e low duration and high amplitude compared to the constant demand part). The other indicators are the less influenced as highlighted in the WP4. Both seasonal demand duration and seasonal demand ratio (ratio of seasonal consumption over a constant demand) are strongly affecting the relative difference. The seasonal ratio influence confirms that the constant electricity demand tend to flatten the relative time step difference. Thus, for high share of constant demand, considering hourly calculation does not seem relevant. The seasonal demand duration exhibit a peak, different for each environmental indicator. For the seasonal duration below the peak, the seasonal demand multiplied by the grid impact compensate create compensatory effect that limit the relative time step difference. Above the peak, the seasonality is too low and also limit the relative time step difference. The model was created in order to characterize the range of relative time step difference and aims at helping to identify specific consumption profiles for which higher time step resolution than annual would be necessary to calculate the environmental impacts. From this assessment, it appears that buildings with high amplitude of the seasonal demand (compared to constant demand) would induce a sensitivity in the time step resolution choice.

Thus, from this sensitivity analysis work, it appears that the time step consideration could have to be considered especially when considering smart buildings which are low energy demand intensive, with a high seasonality and when these buildings include advanced energy production and management strategies including in particular batteries. For current buildings with standard energy conversion systems, the time step influence appears to be minor. Nevertheless, considering the long lifetime of the building coupled with an expected deep modification of the Swiss electricity production mix, it can be expected that the D-LCA should gain in interest in a near future.

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ECODYNBAT Project

Dynamic Life Cycle Assessment of Buildings

Chapter 6: Recommendations (WP6)

Final report

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2: EMPA | Technology and Society group | Advancing Life Cycle Assessment

3: SUPSI-DACD-ISAAC

Summary

This report presents the recommendations derived from the different EcoDynBat different chapters (based on the different project's work-packages, WP). Thus, insights are provided on how to efficiently apply in practice the main findings of the project. Finally, future research perspectives are listed, in order to further develop and build up the results of the EcoDynBat project, concerning the Dynamic-LCA for the energy consumption in Switzerland.

Résumé

Ce rapport présente les recommandations qui se sont découlées par chaque chapitre du projet EcoDynBat (relatié chacun des *workpackage,* WP) du projet EcoDynBat. Ces recommandations donnent des idées pour l'exploitation efficace de résultats du projet EcoDynBat. Enfin, une liste de perspectives de recherche est identifiée afin de poursuivre les travaux sur les ACV Dynamique de l'énergie en Suisse.

Zusammenfassung

In diesem Bericht werden die abgeleitete Empfehlungen von jedem *workpackage* (WP) der EcoDynBat vorgestellt. Diese Empfehlungen liefern Ideen für die weiterentwicklung der Ergebnisse des EcoDynBat-Projekts.Schliesslich wird eine Liste von Forschungsperspektiven erstellt, um die Arbeiten im Zusammenhang mit der dynamischen Ökobilanz für den Energieverbrauch in der Schweiz fortzusetzen.

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Abbreviations

AT : Austria
A-W: Air-Water
CH : Switzerland
CHP : Combined Heat and Power
COP: Coefficient Of Performance
CS: Case Study
CZ: Czech Republic
DE : Germany
DHN: District Heating Network
DHW: Domestic Hot Water
DLCA: Dynamic Life Cycle Assessment
ENTSO-E : European Network Transmission System Operator
ES: Ecological Scarcity
FR : France
GHG: Greenhouse Gas
GHGe: Greenhouse Gas emissions
GW: GigaWatt
GWh: Gigawatt hour
GWP: Global Warming Potential
HP: Heat Pumps
IT : Italy
KBOB: Ökobilanzdaten im Baubereich 2009/1:2016
LCA: Life Cycle Assessment
MFH: multi-Family House
MW : MegaWatt
MWh : Megawatt hour
NRE: Non Renewable primary energy
PV : Photovoltaic
RE: Renewable primary energy
SFH: Single Family house
STEP: Station de Turbinage et Pompage
UBP: Eco-Points
WP: Work Package
WP1: Work Package 1 – Review of methodologies
WP2: Work Package 2 – Input data with temporal variability considerations
WP3: Work Package 3 – Development of a DLCA framework for the project
WP4: Work Package 4 – Case studies
WP5: Work Package 5 – Sensitivity Analysis
WP6: Work Package 6 – Recommendations and dissemination of results

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1. Introduction

The EcoDynBat project aimed at assessing the effect of the time step of the Swiss electricity mix, on the environmental impacts of the building electricity demand. To do so, the project has been divided in six work-packages (WPs) which implied a specific report chapter for the final project document. The WP1 focused on the analysis of the scientific literature of the dynamic life cycle assessment (DLCA) method, in the building context. The WP2 aimed at identifying, gathering, and characterizing the available data, regarding the energy flows of the Swiss electricity grid (national production, imports, exports) necessary for its environmental impact evaluation. In the WP3, the methodological framework was determined, concerning the dynamic life cycle assessment, of the energy flows, at the building level. Following this section, the WP4 aimed at quantifying the influence of the time step on the environmental impacts of the electricity demand, of different case studies (equipped with PVs, heat pumps and micro – CHP) and thus in the beginning the impacts of the electricity mix were defined. Finally, the WP5 studied the sensitivity of the impacts in combination to the energy storage, as well as to the time step in combination to other parameters, too. The present WP offers a summary of the recommendations made from all the previous WPs.

2. Recommendations for the DLCA (WP1)

The WP1 is focused on the literature review of the DLCA methods in building applications. The following recommendations can be proposed, concerning the modelling choices and the computational structure of the DLCA.

2.1 System modelling choices

A limited number of studies exist in the literature, concerning the systems' dynamics for the environmental assessment of buildings. The recent Swiss publications on the subject provide interesting ideas, but simplifications are still made on the temporal variability of imports and exports of the electricity flows. For example, the authors use annual average values, for the import/exports between Switzerland and Germany, without controlling the influence of such a simplification in their work. Moreover, the existing DLCA frameworks for buildings do not propose a clear strategy, for the considerations of such variations. The literature review, thus, confirms the relevance of carrying out further DLCA studies on intra-annual energy flows for Swiss buildings, at different levels of temporal and regional precision, to evaluate the level of variability from such assessment.

For decentralized renewable energy production systems, site-specific aspects should be considered, when possible, in order to increase the overall assessment representativeness by considering the systems' dynamics. For example, when considering PV production, the specific environmental impact per kWh should be calculated, based on the energy production measured or simulated, given the building location and roof configuration (orientation, inclination). Using database unitary values should be avoided, since they would provide inconsistencies and erroneous results. .

When focusing on calculating the energy flows in the building level, it is important to provide a transparent and detailed description of the data sources of the systems' dynamics (i.e. the Swiss electricity mix), as for example their corresponding assumptions and limits. Some scientific publications offer insights on the key information and choices that need to be considered, but they are not very detailed, probably because of their usual concise format.. Up to now, useful ideas have been presented, for the consideration of the temporal variations for energy flows in buildings with decentralized production, but more details will be necessary to describe the use of the Swiss electricity mix at different periods (e.g. day, week).

Some modelling simplifications are necessary, in order to perform DLCA studies, mainly because there is still an important lack of temporally differentiated LCA data. Indeed, all temporally differentiated flows that need to be considered should be defined by the project partners to ensure transparency in the assessment. The temporal simplifications should be kept at a minimum level for foreground processes, while finding a balance between increased precision and the time needed for system modelling and computation of DLCIs. For background processes, it seems necessary to neglect the time-lag between emissions and use of energy, since considering such an element would force a temporal description of all flows in the chosen databases.

2.2 Computational structure

Graph traversal computational methods and tools are really promising for the future of DLCA, but their use is impeded by the lack of temporally differentiated data in LCA databases. Indeed, such methods and tools rely on descriptions of flows by process-relative temporal distributions, which are not provided in the latest version of the ecoinvent and KBOB databases. Until the tools and databases enable graph traversal computational methods, the use of matrix-based computational structure is therefore recommended for DLCA calculation of the electricity impacts. The use of the matrix-based computational structure has been demonstrated and implemented in some LCA software options, with a limitation that is linked to the complexity of creating the required processes for detailed models with high temporal precision (e.g. hourly differentiation). Computational time can also become a limit that depends on the chosen software tools. As a recommendation from the WP1, we suggest to assess the feasibility of developing computationally optimized tools for performing DLCA calculations with the matrix based approach.The main recommendations for the modelling choices in building DLCA are presented in Table 28.

Table 28: Main recommendations for a building DLCA

For modelling energy

- Focus on intra-annual variations (short-term)
- Consider the detailed production of neighboring countries to model Swiss imports
- Ensure consistency with other assessment methods in the model's structure of:
    o Electricity mixes
    o Decentralized production
- Employ site specific data when available
- Offer transparent and detailed descriptions of data sources
- Minimize the amount of temporal simplifications
- Neglect time-lag in:
    o Background databases
    o Decentralized renewable energy production

For the computational structure
- Use matrix-based calculations to obtain DLCIs   o Can also be applied on processes instead of emissions

3. Recommendations for data collection regarding the Swiss electricity (WP2)

The data collection for the building DLCA and the harmonization method, developed for the needs of the project, led to the following recommendations:

1- The Swiss electricity mix presents an important inter – annual variability and thus, special attention should be taken on the dynamics of the system, in future studies.

2- Considering DLCA for the electricity requires handling a large amount of data. This large amount requires developing a specific collection framework and platform that should be, regularly, updated. Within EcoDynBat, we recommend to develop a dedicated Swiss transparent platform that could provide the national mix, on an hourly basis. This platform could then be used for different projects, related to the Swiss electricity production and consumption. It would, thus, provide a common basis for these studies, which would be of interest for the development of a coherent Swiss energy strategy. This platform could be linked with the existing Swissgrid or Swiss Federal Office of Energy.

3- Some discrepancies have been identified between the ENTSO-E data and the Swiss national data (Swissgrid or the annual report on electricity). It would be necessary to fill the gap between these data sources, in order to provide a coherent set of information, regarding the Swiss electricity mix.

4. Recommendations for the DLCA methodology (WP3)

Based on the WP3 research work, the following steps are proposed, in order to calculate the dynamic environmental impact of the building electricity demand, see Figure 70:

5. Multiplication of one of the four different temporal distributions, describing the impacts of the Swiss electricity mix, with the temporal distribution of the electricity imported from the grid.

   ⇨ <u>This step evaluates the impacts of the electricity use in the building, when it is provided by the grid for every time step, over the full period of the assessment (i.e. 1 year).</u>

6. Multiplication of the temporal distributions for the self-consumed electricity with the impacts of the decentralized installation per kWh

   ⇨ <u>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 the assessment (i.e. 1 year).</u>

7. Summation of the obtained temporal distributions for the grid and self-consumption

   ⇨ <u>This step combines the impacts of all electricity uses in the building for every time step over the full period of the assessment (i.e. 1 year). Values can be divided by the Energy Reference Area (ERA) of the building to provide the results that can be compared between building (Functional unit choice).</u>

8. [Optional] Integrate the results of step 3 over 1 year to get values that can be compared with "standard" LCA results

   ⇨ <u>This summation of impacts, from this DLCA framework, over the full year is necessary to be compared to the results to results from a non-dynamic LCA.</u>

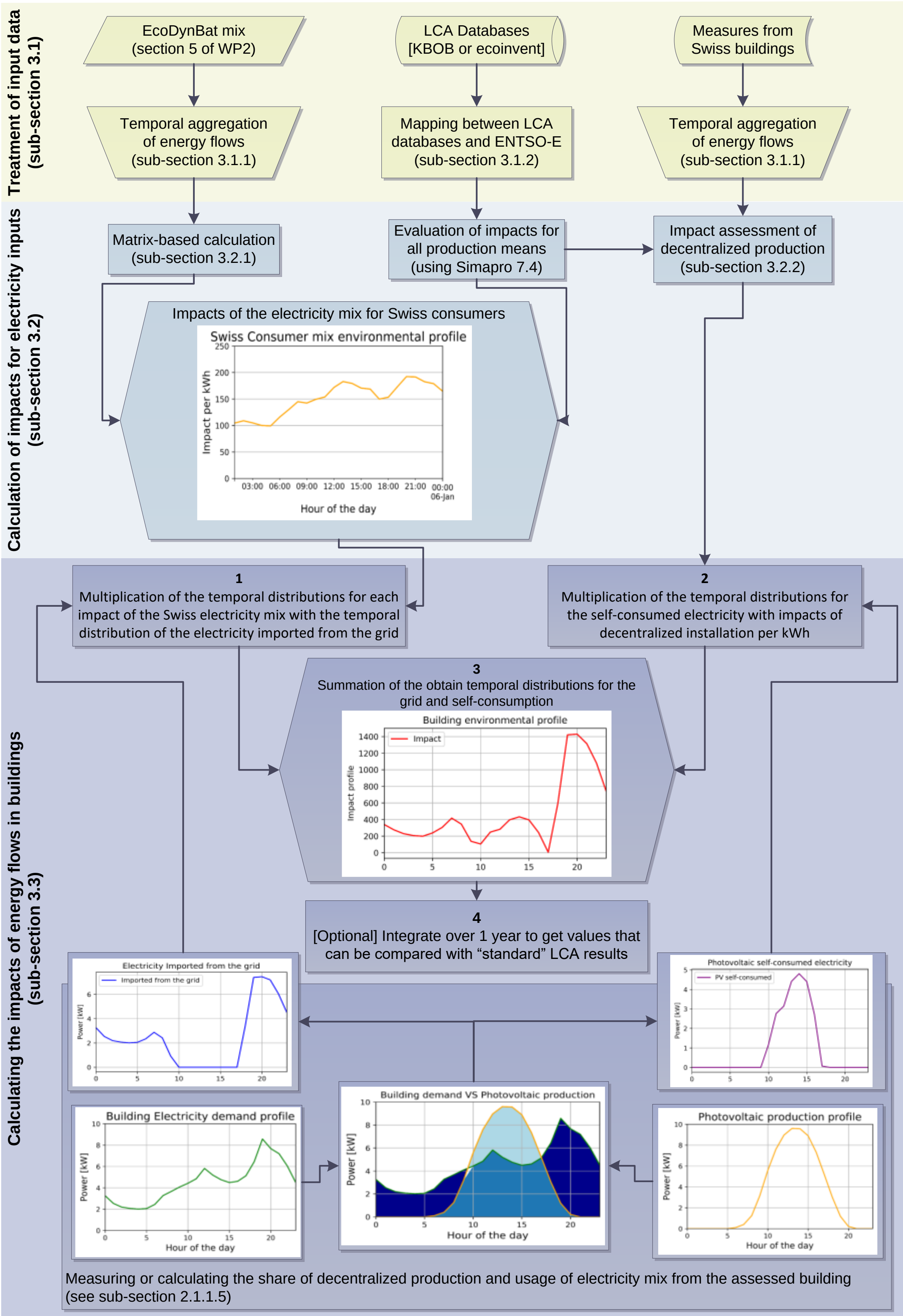

Figure 70: Graphical example of the computational structure for the EcoDynBat framework and further DLCA studies

5. Recommendations for the environmental assessment of the electricity building impacts (WP4 – WP 5)

From the EcoDynBat WP4 and WP5 research work, the following recommendations can be made:

- It would be necessary to compare the various approaches, regarding the environmental impact of the Swiss grid electricity. Indeed, there are different methods or they are under investigation and the results of the impacts evaluation significantly vary. In addition to the ecoinvent and KBOB methods, there are other studies, e.g. those of Vuarnoz et al. (2018), Romano et al. (2018) and the PhD thesis of Emilie Simon (2020) at HES-Valais Wallis. The large number of different methods could be misleading for non-specialists and could lead to an erroneous characterization of the real environmental impacts of the Swiss grid electricity. It appears necessary to form a dedicated taskforce, regarding the environmental impact characterization of the Swiss grid electricity. This working group could either provide a common framework for the environmental impact calculation, or meticulously describe the differences among the sources, in order to help the non-expert, to their interpretation;
- The EcoDynBat results have shown an important inter-annual variability, regarding the environmental impacts of the grid electricity. Because of this fact, there are two aspects that should be taken into account, in further impact calculations. First, the uncertainty, regarding the environmental impact of the Swiss electricity should be characterized, by considering uncertainty of the production means availability. Second, the Swiss production mix is expected to significantly vary (as for the neighboring countries, too), thus, it would be necessary to consider this evolution, when assessing the environmental impacts over a long period of time, as it is the case for buildings. The large changes in the production mix of the countries could cause an important variability that would require hourly impact calculations to be considered;
- Currently, the concept of smart-buildings is emerging in Switzerland. It can be expected that soon, there will be a large number of buildings that will have pro-active energy management solutions (storage, load shifting, etc.). The smart-buildings require detailed information, regarding the energy flows, i.e. high time step resolutions mainly of electricity flows. Including the environmental impact information in the smart-building management could help mitigating the environmental impacts of their energy demand. For this purpose, DLCA would be of interest and its development should be further considered. The study regarding the battery within the WP5 has introduced this interest and the research development should be pursued. In addition, the photovoltaic influence assessment within WP4 has also shown that by managing efficiently the self-consumption, it could be possible to maximize the environmental gains;
- The hourly environmental impact of the Swiss grid electricity could be also used, in order to further develop the national electricity strategy. Indeed, there are already discussions, related to the future electricity mix (nuclear phase-out, development of the wind electricity, small hydro, etc.). Considering hourly impacts, mainly for the electricity imports can contribute to a clear image of the grid electricity. Thus, based on and accurate environmental assessment new production means can be developed, in order to substitute the electricity imports.
- The time step consideration has been identified as being significant for demands that are highly seasonal. The case studies of WP4 and the sensitivity analysis of WP5 have quantified this influence on the environmental impacts. Thus, for high seasonal demands, there is a need to consider the environmental impact fluctuation, over time. Two ways are suggested. The first includes the determination of a specific environmental impact content for the electricity, for the seasonal or constant uses of the building. For example, the impact of the electricity consumed for heating could be different from the environmental impact of the electricity for the domestic uses. This approach can simplify the problem of the seasonality, and it has the advantage of being easily applicable in practice. The second approach includes the hourly impact calculation, in case of an important seasonality of the building energy profile. , identifying. It would, thus, be necessary to set a framework and a potential threshold, in order to decide whether a DLCA is required or if an annual calculation is sufficient. Both approaches should be investigated;

- For constant or low fluctuating electricity demands, the use of an annual value for the environmental impacts of the grid electricity should be used. DLCA is not found to be relevant for this situation ;
- The first sensitivity analysis showed that the time step influence is higher for the climate change impact, than for the other indicators and thus, the choice of the time step is relevant should be performed, by evaluating this impact indicator. In addition, the second sensitivity analysis showed that the most influential parameters on the environmental impacts are the building load profile and their inter – annual variability. Thus, it is recommended that for future predictions of the impacts of the electricity mix, the inter – annual variability to be taken into account. Uncertainty profiles or scenarios for the electricity grid impacts could be defined, as well as for the building load profile, as a function of external forecasted parameters (external temperature, population, development of productions means, etc.).
- The EcoDynBat findings have been derived based on six case studies that included heat pumps and PV. The WP5 offered a generalization of this assessment. Nevertheless, it would be necessary to investigate the time step influence over a big set of buildings or to consider archetypes of demand profiles, in order to consolidate the findings derived from these WPs;
- Regarding the micro-CHP assessment, the time step is not influent and annual time step should be considered. Nevertheless, it has to be noticed that this statement is valid when the micro-CHP covers a high share of the building electricity demand. In addition, for low electricity shares and high seasonal profiles, the choice of time step resolution should be investigated.
- There is a clear need to answer the question, concerning the biogas impact allocation. Indeed, until now, depending on the allocation choice, the bio-methane and the micro-CHP solutions should be either promoted or avoided. This situation is problematic, especially since the biogas and consequently the bio-methane is one of the possible solutions that could contribute to the national energy turnaround. Thus, it would be necessary to clearly define how to account for the environmental impact of the biogas production;
- The DLCA of the Swiss grid electricity could be used for other sectors. For example, the e-mobility domain could be also investigated, using this method. In addition, seasonal grid electricity profiles could be considered, to evaluate touristic activities, seasonal residences, etc., because of the high seasonality linked to the touristic domain;
- The benefits of the energy storage versus those of the grid electricity should be evaluated, using, an hourly time step resolution.
- Further investigation of the energy storage should be performed, by analyzing different building case studies, with energy self – generation and storage systems (both thermal and electric systems), as well as the control strategy, in order to clarify the influence and the potential of the energy storage on the environmental mitigation of the Swiss building stock.

6. Dissemination activities

In the EcoDynBat project, the following scientific communications have been made:

- 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.
- Beloin-Saint-Pierre, D., P. Padey, K. Goulouti, P. Collet, A. Hélias, R. Hischier, « The Challenge of Temporal Resolution in Dynamic LCA", 2020, SETAC conference
- Maayan Tardif, J.; Medici, V.; Padey, P., "Dynamic life cycle assessment of building electricity demand with storage systems – potential for environmental impact mitigation", IBPSA conference 2021 (submitted)
- Padey, P,; Goulouti, K.; Beloin Saint-Pierre, D. (2); Lasvaux, S. (1); Capezzali, M. (1); Medici, V. (3); Maayan Tardif, J. (3); Citherlet, S. (1), "Dynamic Life Cycle Assessment of the building electricity demand", Status Seminar 2020

One scientific paper in a peer reviewed communication is also under preparation.

7. Future work

The EcoDynBat project provided an overview of the DLCA considerations, regarding the building electricity demand. The following points have been identified as possible future research work on this topic:

- <u>Provide appropriate data on the national electricity production:</u> Switzerland's future energy state will rely mainly on electricity. While for many of the European countries, electricity data are available on an hourly basis (for some of them even at a 15 minutes time step), accurate Swiss data, regarding the national production means are missing. Providing this data transparently, and in an open access platform, would provide the necessary basis in the development of environmentally oriented demand-side management strategies;
- <u>Clarify and harmonize the environmental impact calculation method:</u> There are currently several studies providing environmental impact data on the Swiss grid electricity. These methods lead to a wide range of results. Based on one study or another, the electricity uses can be either promoted or restricted. It seems relevant to harmonize this situation, so as to provide the necessary inputs, regarding the environmental impact of the Swiss grid electricity that could be used to create the conditions of a successful energy turnaround;
- <u>Provide a regular update of the environmental impacts:</u> The Swiss and more generally the European electricity panorama is currently evolving quite fast. The latest development of renewables and the energy transition in Europe lead to a rapid evolution of the environmental impact of the Swiss grid electricity. Thus, tt is necessary to provide an up-to-date version of the impacts on an annual or bi-annual basis;
- <u>Combine DLCA with smart buildings and micro-grids:</u> The smart building and micro-grids concepts, including demand-side management (DSM) and various technologies for electricity, heat production and storage are now emerging in Switzerland. It is expected that these solutions will play an important role in the reduction of the national building energy consumption and its' related environmental impact. These solutions can be designed and operated by including the dynamic environmental aspects of the electricity consumed, in order to develop solutions that will mitigate the impacts;
- <u>Provide appropriate data on stationary batteries:</u> While electric mobility is extensively assessed, especially the contribution of the battery to their environmental impacts, the literature review in EcoDynBat, showed that only few works were dedicated to stationary batteries on building applications. Considering the EcoDynBat results, it would be necessary to develop a specific environmental impact assessment of the stationary batteries, which can be market competitive.

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- Simon, E., Cimmino, F. M., & Genoud, S. (2021). CHP plants fuelled by natural gas as a power generation solution for the energy transition—Impact on the hourly carbon footprint of the electricity consumed in Switzerland. *IAEE, Paris*.
- Vuarnoz, Didier, et Thomas Jusselme. « Temporal Variations in the Primary Energy Use and Greenhouse Gas Emissions of Electricity Provided by the Swiss Grid ». *Energy* 161 (15 octobre 2018): 573-82. https://doi.org/10.1016/j.energy.2018.07.087.
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ECODYNBAT Project

Annexes

Annexes to chapters

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Chapter 2: Annex

Annex 2.1: Comparison of the energy production data sources

The ENTSO-E data collected within EcoDynBat have been compared to the national dataset found from various source. It has been decided to compare these data with national data sources to check consistency for the project.

Three comparisons have been performed:

1- For France, ENTSO-E data are compared with the national data provided by RTE, the French TSO (cf. Figure 11);

2- For Austria, ENSTO-E data are compared with the data from the E-Control regulator;

3- For Italy, ENTSO-E data are compared with the data from Terna (TSO;)

4- For Germany, ENTSO-E data are compared with the data from the grid operators;

5- For Switzerland, ENSTO-E data are compared with Swissgrid and SFOE data.

These comparaisons are detailed below.

Comparison of the French data

Based on available data from France, a comparison of the overall energy production and the production of three types of energy carriers (namely gas, coal and nuclear) is performed. Indeed, the French data presents the advantage of having the energy production breakdown per energy carriers just like ENTSO-E. The results are presented in Figure 71 for which the left graphics represent the production curves according to RTE and ENTSO-E while the right graphics presents the differences between the two sources for each time steps.

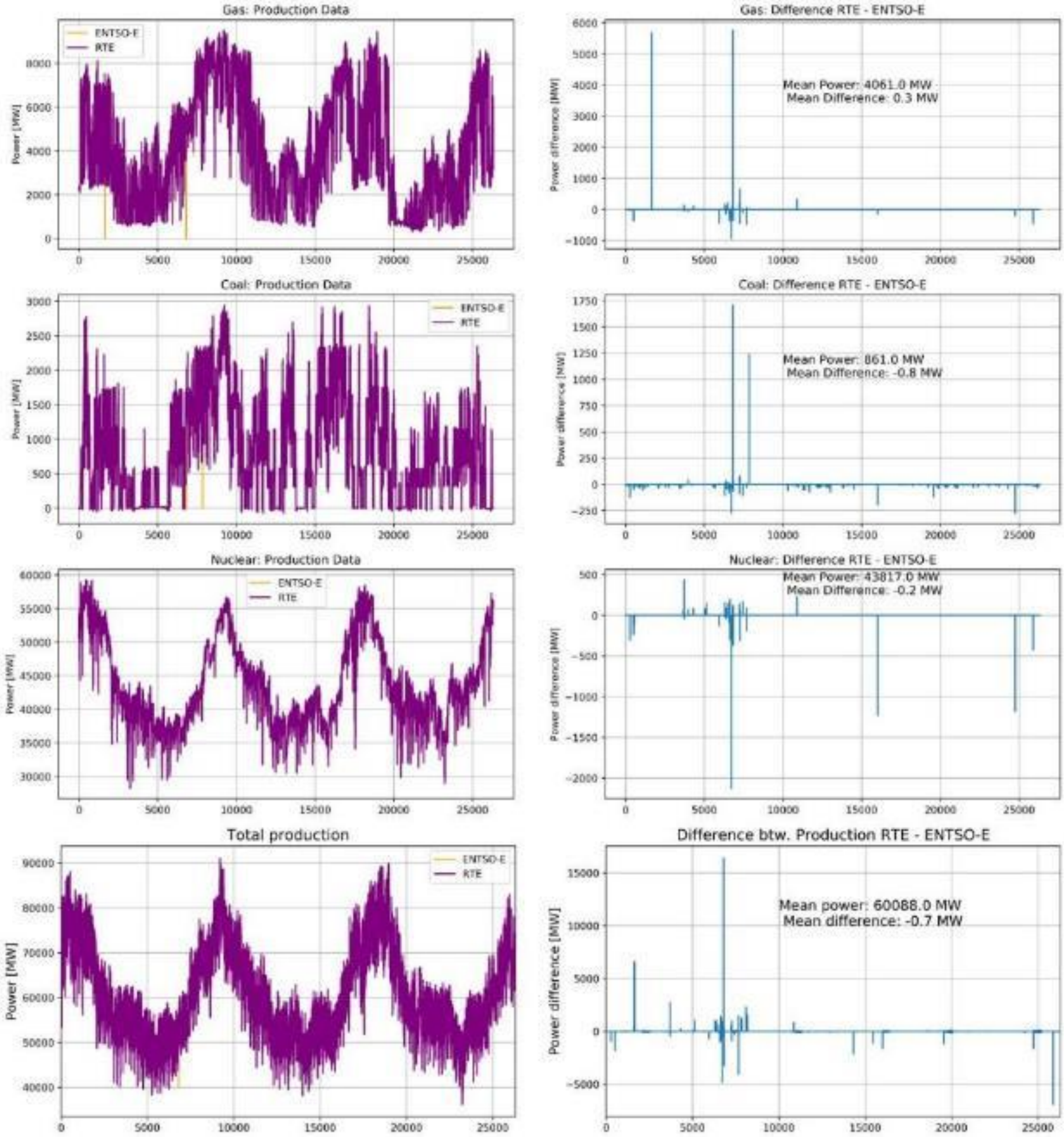


Figure 71. Comparison for 2016 to 2018 of the data provided by the French TSO and ENTSO-E (x axis correspond to hour composing the three years)

The two data sources are very close to each other. Some peaks are observed (right graphics) but correspond mostly to a lack of data for few hours in one or the other datasets. The relative mean difference is 0.025% over the sample of 26'304 hours, which is found to be extremely low. Thus, ENTSO-E data for France are consistent and can be used for this country and for the export to neighbouring countries like Switzerland.

Comparison of the Austrian data

The ENTSO-E data for Austria are also compared with the one provided by the E-Control regulator. Figure 72 presents the comparison of the national electricity production on a monthly basis.

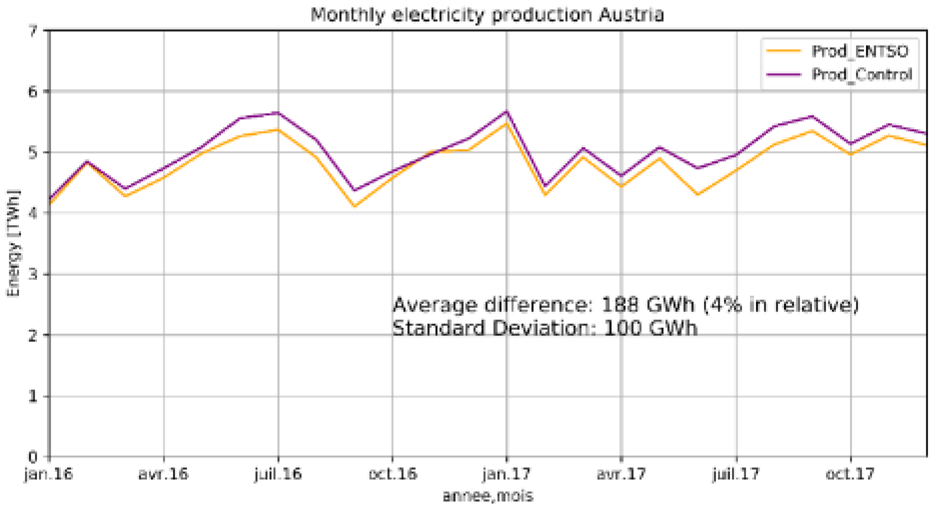


Figure 72. Comparison for 2016 and 2017 of the data provided by the Austrian source and ENTSO-E: Production

Both datasets provide a similar trend across the year. However, a gap between the two datasets is noticed with an average relative difference of 4%. A comparison per energy carriers revealed that the biggest differences are related to the hydropower production as well as the “other” category.

This difference is explained by the fact that E-Control inventories the overall electricity production means from low to high voltage while ENTSO-E focus on electricity production means operating on the high voltage grid. The difference can also be due to the lack of information related to the “other” category in ENSTO-E. Nevertheless, the difference is deemed acceptable for the calculations aimed in the present project.

Regarding the global national imports (considering all countries), the comparison between the two sources is shown in Figure 73.

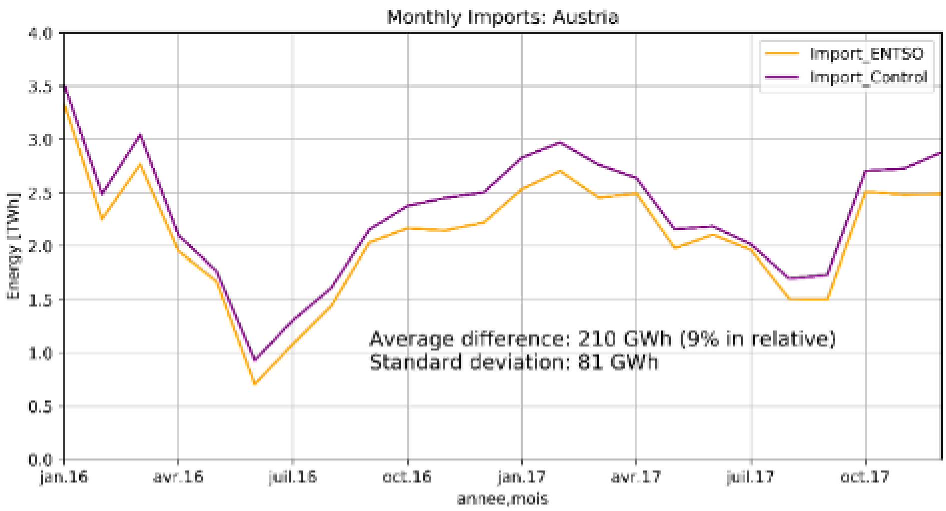


Figure 73. Comparison for 2016 and 2017 of the data provided by the Austrian source and ENTSO-E: Imports

As for the production means, the two datasets show the same monthly trend. ENTSO-E is on average 9% lower than the E-Control data. The difference is again considered acceptable. An analysis per importing countries shows that the imports from Germany are responsible from most of the difference. It could be necessary to obtain a coherent and comprehensive framework between all stakeholders involved in the electricity production and transport in order to get harmonized and reliable data at the European level. This is the purpose of ENTSO-E, but there is still a need for improving the data quality. For the present project, the data are considered as acceptable for the LCA of electricity consumed by Swiss buildings.

Regarding the national exports (i.e considering all exporting countries), the data comparison is displayed in Figure 74.

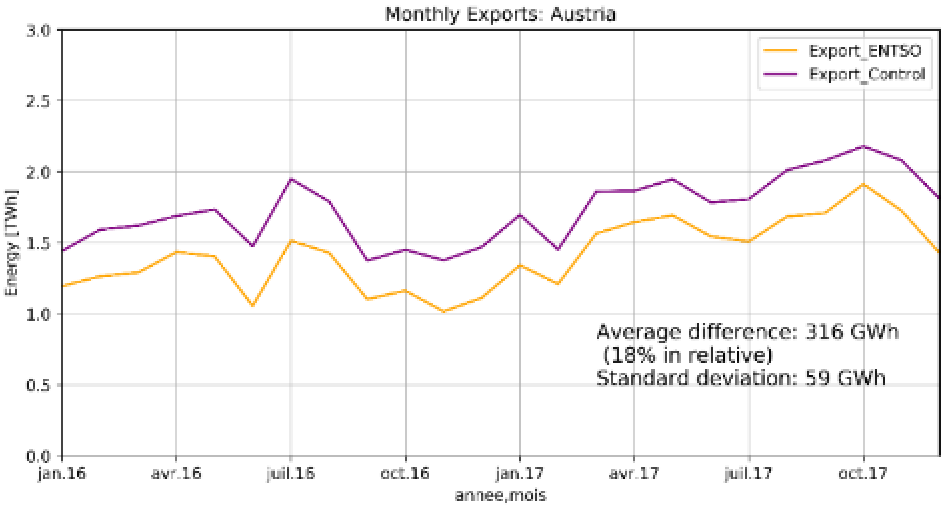


Figure 74. Comparison for 2016 and 2017 of the data provided by the Austrian source and ENTSO-E: Exports

For the Austrian exports, the trends between the two data sources are similar but the relative difference is twice as much as for the imports (18%). The difference is once more due to the exchanges with Germany as confirmed by the Figure 75 which present the Austrian exports per countries of exportation. The E-Control data shows a relatively constant export to Germany of 200 GWh per month in 2017 while ENTSO-E provides information about a very limited exchange between the two countries. The exports to Switzerland appear to have slight deviation but the average difference is very limited. Finally, the comparisons for the other countries show a good match between the data sources.

While the difference between the two data sources seems important, it has to be positioned in the overall project scope. First, the difference in the Austrian exports to Germany, is, on average 259 GWh. It represents a minor part of the Germany electricity mix. Indeed, for example, in October 2017, Germany has produced 44TWh, the difference between E-Control and ENTSO-E represents thus 0.6% of the production mix (which does not consider the import from the other countries).

As this study focuses on the electricity consumed in Switzerland, it is assumed that such differences on the exports from one neighbouring country (Austria) to another (Germany) will have a minor influence on the Swiss electricity mix. So, the electricity mixes and exchanges between the neighbouring countries are thus considered usable for the next calculations.

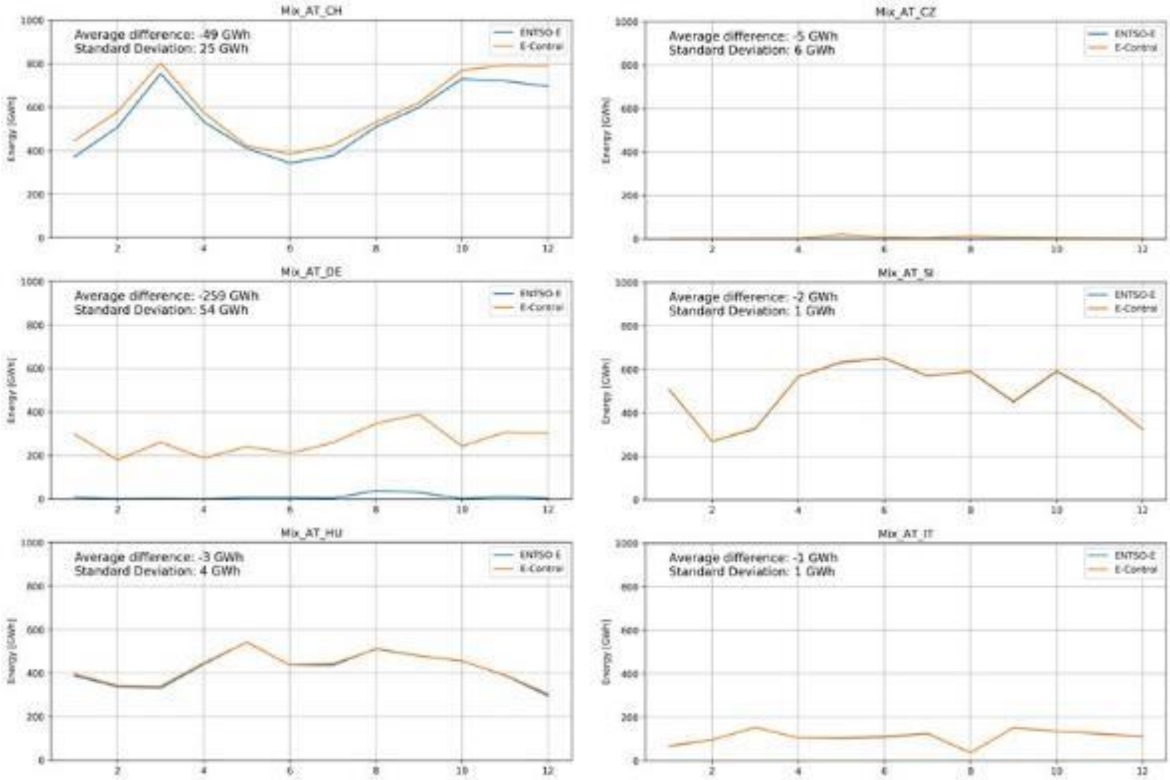


Figure 75. Comparison of the data provided by the Austrian source and ENTSO-E: Exports from Austria (AT) to neighbouring countries

Comparison of the Italian data

For Italy, the data from ENTSO-E has been compared with the data provided by Terna (the national TSO). Terna publishes monthly report on the production mix, imports and exports. The comparison is presented for the production mix in the Figure 76, and for the imports in the Figure 77 for three year from 2016 to 2018.

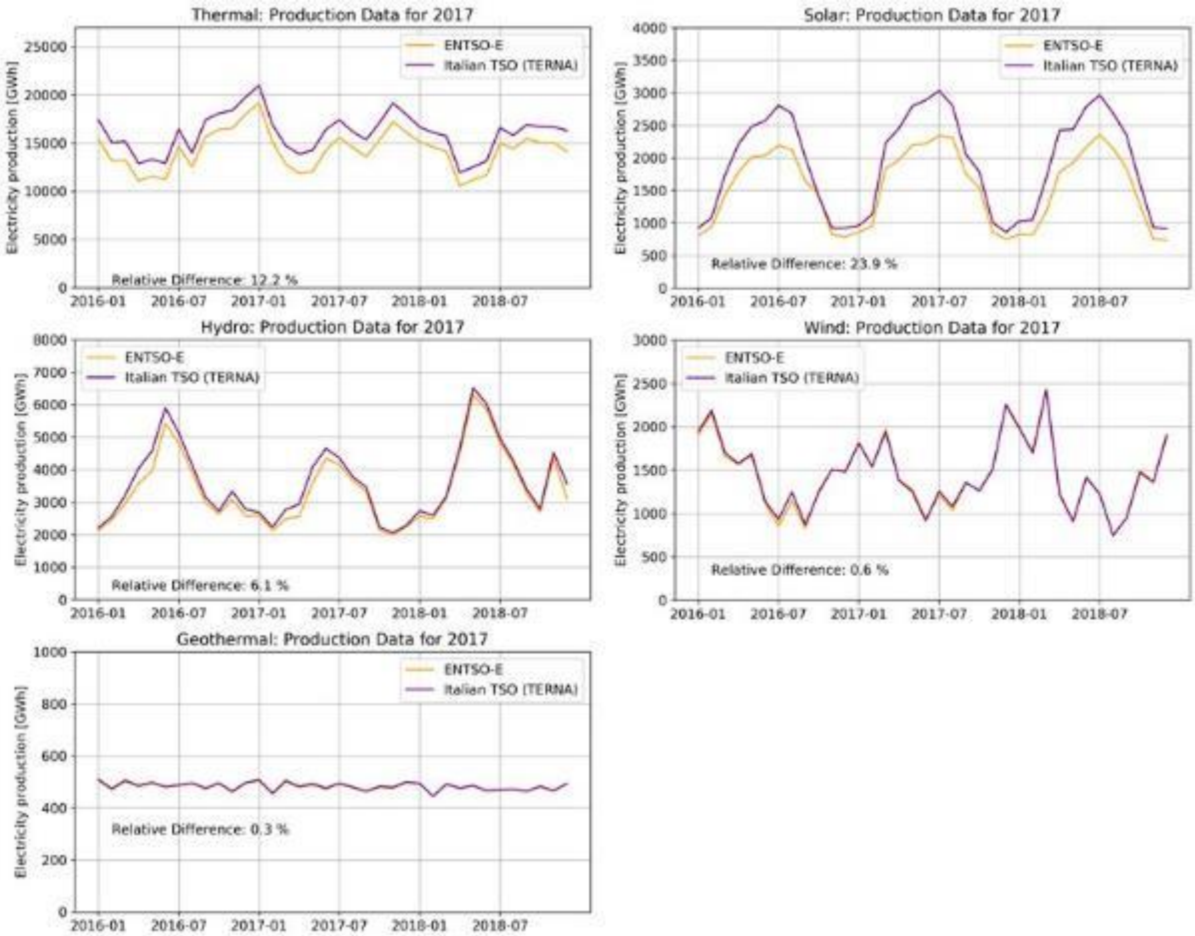


Figure 76. Comparison of the data provided by the Italian source and ENTSO-E: production sources comparisons

Regarding the production sources, it appears that ENTSO-E and Italian national data are in good adequacy especially for wind, geothermal and hydro technologies. Solar and thermal data show a higher discrepancy (difference of 24% and 12% respectively). This difference tends to be mostly explained by the fact that ENTSO-E considers data at the high voltage level while the national data are considering all the electricity production at all voltages. It would be necessary to increase data consistency between ENTSO-E and national data sources, nevertheless, it is not the purpose of the EcoDynBat project.

The biggest discrepancy is related to solar electricity (24%) production but the share of solar electricity in the mix is on average 8%, thus the influence on an annual basis, is found to be 2% which is found to be acceptable. The thermal production sources represents on an annual basis 68% of the Italian production mix with a difference between ENTSO-E and Terna of 12% which implies an possible uncertainty of 8%. Thus, the overall difference between the two data sources and their possible influence is found to be acceptable for the EcoDynBat project.

Regarding the Italian imports, the comparison is presented in the Figure 77:

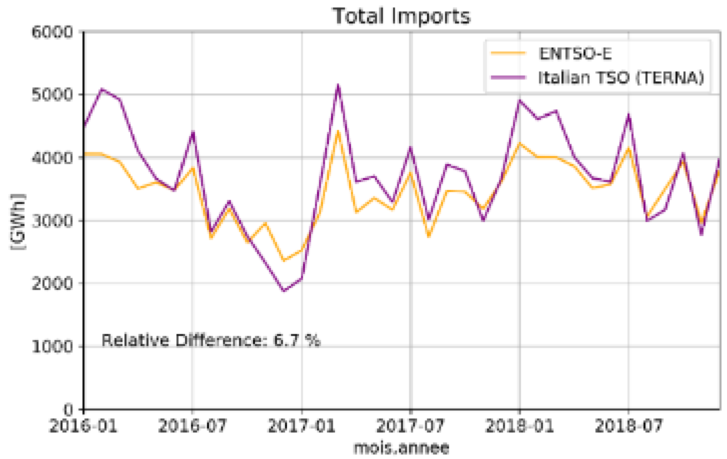


Figure 77. Comparison of the data provided by the Italian source and ENTSO-E: total Imports from Italy

The comparison of the two sources regarding the Italian imports has an average difference of 6.7% for the three considered years. For 2016, it appears that the differences are more fluctuating over the months (relative standard deviation of 15%), while 2017 and 2018, the monthly differences show less fluctuations (relative difference of 10% and 9% respectively). For these last two years, the data source comparison shows that ENTSO-E is generally underestimating the Italian imports.

Based on this comparison, the ENTSO-E data for Italy a considered as sufficiently reliable to be used for the environmental impact calculation to be performed in the EcoDynBat project.

Comparison of the German data

The German production mix data from ENTSO-E have been compared to the national data compiled by the Fraunhofer Institute which compile the information for the five sources, namely, 50 Hertz, Amprion, Tennet, TransnetBW and EEX. For the sake of simplicity, the thermal production sources have been aggregated together (coal, gas, oil, biomass). The comparison is presented for three years from 2016 to 2018 and is displayed in the Figure 78:

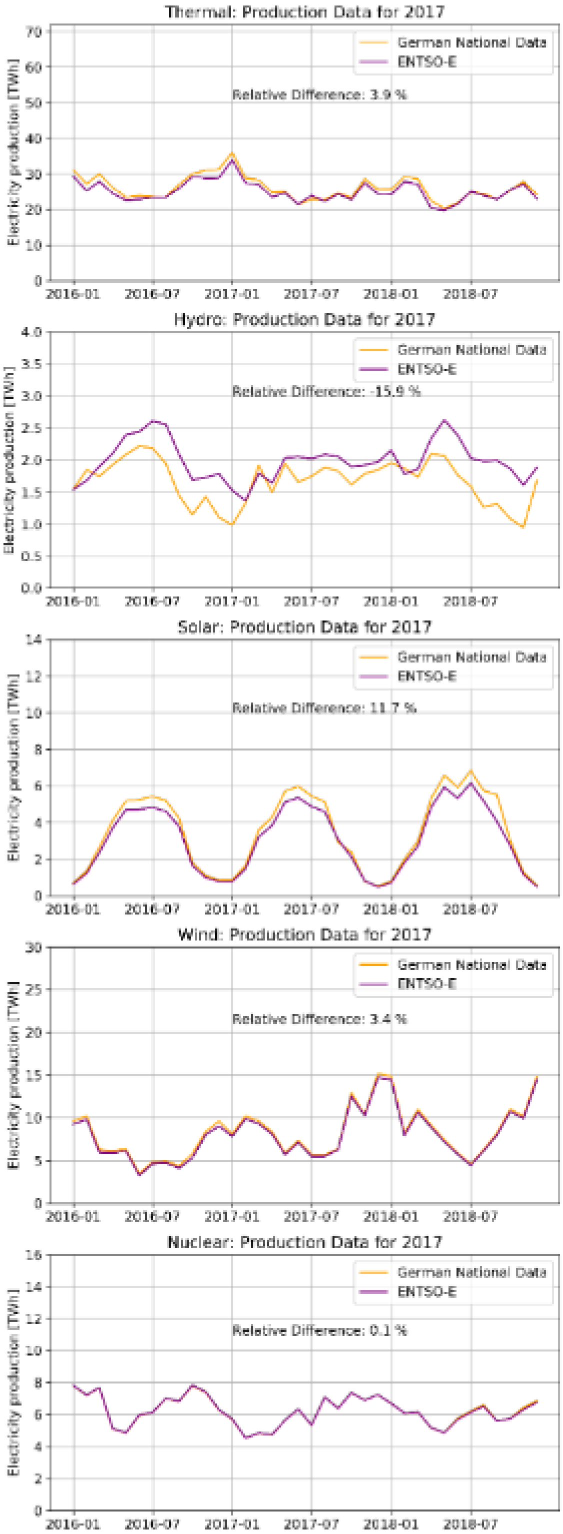


Figure 78. Comparison of the data provided by the German source and ENTSO-E: production sources comparisons

The comparison shows that the two sources are globally coherent. For thermal, wind and nuclear production sources, the difference between ENTSO-E and the national German data are found to be low (relative difference of 3.9%, 3.4% and 0.1% respectively). Conversely, for the solar and hydro production sources, the difference is found larger (11.7% and -15.9% respectively). The hydro source represent, over the three year a share of 4.4% of the contribution mix and the solar source represents 7%. Thus the uncertainty regarding the difference between the national data and the ENTSO-E data can represent between -0.7% and 0.8% which is considered to be low for the EcoDynBat purpose.

Regarding the imports and exports, the Fraunhofer Institute data rely on ENTSO-E which tend to confirm the reliability of the considered EcoDynBat source.

Comparison of the Swiss data

Hereafter, the ENTSO-E dataset is compared to the two Swiss national sources from Swissgrid and SFOE. The comparison with the Swissgrid dataset is made on an hourly basis while the comparison with the SFOE dataset is made on a monthly basis being the SFOE time resolution.The data comparison between all these sources is made for three years, from 2016 to 2018.

It has to be reminded (see Table 5 on page 80) that the Swissgrid and SFOE data provide information at the national level considering the overall electricity production and the gross exchange at the border (electricity go in both direction simultaneously) while the ENTSO-E data only consider net exchange, i.e the difference between import and export at each time step.

Swiss production mix

Figure 79 presents hourly results of the electricity production in Switzerland for ENTSO-E and Swissgrid data. Figure 80 presents the monthly variation of the three different sources.

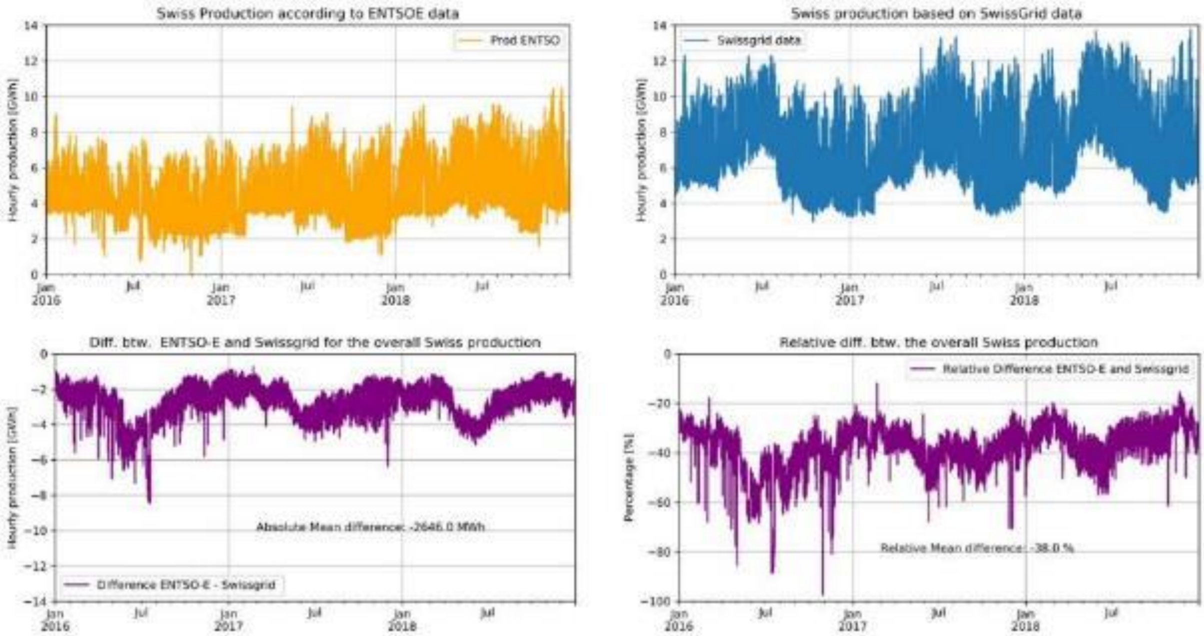


Figure 79. Hourly difference for the overall Swiss electricity production, comparison of the data from Swissgrid and ENTSO-E

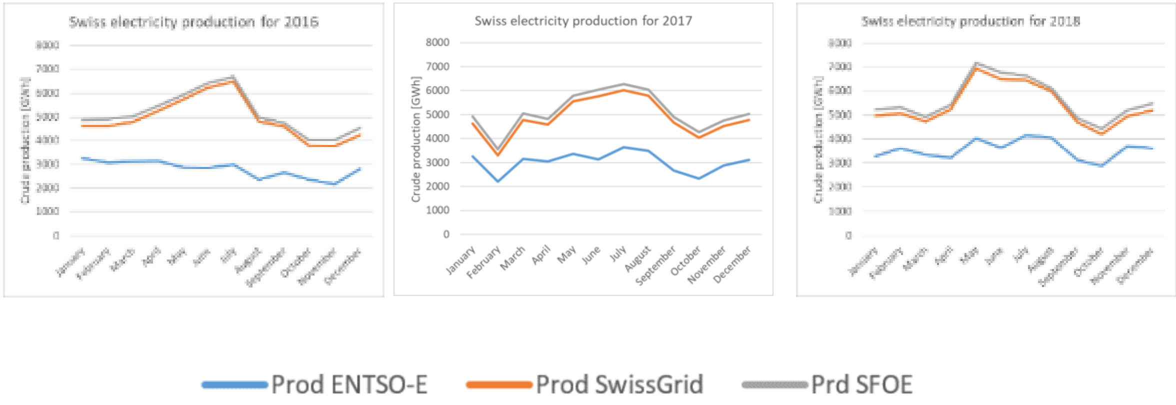


Figure 80. Comparison of the Swiss production mix on a monthly basis for the year 2016 to 2018

Regarding the hourly Swiss production mix, it appears in Figure 79 that the ENTSO-E data show an underestimation compared to the overall Swissgrid data with a gap of 2.65 GWh. It represents approximatively 38% less than Swiss grid. Figure 80 shows that the two Swiss datasets are similar, while the differences between the ENTSO-E and the two Swiss datasets are more important for 2016, while in 2017 and 2018, they are less important. While ENTSO-E has a lower overall production for 2017 and 2018, the trends between the three datasets are similar. Only year 2016 shows a divergence in trends and values.

As for the Austrian case, national data from Swissgrid and SFOE consider the overall Swiss electricity production mix while ENTSO-E focus on the electricity produced at high voltage. Discussions with Swissgrid have confirmed this assumption. In addition, SFOE annually reports information on the Swiss production mix on a daily basis for three days per month for each year. The three days each month correspond to one weekday (3rd Wednesday of each month), one Saturday and one Sunday (both being the 3rd of each month). Since the comparison is made for three years, 108 days can be thus used for the dataset comparison.

This comparison has been done by aggregating the ENTSO-E values to obtain the same production mean categories as those used in the SFOE datasets (i.e., nuclear, hydro reservoir+ pumping storage, hydro run off river and a thermal + renewable energy category). By doing so, it is possible to identify the source of the data difference in Figure 81. The relative difference per production means for the 108 days of comparison as well as the mean relative difference evolution over the three considered years are given in Figure 82.

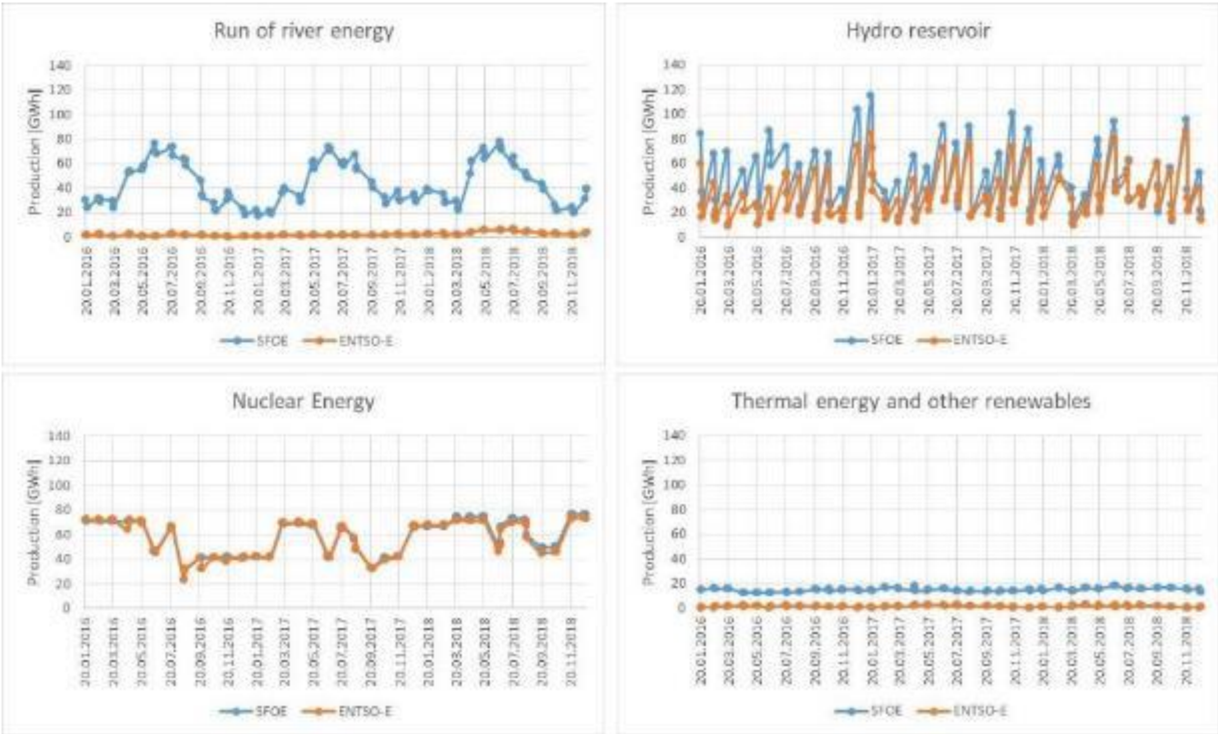


Figure 81. Comparison of ENTSO-E and SFOE data for the nuclear, hydropower and other production means in Switzerland

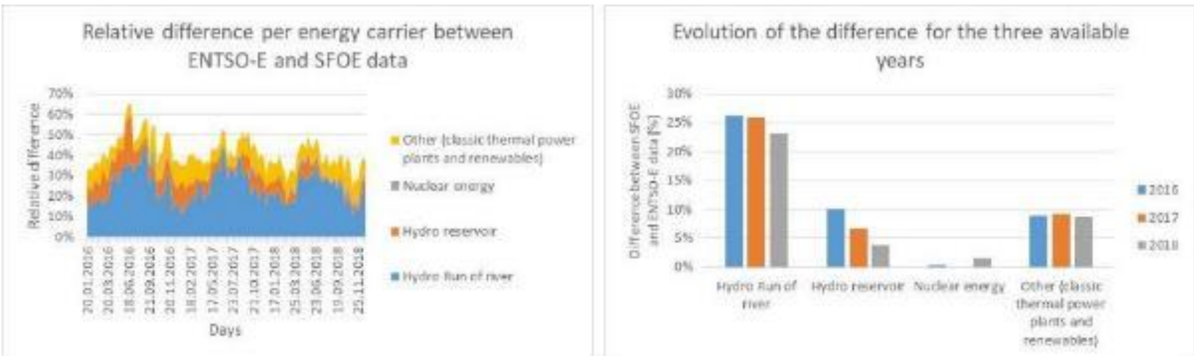


Figure 82 Comparison between SFOE and ENTSO-E data for Switzerland..Relative difference for 108 days per energy sources (hourly time step), (left),Evolution of the annual difference per energy sources, for different years (right)

Note: For the two figures above, the abscise corresponds to the 108 days for which production mix is available via the SFOE reports.

From the two above figures, several observations can be made:

- The ENTSO-E data for the nuclear energy match the SFOE data. The relative difference of the three years represents 0.5% of the overall difference between the two datasets with only a small variation among the years,
- The data for the hydro electricity from reservoirs present the same shape in the ENTSO-E and the SFOE data. However, a small difference is observed being 6.9% of the overall difference between the two datasets over the three years. It should be mentioned that the difference is decreasing overs the years from 10.1% in 2016 to 3.8% in 2018,
- The electricity production from hydro run-of-river shows the greatest divergence between ENTSO-E and SFOE, being 25.1% of the overall difference between the two datasets on

average for the three years with only a small decrease among the year, from 26.3% in 2016 to 23.2% in 2018. The two datasets dot not have the same profile,
- The conventional thermal power plants and other renewables present a significant relative difference, constituting over the three years 9% of the overall difference between the two datasets. The trend over the years is not changing.

Thus, it appears that there is a significant difference (38% on average, see Figure 79) between the national datasets and the ENTSO-E values. The same trends are found in ENTSO-E and national datasets (except for 2016). It appears that the electricity produced by run-of-river power plants, and conventional + renewable power plants are operated at low to medium voltage. There are thus out of the scope of the ENTSO-E goal and scope as confirmed through discussions by Swissgrid.

Further discussions with Swissgrid did not obtain specific time series regarding the electricity production in Switzerland per energy carriers. The complexity of the Swiss electricity market with hundreds of utilities is the reason. Therefore, ENTSO-E is the only source that provides information regarding the Swiss production mix on an hourly basis, but only for high voltage energy production.

To fill in the gap between ENTSO-E and SFOE production mix, a harmonization scheme will be adopted in order to adjust the ENTSO-E data. This adjustment is presented in the chapter 5.

Imports to Switzerland

In this section, the imports are compared, among the different sources, on a net basis. The Swissgrid data, presented by default on a gross basis, are aggregated. Figure 83 presents the results for the 2016-2018 years.

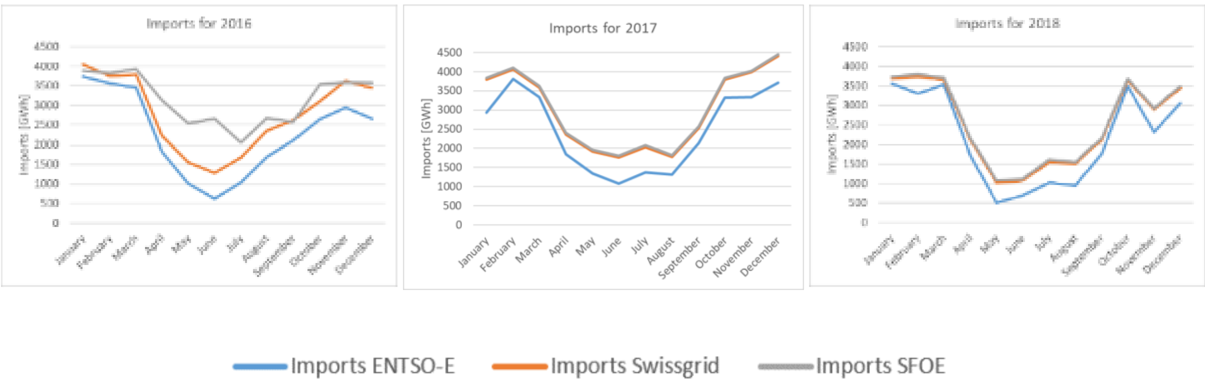


Figure 83. Net imports comparison between the three Swiss sources from 2016 to 2018

From Figure 83 it appears:

- For each year, the ENTSO-E data are systematically lower than the two other sources. From April to November, the difference is higher.
- The trends are similar between the three sources. However, the years 2017 and 2018 seem to have a lower dispersion in the data than the year 2016.

Thus, regarding the imports, the ENTSO-E data presents two aspects to be considered for the project:

- The imports are given in net, i.e., the difference between the imports and exports is made for each time step. In the present project, the choice between net or gross import and export will be made in the chapter 3 and thus in the chapter 2, the datasets prepared have has to be as exhaustive as possible,
- The ENTSO-E values are lower than the Swissgrid data. Since the trend is found to be identical between datasets, a harmonization scheme will be proposed.

Exports from Switzerland

The same approach as for the imports is used for the exports from Switzerland. Figure 84 presents the results for the yearsyear 2016 to 2018 on a monthly basis.

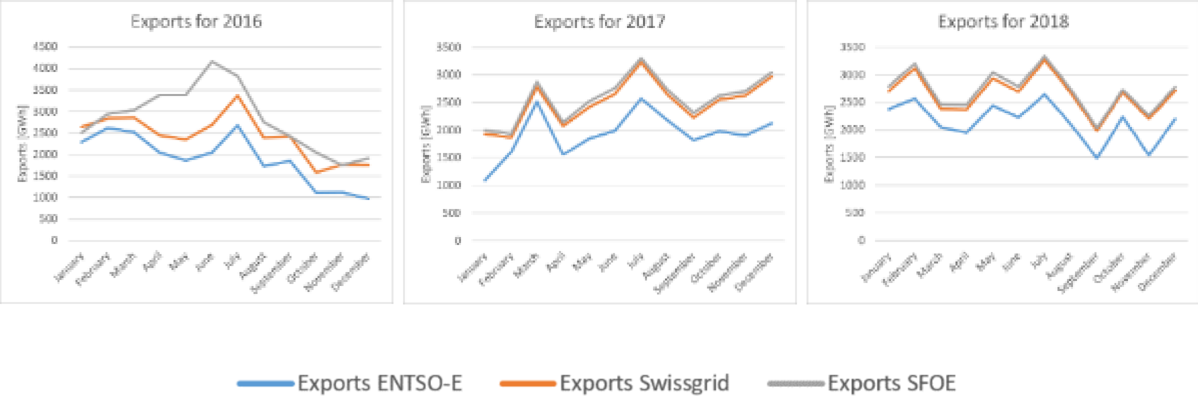


Figure 84. Net exports comparison between the three Swiss sources from 2016 to 2018

The same trends are observed for the exports as for the imports:

- The year 2016 presents some inconsistencies between the national SFOE and Swissgrid datasets. These inconsistencies are not found in the yearsyear 2017 and 2018,
- The ENTSO-E data present lower values than the national datasets but the trend is identical for the years 2017 and 2018.

Annex 2.2: EcoDynBat Dataset (weekly, in MW)

The following table presents the weekly supply mix of Switzerland for the years 2017 and 2018. It is the EcoDynBat dataset to be used for the environmental impact calculation (i.e including the adjustments producedures).

Date	Hydro Run of river and poundage	Wind Onshore	Hydro Pumped Storage	Hydro Water Reservoir	Nuclear	Solar	Residue Hydro (rule 1)	Residue Other (rule 1)	AT to CH	DE To CH	FR to CH	IT to CH	CH to DE	CH to FR	CH to IT	CH to AT
01.01.2017	29	9	636	1554	1740	6	940	634	563	2610	776	970	188	1804	271	61
08.01.2017	34	10	996	1762	1732	3	1148	770	546	3093	1500	125	54	797	1979	199
15.01.2017	33	8	1086	1991	1741	4	1258	846	607	3053	1144	174	62	1211	1470	94
22.01.2017	33	5	921	1692	1740	12	1126	751	575	2900	1187	296	51	941	1051	118
29.01.2017	72	16	455	777	1734	15	978	731	827	3813	1944	19	28	218	2440	152
05.02.2017	62	7	569	761	1739	18	924	732	860	3729	1758	9	12	254	2367	106
12.02.2017	43	7	490	602	1743	31	866	686	735	3755	1617	47	38	298	2010	158
19.02.2017	46	16	506	544	2721	44	887	703	972	2949	1274	31	14	288	2580	28
26.02.2017	58	21	456	642	2927	37	1148	577	1096	2690	1411	40	26	255	2920	40
05.03.2017	70	11	472	632	2919	41	1495	627	1094	2503	1296	12	23	166	2989	45
12.03.2017	78	10	450	588	2915	55	1581	664	1031	2480	1481	18	18	110	3769	75
19.03.2017	75	9	721	763	2913	48	1740	733	1137	2148	1017	76	53	340	3678	27
26.03.2017	72	5	513	684	2910	70	1527	683	893	1827	1378	135	228	219	3266	76
02.04.2017	61	5	552	516	2905	72	1468	612	832	1294	1110	146	175	189	2403	69
09.04.2017	58	9	361	599	2905	66	1529	639	730	1543	1054	208	191	300	2692	104
16.04.2017	66	9	632	727	2925	78	1466	610	798	1173	899	239	183	337	2190	42
23.04.2017	79	8	676	778	2919	55	1563	653	804	1287	754	365	217	648	1835	23
30.04.2017	81	8	684	508	2906	55	1861	381	704	1395	878	301	162	413	2050	6
07.05.2017	77	7	511	462	2893	62	2209	451	699	1361	899	145	174	329	2452	0
14.05.2017	83	7	626	839	2876	80	2709	552	397	764	738	240	408	420	2331	4
21.05.2017	75	7	787	808	2857	103	2744	560	445	781	481	315	445	644	2496	4

Date	Hydro Run of river and poundage	Wind Onshore	Hydro Pumped Storage	Hydro Water Reservoir	Nuclear	Solar	Residue Hydro (rule 1)	Residue Other (rule 1)	AT to CH	DE To CH	FR to CH	IT to CH	CH to DE	CH to FR	CH to IT	CH to AT
28.05.2017	86	4	1159	1271	2684	93	3135	605	367	632	412	298	672	981	2341	16
04.06.2017	88	8	837	1010	1836	76	3012	557	517	1007	602	276	340	562	2216	6
11.06.2017	75	8	1067	1088	1809	96	3132	580	577	1283	337	404	307	1008	2408	0
18.06.2017	72	6	1090	1147	1778	89	3072	568	470	1346	498	312	182	1028	2329	0
25.06.2017	86	5	1174	1324	2141	74	3055	574	754	1293	645	172	123	1274	3204	1
02.07.2017	81	3	1120	1135	2753	90	2794	547	693	1366	740	131	252	1549	2936	8
09.07.2017	78	10	911	1114	2754	77	2781	545	408	1272	945	84	394	845	3023	104
16.07.2017	72	8	852	1285	2770	85	2426	476	548	1426	1036	61	228	1017	3250	54
23.07.2017	86	12	627	1017	2771	65	2646	519	496	1133	621	62	254	587	2833	52
30.07.2017	86	8	914	1331	2641	75	2640	491	587	1051	568	55	329	877	3041	28
06.08.2017	86	6	1023	1422	2678	55	2803	514	433	682	676	106	717	493	2580	154
13.08.2017	87	6	771	1160	2260	79	2598	476	755	748	612	107	598	669	1777	9
20.08.2017	77	5	921	1257	1993	70	2452	446	931	1250	542	24	348	767	2183	4
27.08.2017	81	7	909	1321	2044	50	2460	544	772	1289	588	43	259	627	2326	20
03.09.2017	90	8	784	1082	2184	55	2226	631	688	1351	804	80	238	367	2502	9
10.09.2017	79	14	909	920	2372	44	2243	635	749	1471	793	71	220	583	2504	28
17.09.2017	72	5	778	629	1376	59	2017	570	1054	2315	886	51	172	308	2410	1
24.09.2017	68	3	745	604	1502	47	1936	583	992	2467	927	54	149	327	2450	10
01.10.2017	113	11	509	642	1650	43	1798	748	935	2702	1078	54	85	483	2639	41
08.10.2017	106	5	576	683	1637	51	1617	670	1044	3044	973	47	60	692	2750	36
15.10.2017	93	9	559	733	1636	38	1480	615	1041	3162	1061	44	82	697	2718	43
22.10.2017	100	9	617	958	1667	25	1485	616	1021	3093	1031	96	109	805	2379	53

Date	Hydro Run of river and poundage	Wind Onshore	Hydro Pumped Storage	Hydro Water Reservoir	Nuclear	Solar	Residue Hydro (rule 1)	Residue Other (rule 1)	AT to CH	DE To CH	FR to CH	IT to CH	CH to DE	CH to FR	CH to IT	CH to AT
29.10.2017	101	11	477	921	1683	33	1496	596	1187	3411	883	110	48	999	2286	21
05.11.2017	115	11	883	1418	1678	11	1835	716	1001	2912	811	119	99	1277	1933	44
12.11.2017	115	12	887	1582	1741	15	1755	685	1043	3242	769	128	75	1472	2010	79
19.11.2017	94	16	475	1289	1698	18	1570	620	1149	3949	1107	93	23	1172	2597	77
26.11.2017	101	9	1182	1405	1374	10	2039	878	1166	3731	933	76	53	1550	2724	54
03.12.2017	98	15	1386	1681	1741	8	1405	656	769	3437	1213	126	40	1423	2419	152
10.12.2017	128	17	997	1387	1738	7	1590	742	1183	3974	1199	82	12	1309	2904	39
17.12.2017	103	5	777	1221	2534	6	1438	670	1141	3656	1096	68	14	1078	3166	58
24.12.2017	76	19	240	421	2648	11	1189	587	1027	3449	1089	147	39	762	2274	79
31.12.2017	116	13	427	330	2818	9	1524	620	815	2558	1156	101	60	304	2421	108
07.01.2018	125	5	728	718	2820	11	1742	680	1070	2782	1054	37	13	437	3212	16
14.01.2018	114	22	690	958	2816	11	1609	627	945	2729	1355	4	33	292	3235	54
21.01.2018	119	12	624	1056	2821	17	1618	631	796	2589	1636	1	118	119	3668	114
28.01.2018	119	6	670	1177	2808	20	1451	689	1147	3056	1098	15	18	499	3550	39
04.02.2018	128	4	1058	1382	2829	8	1410	746	1159	3304	857	35	70	1198	3241	47
11.02.2018	121	6	672	1136	2824	8	1382	739	1136	3817	1001	3	23	735	3786	38
18.02.2018	129	6	1089	1422	2827	1	1472	782	1070	3655	895	3	52	906	3819	31
25.02.2018	133	8	1753	2080	2824	19	1506	763	832	3187	917	17	56	1099	3900	132
04.03.2018	108	11	498	907	2749	26	1143	560	968	3064	1347	49	98	152	2972	111
11.03.2018	124	3	548	655	2816	21	1186	584	897	2502	1389	47	82	59	2520	111
18.03.2018	102	7	539	606	2916	51	1248	614	1096	3064	823	43	21	204	2539	52
25.03.2018	93	7	531	518	3000	34	1387	616	822	2152	803	292	229	262	2123	103

Date	Hydro Run of river and poundage	Wind Onshore	Hydro Pumped Storage	Hydro Water Reservoir	Nuclear	Solar	Residue Hydro (rule 1)	Residue Other (rule 1)	AT to CH	DE To CH	FR to CH	IT to CH	CH to DE	CH to FR	CH to IT	CH to AT
01.04.2018	92	9	377	400	2991	55	1728	464	972	1682	911	199	222	168	2173	64
08.04.2018	138	5	792	557	2983	51	1936	521	1008	1459	704	81	217	416	2640	37
15.04.2018	166	5	534	672	2972	85	2427	649	709	868	1232	121	635	76	2753	121
22.04.2018	216	9	798	919	2976	80	2836	762	339	492	1017	242	979	151	2681	172
29.04.2018	237	10	870	1005	2962	58	2893	665	302	413	396	427	810	444	2018	80
06.05.2018	263	6	1023	1043	2967	73	3194	706	250	217	407	306	1181	435	2163	115
13.05.2018	253	5	1119	971	2974	55	3178	702	84	210	1090	278	1638	205	1830	357
20.05.2018	260	4	1031	1058	2947	72	3242	717	128	201	612	248	1453	363	1902	234
27.05.2018	266	4	1242	1322	2658	70	3421	775	172	211	439	351	1865	328	1824	171
03.06.2018	255	3	1251	1658	1948	64	3459	795	158	275	575	266	1486	185	2161	145
10.06.2018	266	3	1117	1584	1959	50	3341	766	218	320	628	202	1113	224	2201	84
17.06.2018	258	4	952	1250	2072	64	3165	726	245	740	777	194	681	173	2363	176
24.06.2018	310	6	1306	1176	2561	63	2741	639	395	746	469	169	800	400	2686	36
01.07.2018	317	4	1086	1545	2566	49	2792	696	558	916	286	243	399	762	3268	63
08.07.2018	280	4	956	1403	2881	86	2379	592	504	1036	414	274	254	777	3328	86
15.07.2018	278	4	900	1500	2913	75	2310	576	336	919	539	189	375	686	3010	179
22.07.2018	260	3	907	1585	2877	66	2272	566	392	963	607	140	487	777	3112	119
29.07.2018	258	4	1072	1920	2791	79	2244	609	256	804	369	123	931	1111	2331	201
05.08.2018	250	6	811	1661	2789	61	2097	589	219	992	628	148	887	610	1971	285
12.08.2018	220	5	606	1434	2821	63	1921	539	252	794	865	147	911	323	1760	281
19.08.2018	230	7	821	1620	2513	47	1982	556	424	1298	430	163	657	721	1886	187
26.08.2018	157	7	647	1464	2580	34	1814	561	356	1398	512	149	230	624	1986	139

Date	Hydro Run of river and poundage	Wind Onshore	Hydro Pumped Storage	Hydro Water Reservoir	Nuclear	Solar	Residue Hydro (rule 1)	Residue Other (rule 1)	AT to CH	DE To CH	FR to CH	IT to CH	CH to DE	CH to FR	CH to IT	CH to AT
02.09.2018	120	3	684	1206	2578	49	1704	637	437	1205	781	152	406	397	2025	56
09.09.2018	123	3	638	1123	2621	65	1596	596	196	1395	1140	12	442	184	1732	272
16.09.2018	127	8	752	1393	1888	55	1529	571	271	1753	1070	6	398	349	1660	231
23.09.2018	140	11	665	1381	1899	68	1515	564	495	2074	824	13	289	733	1754	71
30.09.2018	155	6	776	995	1907	43	1140	784	856	2823	1073	6	110	449	3223	50
07.10.2018	129	5	431	1034	1902	38	1064	733	742	3004	1474	2	177	217	3319	123
14.10.2018	126	9	479	1111	1907	33	1004	692	689	3001	1586	5	136	228	3423	133
21.10.2018	121	10	473	1337	1903	20	960	664	641	3104	985	27	91	295	2579	113
28.10.2018	158	3	572	1362	2265	8	1140	788	626	2307	791	225	114	855	1633	117
04.11.2018	174	10	643	1203	3049	20	1083	753	792	2053	888	112	270	412	2451	255
11.11.2018	120	8	468	1112	3054	11	1011	703	938	2564	814	169	172	494	2489	100
18.11.2018	106	5	1055	1789	3059	10	1008	699	561	2118	609	226	350	1075	1435	183
25.11.2018	110	8	633	1220	3060	10	997	574	859	2597	857	188	214	551	1896	233
02.12.2018	155	1	446	856	3024	8	1426	714	1073	2534	1572	34	173	115	3178	327
09.12.2018	163	2	1210	1808	3061	6	1522	774	976	2284	676	40	232	828	2824	179
16.12.2018	146	15	564	988	3055	5	1395	685	1031	2562	1243	45	148	168	2891	322
23.12.2018	184	6	392	593	3052	12	1474	740	1149	2629	429	193	187	753	2421	70

Chapter 3 :Annexes

Annex 3.1 : Mapping files

Austria - ecoinvent

Energy sources ENTSO-E	*Ratio*	*Energy sources ecoinvent v3.4*
Biomass	28%	Electricity, high voltage (AT)| heat and power co-generation, biogas, gas engine | Cut-off, U
	72%	Electricity, high voltage (AT)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Fossil Brown coal/Lignite	-	-
Fossil Coal-derived gas	-	-
Fossil Gas	6%	Electricity, high voltage (AT)| electricity production, natural gas, combined cycle power plant | Cut-off, U
	3%	Electricity, high voltage (AT)| electricity production, natural gas, conventional power plant | Cut-off, U
	70%	Electricity, high voltage (AT)| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off,
	21%	Electricity, high voltage (AT)| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U
Fossil Hard coal	92%	Electricity, high voltage (AT)| electricity production, hard coal | Cut-off, U
	8%	Electricity, high voltage (AT)| heat and power co-generation, hard coal | Cut-off, U
Fossil Oil	28%	Electricity, high voltage (AT)| electricity production, oil | Cut-off, U
	72%	Electricity, high voltage (AT)| heat and power co-generation, oil | Cut-off, U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	100%	Electricity, high voltage (AT)| electricity production, deep geothermal | Cut-off, U
Hydro Pumped Storage	100%	Electricity, high voltage (AT)| electricity production, hydro, pumped storage | Cut-off, U
Hydro Run-of-river…	100%	Electricity, high voltage (AT)| electricity production, hydro, run-of-river | Cut-off, U
Hydro Water Reservoir	100%	Electricity, high voltage (AT)| electricity production, hydro, reservoir, alpine region | Cut-off, U

Marine	-	-
Nuclear	-	-
Other (Fossil)	100%	Electricity, high voltage (BG)| electricity production, hard coal | Cut-off, U
Other (renewable)	-	-
Waste	100%	Electricity, for reuse in municipal waste incineration only (AT)| treatment of municipal solid waste, incineration | Cut-off, U
Wind Offshore	-	-
Wind Onshore	3%	Electricity, high voltage (AT)| electricity production, wind, <1MW turbine, onshore | Cut-off, U
	3%	Electricity, high voltage (AT)| electricity production, wind, >3MW turbine, onshore | Cut-off, U
	93%	Electricity, high voltage (AT)| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U
Solar	55%	Electricity, low voltage (AT)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off,
	45%	Electricity, low voltage (AT)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted

Czech Republic – ecoinvent

Energy sources ENTSO-E	*Ratio*	*Energy sources ecoinvent v3.4*
Biomass	8%	Electricity, high voltage (CZ)| heat and power co-generation, biogas, gas engine | Cut-off, U
	92%	Electricity, high voltage (CZ)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Fossil Brown coal/Lignite	73%	Electricity, high voltage (CZ)| electricity production, lignite | Cut-off, U
	27%	Electricity, high voltage (CZ)| heat and power co-generation, lignite | Cut-off, U
Fossil Coal-derived gas	100%	Electricity, high voltage (CZ)| treatment of coal gas, in power plant | Cut-off, U
Fossil Gas	0%	Electricity, high voltage (CZ)| electricity production, natural gas, combined cycle power plant | Cut-off, U
	2%	Electricity, high voltage (CZ)| electricity production, natural gas, conventional power plant | Cut-off, U
	98%	Electricity, high voltage (CZ)| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U
Fossil Hard coal	43%	Electricity, high voltage (CZ)| electricity production, hard coal | Cut-off, U
	57%	Electricity, high voltage (CZ)| heat and power co-generation, hard coal | Cut-off, U
Fossil Oil	59%	Electricity, high voltage (CZ)| electricity production, oil | Cut-off, U
	41%	Electricity, high voltage (CZ)| heat and power co-generation, oil | Cut-off, U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	-	-
Hydro Pumped Storage	100%	Electricity, high voltage (CZ)| electricity production, hydro, pumped storage | Cut-off, U
Hydro Run-of-river…	100%	Electricity, high voltage (CZ)| electricity production, hydro, run-of-river | Cut-off, U
Hydro Water Reservoir	100%	Electricity, high voltage (CZ)| electricity production, hydro, reservoir, non-alpine region | Cut-off, U
Marine	-	-

Nuclear	100%	Electricity, high voltage (CZ)| electricity production, nuclear, pressure water reactor | Cut-off, U
Other (Fossil)	100%	Electricity, high voltage (BG)| electricity production, hard coal | Cut-off, U
Other (renewable)	100%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp facade installation, single-Si, panel, mounted | Cut-off, U
Waste	100%	Electricity, for reuse in municipal waste incineration only (CZ)| treatment of municipal solid waste, incineration | Cut-off, U
Wind Offshore	-	-
Wind Onshore	11%	Electricity, high voltage (CZ)| electricity production, wind, <1MW turbine, onshore | Cut-off, U
	89%	Electricity, high voltage (CZ)| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U
Solar	50%	Electricity, low voltage (CZ)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off
	50%	Electricity, low voltage (CZ)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off

France - ecoinvent

Energy sources ENTSO-E	*Ratio*	*Energy sources ecoinvent v3.4*
Biomass	30%	Electricity, high voltage (FR)| heat and power co-generation, biogas, gas engine | Cut-off, U
	70%	Electricity, high voltage (FR)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Fossil Brown coal/Lignite		-
Fossil Coal-derived gas		-
Fossil Gas	32%	Electricity, high voltage (FR)| electricity production, natural gas, combined cycle power plant | Cut-off, U
	6%	Electricity, high voltage (FR)| electricity production, natural gas, conventional power plant | Cut-off, U
	61%	Electricity, high voltage (FR)| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U
Fossil Hard coal	100%	Electricity, high voltage (FR)| electricity production, hard coal | Cut-off, U
Fossil Oil	86%	Electricity, high voltage (FR)| electricity production, oil | Cut-off, U
	14%	Electricity, high voltage (FR)| heat and power co-generation, oil | Cut-off, U
Fossil Oil shale		-
Fossil Peat		-
Geothermal		-
Hydro Pumped Storage	100%	Electricity, high voltage (FR)| electricity production, hydro, pumped storage | Cut-off, U
Hydro Run-of-river…	100%	Electricity, high voltage (FR)| electricity production, hydro, run-of-river | Cut-off, U
Hydro Water Reservoir	100%	Electricity, high voltage (FR)| electricity production, hydro, reservoir, alpine region | Cut-off, U
Marine		-
Nuclear	100%	Electricity, high voltage (FR)| electricity production, nuclear, pressure water reactor | Cut-off, U
Other (Fossil)		-

Other (renewable)		-
Waste	100%	Electricity, for reuse in municipal waste incineration only [7]| treatment of municipal solid waste, incineration | Cut-off, U
Wind Offshore	100%	Electricity, high voltage (FR)| electricity production, wind, 1-3MW turbine, offshore | Cut-off, U
Wind Onshore	6%	Electricity, high voltage (FR)| electricity production, wind, <1MW turbine, onshore | Cut-off, U
	0%	Electricity, high voltage (FR)| electricity production, wind, >3MW turbine, onshore | Cut-off, U
	94%	Electricity, high voltage (FR)| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U
Solar	41%	Electricity, low voltage (FR)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off,
	33%	Electricity, low voltage (FR)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off
	26%	Electricity, low voltage (FR)| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U

Germany - ecoinvent

Energy sources ENTSO-E	*Ratio*	*Energy sources ecoinvent v3.4*
Biomass	80%	Electricity, high voltage (DE)| heat and power co-generation, biogas, gas engine | Cut-off, U
	20%	Electricity, high voltage (DE)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Fossil Brown coal/Lignite	97%	Electricity, high voltage (DE)| electricity production, lignite | Cut-off, U
	3%	Electricity, high voltage (DE)| heat and power co-generation, lignite | Cut-off, U
Fossil Coal-derived gas	100%	Electricity, high voltage (DE)| treatment of coal gas, in power plant | Cut-off, U
Fossil Gas	14%	Electricity, high voltage (DE)| electricity production, natural gas, combined cycle power plant | Cut-off, U
	9%	Electricity, high voltage (DE)| electricity production, natural gas, conventional power plant | Cut-off, U
	1%	Electricity, high voltage (DE)| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off
	75%	Electricity, high voltage (DE)| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U
Fossil Hard coal	89%	Electricity, high voltage (DE)| electricity production, hard coal | Cut-off, U
	11%	Electricity, high voltage (DE)| heat and power co-generation, hard coal | Cut-off, U
Fossil Oil	79%	Electricity, high voltage (DE)| electricity production, oil | Cut-off, U
	21%	Electricity, high voltage (DE)| heat and power co-generation, oil | Cut-off, U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	100%	Electricity, high voltage (DE)| electricity production, deep geothermal | Cut-off, U
Hydro Pumped Storage	100%	Electricity, high voltage (DE)| electricity production, hydro, pumped storage | Cut-off, U
Hydro Run-of-river…	100%	Electricity, high voltage (DE)| electricity production, hydro, run-of-river | Cut-off, U
Hydro Water Reservoir	100%	Electricity, high voltage (DE)| electricity production, hydro, reservoir, non-alpine region | Cut-off, U

Marine	-	-
Nuclear	21%	Electricity, high voltage (DE)| electricity production, nuclear, boiling water reactor | Cut-off, U
	79%	Electricity, high voltage (DE)| electricity production, nuclear, pressure water reactor | Cut-off, U
Other (Fossil)	100%	Electricity, high voltage (BG)| electricity production, hard coal | Cut-off, U
Other (renewable)	100%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp facade installation, single-Si, panel, mounted | Cut-off, U
Waste	100%	Electricity, for reuse in municipal waste incineration only (DE)| treatment of municipal solid waste, incineration | Cut-off, U
Wind Offshore	100%	Electricity, high voltage (DE)| electricity production, wind, 1-3MW turbine, offshore | Cut-off, U
Wind Onshore	14%	Electricity, high voltage (DE)| electricity production, wind, <1MW turbine, onshore | Cut-off, U
	8%	Electricity, high voltage (DE)| electricity production, wind, >3MW turbine, onshore | Cut-off, U
	77%	Electricity, high voltage (DE)| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U
Solar	41%	Electricity, low voltage (DE)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off
	33%	Electricity, low voltage (DE)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off
	26%	Electricity, low voltage (DE)| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U

Italy - ecoinvent

Energy sources ENTSO-E	*Ratio*	*Energy sources ecoinvent v3.4*
Biomass	76%	Electricity, high voltage (IT)| heat and power co-generation, biogas, gas engine | Cut-off, U
	24%	Electricity, high voltage (IT)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Fossil Brown coal/Lignite	100%	Electricity, high voltage (IT)| electricity production, lignite | Cut-off, U
Fossil Coal-derived gas	100%	Electricity, high voltage (IT)| treatment of coal gas, in power plant | Cut-off, U
Fossil Gas	31%	Electricity, high voltage (IT)| electricity production, natural gas, combined cycle power plant | Cut-off, U
	8%	Electricity, high voltage (IT)| electricity production, natural gas, conventional power plant | Cut-off, U
	38%	Electricity, high voltage (IT)| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U
	23%	Electricity, high voltage (IT)| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U
Fossil Hard coal	100%	Electricity, high voltage (IT)| electricity production, hard coal | Cut-off, U
	0%	Electricity, high voltage (IT)| heat and power co-generation, hard coal | Cut-off, U
Fossil Oil	22%	Electricity, high voltage (IT)| electricity production, oil | Cut-off, U
	78%	Electricity, high voltage (IT)| heat and power co-generation, oil | Cut-off, U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	100%	Electricity, high voltage (IT)| electricity production, deep geothermal | Cut-off, U
Hydro Pumped Storage	100%	Electricity, high voltage (IT)| electricity production, hydro, pumped storage | Cut-off, U
Hydro Run-of-river…	100%	Electricity, high voltage (IT)| electricity production, hydro, run-of-river | Cut-off, U
Hydro Water Reservoir	100%	Electricity, high voltage (IT)| electricity production, hydro, reservoir, alpine region | Cut-off, U

Marine	-	-
Nuclear	-	-
Other (Fossil)	100%	Electricity, high voltage (BG)| electricity production, hard coal | Cut-off, U
Other (renewable)	-	-
Waste	100%	Electricity, for reuse in municipal waste incineration only (IT)| treatment of municipal solid waste, incineration | Cut-off, U
Wind Offshore	-	-
Wind Onshore	28%	Electricity, high voltage (IT)| electricity production, wind, <1MW turbine, onshore | Cut-off, U
	9%	Electricity, high voltage (IT)| electricity production, wind, >3MW turbine, onshore | Cut-off, U
	63%	Electricity, high voltage (IT)| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U
Solar	20%	Electricity, low voltage (IT)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off
	16%	Electricity, low voltage (IT)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off
	63%	Electricity, low voltage (IT)| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U

Switzerland - ecoinvent

Energy sources ENTSO-E	*Ratio*	*Energy sources ecoinvent v3.4*
Biomass	80%	Electricity, high voltage (CH)| heat and power co-generation, biogas, gas engine | Cut-off, U
	20%	Electricity, high voltage (CH)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Fossil Brown coal/Lignite	-	-
Fossil Coal-derived gas	-	-
Fossil Gas	100%	Electricity, high voltage (CH)| heat and power co-generation, natural gas, 500kW electrical, lean burn | Cut-off, U
Fossil Hard coal	-	-
Fossil Oil	-	-
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	-	-
Hydro Pumped Storage	100%	Electricity, high voltage (CH)| electricity production, hydro, pumped storage | Cut-off, U
Hydro Run-of-river…	100%	Electricity, high voltage (CH)| electricity production, hydro, run-of-river | Cut-off, U
Hydro Water Reservoir	100%	Electricity, high voltage (CH)| electricity production, hydro, reservoir, alpine region | Cut-off, U
Marine	-	-
Nuclear	47%	Electricity, high voltage (CH)| electricity production, nuclear, boiling water reactor | Cut-off, U
	53%	Electricity, high voltage (CH)| electricity production, nuclear, pressure water reactor | Cut-off, U
Other (Fossil)	-	-
Other (renewable)	-	-
Waste	-	-

Wind Offshore	-	-
Wind Onshore	5%	Electricity, high voltage (CH)| electricity production, wind, <1MW turbine, onshore | Cut-off, U
	10%	Electricity, high voltage (CH)| electricity production, wind, >3MW turbine, onshore | Cut-off, U
	85%	Electricity, high voltage (CH)| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U
Solar	4%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp facade installation, multi-Si, laminated, integrated | Cut-off, U
	4%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp facade installation, multi-Si, panel, mounted | Cut-off, U
	2%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp facade installation, single-Si, laminated, integrated | Cut-off, U
	2%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp facade installation, single-Si, panel, mounted | Cut-off, U
	11%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si | Cut-off, U
	7%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp flat-roof installation, single-Si | Cut-off, U
	0%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, a-Si, laminated, integrated | Cut-off, U
	6%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, a-Si, panel, mounted | Cut-off, U
	7%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, CdTe, laminated, integrated | Cut-off, U
	1%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, CIS, panel, mounted | Cut-off, U
	4%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, laminated, integrated | Cut-off
	29%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, U
	0%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, laminated, integrated | Cut-
	4%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, panel, mounted | Cut-off, U
	2%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, laminated, integrated | Cut-off
	15%	Electricity, low voltage (CH)| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off, U

Austria – KBOB

Energy sources ENTSO-E	*Ratio*	*Energy sources KBOB v2016*
Biomass	76%	Electricity, at cogen 6400kWth, wood, allocation exergy/CH U
	24%	Electricity, at cogen with biogas engine, allocation exergy/CH U
Fossil Brown coal/Lignite	-	-
Fossil Coal-derived gas	-	-
Fossil Gas	11%	Electricity, industrial gas, at power plant/AT U
	89%	Electricity, natural gas, at power plant/AT U
Fossil Hard coal	100%	Electricity, hard coal, at power plant/AT U
Fossil Oil	99%	Electricity, oil, at power plant/AT U
	1%	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	100%	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted/kWh/CH U
Hydro Pumped Storage	100%	electricity, hydropower, at pumped storage power plant/kWh/AT U
Hydro Run-of-river and poundage	100%	electricity, hydropower, at run-of-river power plant/kWh/RER U
Hydro Water Reservoir	100%	electricity, hydropower, at reservoir power plant, alpine region/kWh/RER U
Marine	-	-
Nuclear	-	-

Other (Fossil)	100%	Electricity, hard coal, at power plant/CZ U
Other (renewable)	-	-
Waste	100%	Electricity from waste, at municipal waste incineration plant/CH U
Wind Offshore	-	-
Wind Onshore	100%	Electricity, at wind power plant/RER U
Solar	100%	electricity, production mix photovoltaic, at plant/kWh/AT U

Czech Republic – KBOB

Energy sources ENTSO-E	*Ratio*	*Energy sources KBOB v2016*
Biomass	81%	Electricity, at cogen 6400kWth, wood, allocation exergy/CH U
	19%	Electricity, at cogen with biogas engine, allocation exergy/CH U
Fossil Brown coal/Lignite	100%	Electricity, lignite, at power plant/CZ U
Fossil Coal-derived gas	100%	Electricity, hard coal, at power plant/CZ U
Fossil Gas	26%	Electricity, industrial gas, at power plant/CENTREL U
	74%	Electricity, natural gas, at power plant/CENTREL U
Fossil Hard coal	100%	Electricity, hard coal, at power plant/CZ U
Fossil Oil	93%	Electricity, oil, at power plant/CZ U
	7%	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	-	-
Hydro Pumped Storage	100%	electricity, hydropower, at pumped storage power plant/kWh/CZ U
Hydro Run-of-river and poundage	100%	electricity, hydropower, at run-of-river power plant/kWh/RER U
Hydro Water Reservoir	100%	electricity, hydropower, at reservoir power plant, non alpine regions/kWh/RER U
Marine	-	-
Nuclear	100%	Electricity, nuclear, at power plant pressure water reactor/UCTE U

Other (Fossil)	100%	Electricity, hard coal, at power plant/CZ U
Other (renewable)	100%	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted/kWh/CH U
Waste	100%	Electricity from waste, at municipal waste incineration plant/CH U
Wind Offshore	-	-
Wind Onshore	100%	Electricity, at wind power plant/RER U
Solar	100%	electricity, production mix photovoltaic, at plant/kWh/CZ U

France – KBOB

Energy sources ENTSO-E	*Ratio*	*Energy sources KBOB v2016*
Biomass	68%	Electricity, at cogen 6400kWth, wood, allocation exergy/CH U
	32%	Electricity, at cogen with biogas engine, allocation exergy/CH U
Fossil Brown coal/Lignite	-	-
Fossil Coal-derived gas	-	-
Fossil Gas	15%	Electricity, industrial gas, at power plant/FR U
	85%	Electricity, natural gas, at power plant/FR U
Fossil Hard coal	100%	Electricity, hard coal, at power plant/FR U
Fossil Oil	93%	Electricity, oil, at power plant/FR U
	7%	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	-	-
Hydro Pumped Storage	100%	electricity, hydropower, at pumped storage power plant/kWh/FR U
Hydro Run-of-river and poundage	100%	electricity, hydropower, at run-of-river power plant/kWh/RER U
Hydro Water Reservoir	100%	electricity, hydropower, at reservoir power plant, alpine region/kWh/RER U
Marine	-	-
Nuclear	100%	Electricity, nuclear, at power plant pressure water reactor/FR U

Other (Fossil)	-	-
Other (renewable)	-	-
Waste	100%	Electricity from waste, at municipal waste incineration plant/CH U
Wind Offshore	-	-
Wind Onshore	100%	Electricity, at wind power plant/RER U
Solar	100%	electricity, production mix photovoltaic, at plant/kWh/FR U

Germany – KBOB

Energy sources ENTSO-E	*Ratio*	*Energy sources KBOB v2016*
Biomass	45%	Electricity, at cogen 6400kWth, wood, allocation exergy/CH U
	55%	Electricity, at cogen with biogas engine, allocation exergy/CH U
Fossil Brown coal/Lignite	100%	Electricity, lignite, at power plant/DE U
Fossil Coal-derived gas	100%	Electricity, hard coal, at power plant/CZ U
Fossil Gas	10%	Electricity, industrial gas, at power plant/DE U
	90%	Electricity, natural gas, at power plant/DE U
Fossil Hard coal	100%	Electricity, hard coal, at power plant/DE U
Fossil Oil	92%	Electricity, oil, at power plant/DE U
	8%	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	100%	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted/kWh/CH U
Hydro Pumped Storage	100%	electricity, hydropower, at pumped storage power plant/kWh/DE U
Hydro Run-of-river and poundage	100%	electricity, hydropower, at run-of-river power plant/kWh/RER U
Hydro Water Reservoir	100%	electricity, hydropower, at reservoir power plant, non alpine regions/kWh/RER U
Marine	-	-
Nuclear	79%	Electricity, nuclear, at power plant pressure water reactor/DE U

	21%	Electricity, nuclear, at power plant boiling water reactor/DE U
Other (Fossil)	100%	Electricity, hard coal, at power plant/CZ U
Other (renewable)	100%	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted/kWh/CH U
Waste	100%	Electricity from waste, at municipal waste incineration plant/CH U
Wind Offshore	100%	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted/kWh/CH U
Wind Onshore	100%	Electricity, at wind power plant/RER U
Solar	100%	electricity, production mix photovoltaic, at plant/kWh/DE U

Italy – KBOB

Energy sources ENTSO-E	*Ratio*	*Energy sources KBOB v2016*
Biomass	62%	Electricity, at cogen 6400kWth, wood, allocation exergy/CH U
	38%	Electricity, at cogen with biogas engine, allocation exergy/CH U
Fossil Brown coal/Lignite	-	-
Fossil Coal-derived gas	100%	Electricity, hard coal, at power plant/CZ U
Fossil Gas	3%	Electricity, industrial gas, at power plant/IT U
	97%	Electricity, natural gas, at power plant/IT U
Fossil Hard coal	100%	Electricity, hard coal, at power plant/IT U
Fossil Oil	98%	Electricity, oil, at power plant/IT U
	2%	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	100%	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted/kWh/CH U
Hydro Pumped Storage	100%	electricity, hydropower, at pumped storage power plant/kWh/IT U
Hydro Run-of-river and poundage	100%	electricity, hydropower, at run-of-river power plant/kWh/RER U
Hydro Water Reservoir	100%	electricity, hydropower, at reservoir power plant, alpine region/kWh/RER U
Marine	-	-
Nuclear	-	-

Other (Fossil)	100%	Electricity, hard coal, at power plant/CZ U
Other (renewable)	-	-
Waste	100%	Electricity from waste, at municipal waste incineration plant/CH U
Wind Offshore	-	-
Wind Onshore	100%	Electricity, at wind power plant/RER U
Solar	100%	electricity, production mix photovoltaic, at plant/kWh/IT U

Switzerland – KBOB

Energy sources ENTSO-E	*Ratio*	*Energy sources KBOB v2016*
Biomass	46%	Electricity, at cogen 6400kWth, wood, emission control, allocation exergy/CH U
	12%	Electricity, at cogen with biogas engine, agricultural covered, alloc. exergy/CH
	42%	Electricity, at cogen with biogas engine, methane 96%-vol allocation exergy/CH U
Fossil Brown coal/Lignite	-	-
Fossil Coal-derived gas	-	-
Fossil Gas	100%	Electricity, at cogen 500kWe lean burn, allocation exergy/CH U
Fossil Hard coal	100%	Electricity, hard coal, at power plant/DE U
Fossil Oil	100%	Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U
Fossil Oil shale	-	-
Fossil Peat	-	-
Geothermal	-	-
Hydro Pumped Storage	100%	Electricity, hydropower, at pumped storage power plant/kWh/CH U
Hydro Run-of-river…	100%	Electricity, hydropower, at run-of-river power plant/kWh/CH U
Hydro Water Reservoir	84%	Electricity, hydropower, at reservoir power plant/kWh/CH U
	16%	Electricity, hydropower, at small hydropower plant/kWh/CH U
Marine	-	-
Nuclear	53%	Electricity, nuclear, at power plant pressure water reactor/kWh/CH U
	47%	Electricity, nuclear, at power plant boiling water reactor/kWh/CH U
Other (Fossil)	-	-

Other (renewable)	-	-
Waste	100%	Electricity from waste, at municipal waste incineration plant/CH U
Wind Offshore	-	-
Wind Onshore	100%	Electricity, at wind power plant/CH U
Solar	100%	Electricity, production mix photovoltaic, at plant/kWh/CH U

Annex 3.2: Environmental impacts of all production means

For ecoinvent v3.4

Production means	GWP IPCC2013 v1.03 (kg of CO_2 eq./kWh)	CED renewable v2.05 (MJ primary/kWh)	CED non-renewable v2.05 (MJ primary/kWh)	ES2013 v1.05 (UBP/kWh)
	Impacts			
Austria – ecoinvent v3.4				
Biomass	0.0795	12.2	0.551	476
Fossil Gas	0.591	0.0123	10.6	358
Fossil Hard coal	1.01	0.132	12.2	562
Fossil Oil	1.01	0.0521	15.3	779
Geothermal	0.0812	0.087	0.996	104
Hydro Pumped Storage	0.451	4.04	6.95	372
Hydro Run-of-river	0.00434	3.79	0.0433	11.9
Hydro Water Reservoir	0.00689	3.79	0.0582	14.1
Other (Fossil)	2.04	0.22	19.0994	1486.1
Waste	0	0.00	0.0000	0.0
Wind Onshore	0.0174	3.89	0.236	41.6
Solar	0.106	4.06	1.33	189
Czech Republic – ecoinvent v3.4				
Biomass	0.0571	15.5	0.567	393
Fossil Brown coal/Lignite	1.32	0.0438	11.0	839
Fossil Coal-derived gas	1.41	0.337	27.8	2780
Fossil Gas	0.884	0.0166	15.2	543
Fossil Hard coal	1.56	0.177	15.3	993
Fossil Oil	1.25	0.0633	18.6	1127
Hydro Pumped Storage	1.14	0.814	17.3	919
Hydro Run-of-river	0.00434	3.79	0.0433	11.9
Hydro Water Reservoir	0.0511	3.79	0.0582	38.4
Nuclear	0.0119	0.0197	13.4	313
Other (Fossil)	2.04	0.221	19.1	1486
Other (renewable)	0.148	4.12	1.86	252
Waste	0	0	0	0
Wind Onshore	0.019	3.89	0.257	44.1
Solar	0.119	4.09	1.49	210

Production means	GWP IPCC2013 v1.03 (kg of CO_2 eq./kWh)	CED renewable v2.05 (MJ primary/kWh)	CED non-renewable v2.05 (MJ primary/kWh)	ES2013 v1.05 (UBP/kWh)
	Impacts			
France – ecoinvent v3.4				
Biomass	0.0817	11.9	0.549	484
Fossil Gas	0.660	0.0113	11.5	410
Fossil Hard coal	1.1	0.137	12.8	787
Fossil Oil	0.926	0.0476	14.0	969
Hydro Pumped Storage	0.0772	0.957	17.6	489
Hydro Run-of-river	0.00434	3.79	0.0433	11.9
Hydro Water Reservoir	0.00689	3.79	0.0582	19.6
Nuclear	0.0128	0.0211	14.1	365
Waste	0	0	0	0
Wind Offshore	0.0154	3.88	0.190	37.2
Wind Onshore	0.0153	3.88	0.208	36.4
Solar	0.0903	4.03	1.13	161
Germany – ecoinvent v3.4				
Biomass	0.139	3.38	0.507	700
Fossil Brown coal/Lignite	1.22	0.0469	12.8	700
Fossil Coal-derived gas	1.09	0.262	21.6	2161
Fossil Gas	0.545	0.00991	10.2	340
Fossil Hard coal	1.10	0.136	12.6	625
Fossil Oil	0.834	0.0427	12.5	659
Geothermal	0.0812	0.0867	0.996	104
Hydro Pumped Storage	0.964	1.40	14.0	728
Hydro Run-of-river	0.00434	3.79	0.0433	11.9
Hydro Water Reservoir	0.0511	3.79	0.0582	46.0
Nuclear	0.0112	0.0189	12.4	317
Other (Fossil)	2.04	0.22	19.0994	1486.1
Other (renewable)	0.148	4.12	1.8555	252.1
Waste	0	0	0	0
Wind Offshore	0.0154	3.88	0.1902	37.2
Wind Onshore	0.0196	3.89	0.262	48.0
Solar	0.109	4.07	1.37	194

Production means	Impacts GWP IPCC2013 v1.03 (kg of CO_2 eq./kWh)	CED renewable v2.05 (MJ primary/kWh)	CED non-renewable v2.05 (MJ primary/kWh)	ES2013 v1.05 (UBP/kWh)
Italy – ecoinvent v3.4				
Biomass	0.135	4.05	0.510	683
Fossil Brown coal/Lignite	1.15	0.0414	11.4	2201
Fossil Coal-derived gas	1.25	0.300	24.8	2477
Fossil Gas	0.561	0.0114	9.43	334
Fossil Hard coal	1.15	0.125	10.7	828
Fossil Oil	0.937	0.0462	13.6	959
Geothermal	0.0812	0.0867	0.996	104
Hydro Pumped Storage	0.614	2.28	9.63	554
Hydro Run-of-river	0.00434	3.79	0.0433	11.9
Hydro Water Reservoir	0.00689	3.79	0.0582	29.3
Other (Fossil)	2.04	0.221	19.1	1486
Waste	0	0	0	0
Wind Onshore	0.0192	3.89	0.254	47.1
Solar	0.0806	4.02	1.00	143
Switzerland ecoinvent v3.4				
Biomass	0.139	2.93	0.498	689
Fossil Gas	0.616	0.0146	9.79	382
Hydro Pumped Storage	0.196	3.03	9.56	338
Hydro Run-of-river	0.00434	3.79	0.0433	11.9
Hydro Water Reservoir	0.00689	3.79	0.0582	14.2
Nuclear	0.012	0.0209	13.8	325
Wind Onshore	0.0193	3.89	0.259	48.0
Solar	0.0923	4.03	1.17	169

For KBOB v2016

Production means	GWP IPCC2013 v1.03 (kg of CO_2 eq./kWh)	CED renewable v2.05 (MJ primary/kWh)	CED non-renewable v2.05 (MJ primary/kWh)	ES2013 v1.05 (UBP/kWh)
	Impacts			
Austria – KBOB v2016				
Biomass	0.077	8.965	0.826	246.7
Fossil Gas	0.759	0.041	12.724	558.3
Fossil Hard coal	0.997	0.124	11.443	588.0
Fossil Oil	0.847	0.034	12.033	707.0
Geothermal	0.151	4.071	1.825	206.1
Hydro Pumped Storage	0.453	3.158	6.831	363.9
Hydro Run-of-river	0.004	3.792	0.040	10.1
Hydro Water Reservoir	0.006	3.793	0.045	11.8
Other (Fossil)	1.319	0.147	15.343	811.5
Waste	0.000	0.000	0.000	0.0
Wind Onshore	0.011	3.882	0.165	25.2
Solar	0.098	3.999	1.227	147.4
Czech Republic – KBOB v2016				
Biomass	0.070	9.546	0.799	251.9
Fossil Brown coal/Lignite	1.174	0.027	9.811	725.5
Fossil Coal-derived gas	1.319	0.147	15.343	811.5
Fossil Gas	1.215	0.036	11.559	743.2
Fossil Hard coal	1.319	0.147	15.343	811.5
Fossil Oil	1.208	0.048	16.908	1150.8
Hydro Pumped Storage	1.020	0.417	14.161	848.8
Hydro Run-of-river	0.004	3.792	0.040	10.1
Hydro Water Reservoir	0.017	3.793	0.045	24.4
Nuclear	0.008	0.008	12.638	491.5
Other (Fossil)	1.319	0.147	15.343	811.5
Other (renewable)	0.151	4.071	1.825	206.1
Waste	0.000	0.000	0.000	0.0
Wind Onshore	0.011	3.882	0.165	25.2
Solar	0.099	4.006	1.266	156.1

Production means	Impacts: GWP IPCC2013 v1.03 (kg of CO_2 eq./kWh)	CED renewable v2.05 (MJ primary/kWh)	CED non-renewable v2.05 (MJ primary/kWh)	ES2013 v1.05 (UBP/kWh)
France – KBOB v2016				
Biomass	0.090	7.954	0.871	237.7
Fossil Gas	0.722	0.021	7.144	413.9
Fossil Hard coal	1.079	0.084	12.341	898.7
Fossil Oil	0.778	0.031	11.051	843.0
Hydro Pumped Storage	0.126	0.704	14.547	652.6
Hydro Run-of-river	0.004	3.792	0.040	10.1
Hydro Water Reservoir	0.006	3.793	0.045	11.8
Nuclear	0.006	0.007	13.454	565.5
Waste	0.000	0.000	0.000	0.0
Wind Onshore	0.011	3.882	0.165	25.2
Solar	0.086	3.984	1.095	133.9
Germany – KBOB v2016				
Biomass	0.122	5.332	0.990	214.3
Fossil Brown coal/Lignite	1.220	0.031	12.758	687.6
Fossil Coal-derived gas	1.319	0.147	15.343	811.5
Fossil Gas	0.638	0.018	9.000	411.1
Fossil Hard coal	1.114	0.100	12.680	665.6
Fossil Oil	1.131	0.045	15.983	959.5
Geothermal	0.151	4.071	1.825	206.1
Hydro Pumped Storage	0.810	0.879	12.742	623.1
Hydro Run-of-river	0.004	3.792	0.040	10.1
Hydro Water Reservoir	0.017	3.793	0.045	24.4
Nuclear	0.010	0.007	11.559	359.1
Other (Fossil)	1.319	0.147	15.343	811.5
Other (renewable)	0.151	4.071	1.825	206.1
Waste	0.000	0.000	0.000	0.0
Wind Offshore	0.151	4.071	1.825	206.1
Wind Onshore	0.011	3.882	0.165	25.2
Solar	0.099	4.006	1.266	153.1

Production means	GWP IPCC2013 v1.03 (kg of CO_2 eq./kWh)	CED renewable v2.05 (MJ primary/kWh)	CED non-renewable v2.05 (MJ primary/kWh)	ES2013 v1.05 (UBP/kWh)
	Impacts			
Italy – KBOB v2016				
Biomass	0.097	7.32	0.900	232
Fossil Brown coal/Lignite	-	-	-	-
Fossil Coal-derived gas	1.319	0.147	15.343	811.5
Fossil Gas	0.725	0.034	10.783	428
Fossil Hard coal	1.036	0.085	11.613	829.6
Fossil Oil	0.904	0.035	12.333	947.4
Geothermal	0.151	4.071	1.825	206.13
Hydro Pumped Storage	0.742	1.199	11.362	575.3
Hydro Run-of-river and poundage	0.004	3.792	0.040	10.1
Hydro Water Reservoir	0.006	3.793	0.045	11.8
Other (Fossil)	1.319	0.147	15.343	811.5
Waste	0.000	0.000	0.000	0
Wind Onshore	0.011	3.882	0.165	25.2
Solar	0.086	3.981	1.083	129.7
Switzerland KBOB v2016				
Biomass	0.215	5.58	1.49	260
Fossil Gas	0.599	0.0181	9.50	369
Hydro Pumped Storage	0.119	2.05	10.6	379
Hydro Run-of-river and poundage	0.00372	3.79	0.0398	9.90
Hydro Water Reservoir	0.00876	3.85	0.357	22.2
Nuclear	0.0148	0.00914	13.6	380
Wind Onshore	0.0173	3.89	0.254	38.0
Solar	0.0810	3.98	1.04	129

Chapter 4 – part A: Annexes

Annex 4.1: Swiss electricity mix shares

The monthly shares of the Swiss electricity mix per country is given in *Table 29* and per production means in Table 30.

Table 29: Monthly Swiss consumer mix share per country of origin

	AT	CH	CZ	DE	FR	IT	Other
1.2017	2.9%	60.9%	0.8%	22.8%	8.6%	3.0%	0.9%
2.2017	3.8%	55.9%	1.0%	25.9%	12.4%	0.2%	0.9%
3.2017	5.3%	64.0%	1.1%	18.4%	10.2%	0.4%	0.6%
4.2017	4.6%	70.3%	1.1%	12.6%	8.7%	2.4%	0.4%
5.2017	3.3%	77.5%	0.6%	9.7%	6.6%	2.1%	0.3%
6.2017	2.7%	80.4%	0.4%	9.8%	4.1%	2.3%	0.3%
7.2017	3.1%	77.7%	0.5%	10.9%	6.8%	0.6%	0.4%
8.2017	4.6%	79.0%	0.7%	9.5%	5.6%	0.6%	0.1%
9.2017	5.2%	71.9%	0.9%	14.4%	6.8%	0.4%	0.2%
10.2017	4.8%	62.5%	1.2%	23.2%	7.5%	0.4%	0.5%
11.2017	4.9%	61.9%	1.2%	24.6%	6.0%	0.8%	0.7%
12.2017	4.4%	61.4%	0.9%	24.6%	7.4%	0.6%	0.7%
1.2018	4.8%	64.2%	0.6%	19.7%	10.1%	0.2%	0.4%
2.2018	5.1%	62.7%	0.9%	24.5%	6.1%	0.1%	0.7%
3.2018	4.6%	62.0%	1.1%	22.4%	8.7%	0.4%	0.9%
4.2018	4.9%	75.0%	0.6%	9.4%	8.0%	1.9%	0.3%
5.2018	1.4%	87.9%	0.2%	2.3%	5.7%	2.4%	0.1%
6.2018	1.4%	86.9%	0.2%	4.0%	5.6%	1.8%	0.1%
7.2018	2.6%	81.9%	0.6%	8.7%	4.4%	1.5%	0.2%
8.2018	1.4%	80.9%	0.5%	10.1%	5.6%	1.2%	0.2%
9.2018	2.2%	72.4%	0.7%	14.9%	9.0%	0.4%	0.3%
10.2018	3.2%	60.7%	1.1%	23.8%	10.4%	0.2%	0.7%
11.2018	3.8%	66.7%	1.1%	19.8%	6.4%	1.6%	0.6%
12.2018	4.9%	65.4%	1.1%	20.1%	7.5%	0.7%	0.3%

Table 30: Monthly Swiss consumption mix share per energy carrier

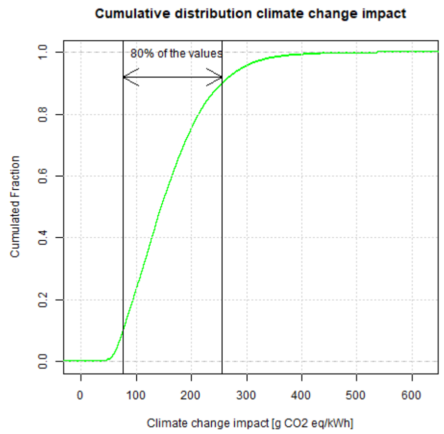
	Fossil	EnR	Nuclear	STEP	Other
1.2017	19.0%	50.6%	22.5%	7.0%	0.9%
2.2017	17.7%	50.1%	27.3%	4.0%	0.9%
3.2017	12.3%	51.1%	31.7%	4.3%	0.6%
4.2017	9.3%	49.7%	35.6%	5.0%	0.4%
5.2017	6.6%	54.6%	32.1%	6.4%	0.3%
6.2017	6.1%	64.0%	20.8%	8.8%	0.3%
7.2017	6.6%	56.7%	29.4%	6.9%	0.4%
8.2017	5.4%	59.4%	27.0%	8.1%	0.1%
9.2017	8.9%	60.4%	23.5%	7.1%	0.2%
10.2017	12.2%	61.1%	21.7%	4.5%	0.5%
11.2017	15.3%	58.3%	20.1%	5.6%	0.7%
12.2017	12.6%	57.3%	23.4%	6.0%	0.7%
1.2018	10.2%	53.4%	30.8%	5.1%	0.4%
2.2018	15.6%	49.5%	26.9%	7.3%	0.7%
3.2018	13.5%	48.5%	31.7%	5.5%	0.9%
4.2018	5.5%	55.6%	33.2%	5.4%	0.3%
5.2018	2.3%	57.5%	31.0%	9.2%	0.1%
6.2018	2.8%	63.4%	23.7%	10.0%	0.1%
7.2018	5.8%	56.5%	29.4%	8.1%	0.2%
8.2018	6.0%	55.0%	31.4%	7.4%	0.2%
9.2018	7.8%	54.7%	30.8%	6.3%	0.3%
10.2018	13.2%	54.4%	26.7%	5.0%	0.7%
11.2018	13.1%	47.7%	32.8%	5.8%	0.6%
12.2018	10.9%	51.9%	32.0%	4.9%	0.3%

Annex 4.2: Swiss electricity mix impacts

In this annex, the environmental impact profile distributions are presented.

Climate change impact

The climate change impact is plotted in a cumulative distribution in Figure 85 and a generic daily GWP impact profile is provided. This typical profile is obtained by averaging all data at each hour of a day into a mean value. The cumulative distribution shows a quite steep curve, 80% of the hourly impact values are ranging from 76 to 255 g CO_2 eq/kWh, while the overall range is from 35 to 579 g CO_2 eq/kWh.



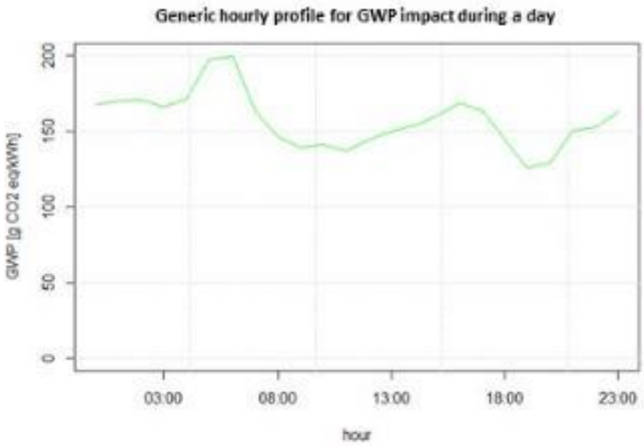


Figure 85: Cumulative distribution of the GHG emissions for the Swiss consumed electricity and generic day

Regarding the daily profile, there are two a peaks occurring in the morning and another in the late afternoon. Nevertheless, these peaks have a smaller amplitude than the seasonal variability. Indeed, the monthly min/max amplitude is 143 g CO_2 eq/kWh, while the daily average min/max amplitude is 75 g CO_2 eq/kWh. Thus, the climate change impact of the Swiss consumed electricity appears to be more fluctuant from one season to another than within a day.

NRE

The generic daily NRE impact profile is provided in the Figure 86 with the cumulative distribution of the hourly impacts for the two considered years. Regarding the generic daily profile, two peaks occur mostly during nights (between 4 and 7 am) and to a smaller extend in late afternoon (between 4 to 6pm). These two peaks correspond to an increase of the imports from France, which mostly produces electricity from nuclear energy. Thereby, especially at night, there is a significant and recurrent increase of the French imports in Switzerland, causing NRE impact peaks. These peaks occur all over the year, they are recurrent.

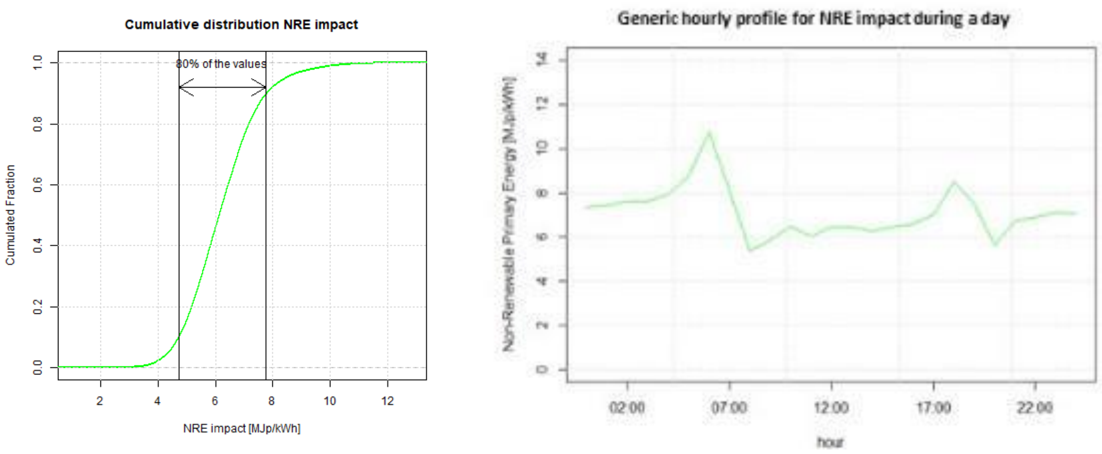


Figure 86: Cumulative distribution of the NRE impact for the Swiss consumed electricity and generic day

The cumulative distribution shows a steep trend, i.e., 80% of the hourly impact values range from 4.72 to 7.77 MJp/kWh, while the overall range is from 1.80 to 12.56 MJp/kWh. The NRE impact amplitude from months to months is 2.1 MJp/kWh while the amplitude for a typical day is 2.7 MJp/kWh. Thus, the intra-day amplitude is higher than the seasonal amplitude which is significantly different compared to the climate change indicator. Considering the NRE indicator, the time step influence would thereby by smaller than for climate change and more affected by intra-days variations.

RE

The Generic daily RE impact profile is provided in Figure 87 with the cumulative distribution of the hourly impacts for the two considered years. Regarding the generic daily profile, as it was the case for the NRE, the peaks are found in the intradays' fluctuation.

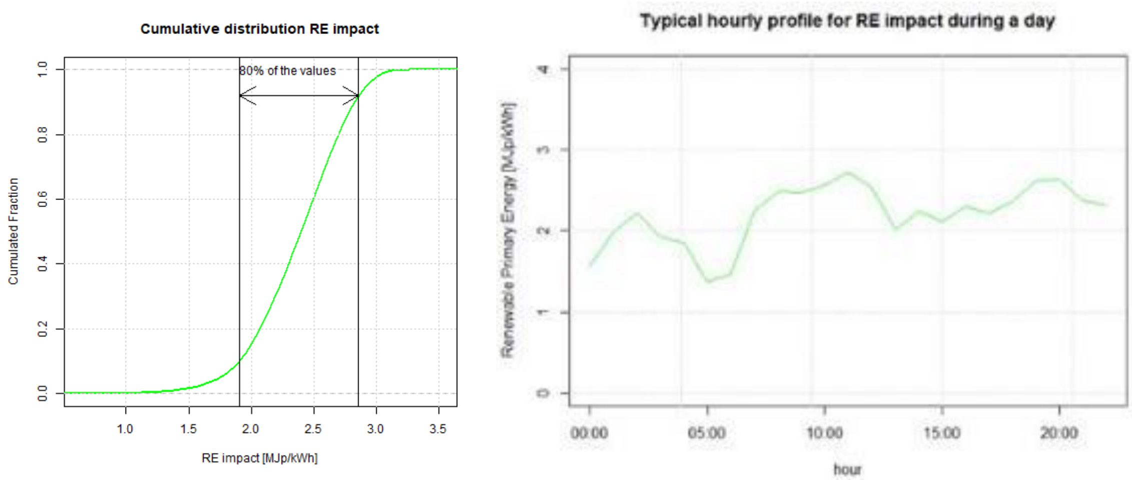


Figure 87: Cumulative distribution of the RE impact for the Swiss consumed electricity and Generic day

The cumulative distribution shows a steep trend i.e., 80% of the hourly impact values range from 1.91 to 2.86 MJp/kWh (median = 2.40 MJp/kWh), while the overall range is from 0.82 to 3.33 MJp/kWh. The RE impact amplitude from months to months is 0.65 MJp/kWh while the amplitude for a typical day is 0.75 MJp/kWh. Such as the NRE indicator, compared to the climate change indicator, the intra-day fluctuation is slightly higher than the seasonal fluctuations. Thus, the intra-day energy demand variations should have more influence than the monthly fluctuations.

ES

For a generic day, the ES impact profile is given in Figure 88 with the cumulated distribution of the hourly impacts for the two considered years. The intraday fluctuation for the ES impacts is similar as for the NRE and this fluctuation is related to the increase of the imports from France. Nevertheless, the intraday fluctuation has a smaller amplitude, 67 UBP/kWh. There is a peak at 6am, which is related to higher electricity demand at that time and consequently higher imports from the neighboring countries.

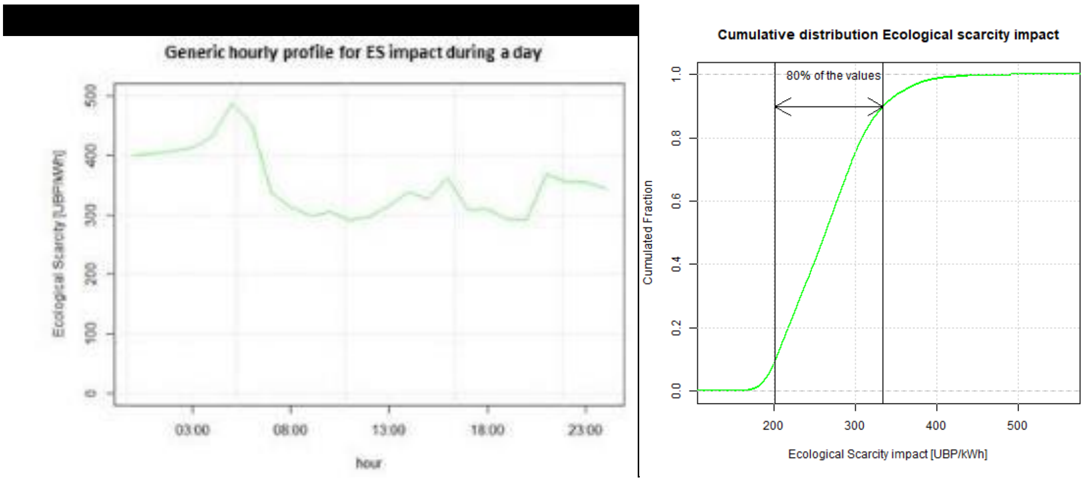


Figure 88: Generic daily ES profile and cumulative distribution

The cumulative distribution shows that 80% of the hourly impact values range from 201 to 334 UBP/kWh (median = 263 UBP/kWh), while the overall range is from 153 to 529 UBP/kWh. The ES impact amplitude from months to months is 123 UBP/kWh while the amplitude for a typical day is 67 UBP/kWh. Thus, the ES indicator tend to have more fluctuation on a monthly basis than on an intraday basis, such as the climate change impact.

From this assessment, it appears thereby that the climate change and ES indicators have a higher seasonal sensitivity than the primary energy indicators. Thus, seasonal variation of the building energy demand should show more sensitivity for GPW and ES indicator than the primary indicators. This observation is confirmed by the case studies (see other chapters and appendix dedicated to case studies assessment).

The overall impact profile for the two considered years, according to the energy carrier (fossil, renewables, pumping storage, nuclear and other) and yearly impact values (weighted by the hourly production) are given in the following tables, for the four studied indicators.

Climate change	AT contribution [g CO$_2$ eq/kWh]	CH contribution [g CO$_2$ eq/kWh]	CZ contribution [g CO$_2$ eq/kWh]	DE contribution [g CO$_2$ eq/kWh]	FR contribution [g CO$_2$ eq/kWh]	IT contribution [g CO$_2$ eq/kWh]	Other [g CO$_2$ eq/kWh]	Swiss electricity [g CO$_2$ eq/kWh]	Yearly impact [g CO$_2$ eq/kWh]
1.2017	10.9	31.1	7.1	186.7	10.9	32.6	3.9	283.2	180.1
2.2017	11.4	28.3	8.9	194.5	13.8	1.8	3.9	262.6	
3.2017	10.5	24.4	9.1	130.0	9.1	3.1	2.5	188.7	
4.2017	6.4	26.7	9.0	83.3	6.8	22.3	1.7	156.3	
5.2017	2.1	26.5	4.5	64.7	4.0	18.3	1.2	121.3	
6.2017	2.7	31.2	3.3	57.0	2.3	21.4	1.2	119.0	
7.2017	2.4	27.3	3.4	72.9	5.6	5.1	1.9	118.6	
8.2017	4.3	28.6	4.9	59.1	2.8	4.5	0.5	104.7	
9.2017	4.7	29.2	7.1	101.2	4.9	3.5	0.9	151.4	
10.2017	8.1	26.5	8.9	133.7	8.9	4.0	2.0	192.0	
11.2017	10.9	26.2	9.1	166.6	7.9	7.3	3.1	231.0	
12.2017	9.4	28.2	7.3	140.9	6.8	5.4	3.3	201.1	
1.2018	10.1	24.7	5.3	99.2	5.5	1.5	1.8	148.1	140.1
2.2018	13.5	29.6	7.1	152.6	5.9	0.9	3.3	212.8	
3.2018	10.7	25.8	9.0	131.5	6.9	3.0	3.8	190.9	
4.2018	4.6	25.5	4.1	49.3	2.9	13.6	1.2	101.2	
5.2018	0.8	33.8	1.3	10.9	1.8	17.2	0.4	66.1	
6.2018	0.9	35.6	1.4	20.6	1.9	12.5	0.3	73.1	
7.2018	2.0	30.7	4.7	52.3	2.8	12.2	0.8	105.5	
8.2018	1.3	29.4	3.8	57.9	3.4	10.0	1.0	106.8	
9.2018	2.4	28.6	5.4	82.1	4.8	3.7	1.3	128.2	
10.2018	6.4	28.7	8.4	134.3	8.4	1.3	3.1	190.7	
11.2018	9.7	28.6	8.9	114.1	6.1	13.0	2.9	183.2	
12.2018	12.5	25.6	8.7	93.2	5.1	3.5	1.6	150.2	

Climate change	Fossil contribution [g CO_2 eq/kWh]	Renewable (EnR) contribution [g CO_2 eq/kWh]	Nuclear contribution [g CO_2 eq/kWh]	Pumping storage (STEP) contribution [g CO_2 eq/kWh]	Other contribution [g CO_2 eq/kWh]	Swiss electricity [g CO_2 eq/kWh]	Yearly impact [g CO_2 eq/kWh]
1.2017	238.8	20.6	2.9	17.0	3.9	283.2	**180.1**
2.2017	219.3	25.0	3.5	10.9	3.9	262.6	
3.2017	151.6	19.3	4.1	11.3	2.5	188.7	
4.2017	119.1	18.8	4.6	12.1	1.7	156.3	
5.2017	87.2	14.4	4.1	14.4	1.2	121.3	
6.2017	80.4	15.6	2.6	19.2	1.2	119.0	
7.2017	83.3	14.5	3.8	15.2	1.9	118.6	
8.2017	68.6	13.9	3.5	18.3	0.5	104.7	
9.2017	112.8	18.1	3.0	16.6	0.9	151.4	
10.2017	152.1	22.8	2.8	12.3	2.0	192.0	
11.2017	191.2	19.6	2.5	14.5	3.1	231.0	
12.2017	158.2	20.9	3.0	15.8	3.3	201.1	
1.2018	111.2	17.8	3.9	13.5	1.8	148.1	**140.1**
2.2018	168.6	19.1	3.4	18.4	3.3	212.8	
3.2018	149.3	19.0	4.1	14.6	3.8	190.9	
4.2018	66.1	16.2	4.3	13.5	1.2	101.2	
5.2018	28.6	13.7	4.0	19.5	0.4	66.1	
6.2018	33.6	15.1	3.0	21.1	0.3	73.1	
7.2018	68.3	14.9	3.8	17.7	0.8	105.5	
8.2018	70.7	14.8	4.0	16.3	1.0	106.8	
9.2018	89.7	18.3	4.0	15.0	1.3	128.2	

10.2018	146.7	23.9	3.4	13.6	3.1	190.7	
11.2018	142.9	18.9	4.2	14.2	2.9	183.2	
12.2018	113.4	18.4	4.1	12.7	1.6	150.2	

NRE	AT contribution [MJp/kWh]	CH contribution [MJp/kWh]	CZ contribution [MJp/kWh]	DE contribution [MJp/kWh]	FR contribution [MJp/kWh]	IT contribution [MJp/kWh]	Other contribution [MJp/kWh]	Swiss electricity [MJp/kWh]	Yearly impact contribution [MJp/kWh]
1.2017	0.18	2.67	0.10	2.38	1.08	0.35	0.08	6.8	6.1
2.2017	0.19	2.70	0.13	2.43	1.52	0.02	0.08	7.1	
3.2017	0.17	3.66	0.14	1.65	1.21	0.03	0.05	6.9	
4.2017	0.10	4.49	0.14	1.09	1.08	0.23	0.04	7.2	
5.2017	0.03	4.39	0.07	0.86	0.78	0.19	0.03	6.4	
6.2017	0.04	3.24	0.05	0.80	0.48	0.23	0.03	4.9	
7.2017	0.04	4.02	0.05	0.97	0.83	0.06	0.04	6.0	
8.2017	0.06	3.82	0.08	0.85	0.69	0.05	0.01	5.6	
9.2017	0.07	2.98	0.11	1.37	0.85	0.04	0.02	5.4	
10.2017	0.12	2.24	0.14	1.92	0.93	0.04	0.04	5.4	
11.2017	0.17	2.29	0.14	2.26	0.73	0.08	0.07	5.7	
12.2017	0.15	2.65	0.11	1.99	0.89	0.06	0.07	5.9	
1.2018	0.16	3.46	0.08	1.49	1.17	0.02	0.04	6.4	6.3
2.2018	0.22	3.48	0.11	2.20	0.73	0.01	0.07	6.8	
3.2018	0.17	3.78	0.14	1.88	1.01	0.03	0.08	7.1	
4.2018	0.07	4.32	0.07	0.71	0.91	0.15	0.03	6.2	
5.2018	0.01	4.78	0.02	0.16	0.64	0.19	0.01	5.8	
6.2018	0.01	3.78	0.02	0.30	0.63	0.14	0.01	4.9	
7.2018	0.03	4.42	0.07	0.75	0.54	0.14	0.02	6.0	

8.2018	0.02	4.47	0.06	0.85	0.69	0.11	0.02	6.2	
9.2018	0.04	3.76	0.09	1.19	1.14	0.04	0.03	6.3	
10.2018	0.10	2.77	0.13	1.93	1.31	0.01	0.07	6.3	
11.2018	0.15	4.25	0.14	1.67	0.79	0.15	0.06	7.2	
12.2018	0.20	3.86	0.14	1.46	0.90	0.05	0.03	6.6	

NRE	Fossil [MJp/kWh]	EnR [MJp/kWh]	Nuclear [MJp/kWh]	STEP [MJp/kWh]	Other [MJp/kWh]	Swiss electricity [MJp/kWh]	Yearly impact [MJp/kWh]
1.2017	2.68	0.14	3.22	0.71	0.08	6.8	6.1
2.2017	2.47	0.17	3.93	0.42	0.08	7.1	
3.2017	1.71	0.14	4.57	0.44	0.05	6.9	
4.2017	1.32	0.14	5.17	0.50	0.04	7.2	
5.2017	0.95	0.11	4.62	0.65	0.03	6.4	
6.2017	0.88	0.12	2.96	0.88	0.03	4.9	
7.2017	0.92	0.11	4.23	0.70	0.04	6.0	
8.2017	0.75	0.11	3.88	0.81	0.01	5.6	
9.2017	1.24	0.13	3.35	0.70	0.02	5.4	
10.2017	1.70	0.16	3.08	0.46	0.04	5.4	
11.2017	2.13	0.13	2.85	0.57	0.07	5.7	
12.2017	1.76	0.14	3.33	0.61	0.07	5.9	
1.2018	1.33	0.12	4.41	0.51	0.04	6.4	6.3
2.2018	2.02	0.13	3.85	0.73	0.07	6.8	
3.2018	1.76	0.14	4.56	0.56	0.08	7.1	

4.2018	0.75	0.12	4.80	0.55	0.03	6.2	
5.2018	0.32	0.10	4.46	0.92	0.01	5.8	
6.2018	0.38	0.11	3.40	1.00	0.01	4.9	
7.2018	0.78	0.11	4.25	0.81	0.02	6.0	
8.2018	0.81	0.11	4.54	0.75	0.02	6.2	
9.2018	1.03	0.14	4.44	0.64	0.03	6.3	
10.2018	1.72	0.17	3.84	0.52	0.07	6.3	
11.2018	1.70	0.13	4.72	0.59	0.06	7.2	
12.2018	1.38	0.13	4.59	0.50	0.03	6.6	

RE	AT Contribution [MJp/kWh]	CH Contribution [MJp/kWh]	CZ Contribution [MJp/kWh]	DE Contribution [MJp/kWh]	FR Contribution [MJp/kWh]	IT Contribution [MJp/kWh]	Other Contribution [MJp/kWh]	Swiss electricity [MJp/kWh]	Yearly impact [MJp/kWh]
1.2017	0.07	1.78	0.01	0.26	0.05	0.03	0.01	2.21	2.41
2.2017	0.11	1.51	0.01	0.37	0.08	0.00	0.01	2.10	
3.2017	0.18	1.59	0.01	0.29	0.08	0.01	0.01	2.17	
4.2017	0.18	1.64	0.01	0.21	0.06	0.04	0.01	2.14	
5.2017	0.14	1.98	0.01	0.15	0.05	0.04	0.00	2.36	
6.2017	0.11	2.43	0.00	0.17	0.04	0.04	0.00	2.78	
7.2017	0.13	2.10	0.01	0.17	0.05	0.01	0.01	2.47	
8.2017	0.19	2.22	0.01	0.15	0.04	0.01	0.00	2.61	
9.2017	0.21	2.13	0.01	0.19	0.04	0.01	0.00	2.59	
10.2017	0.18	1.90	0.01	0.39	0.05	0.01	0.01	2.54	
11.2017	0.16	1.90	0.01	0.35	0.04	0.01	0.01	2.47	
12.2017	0.15	1.78	0.01	0.43	0.05	0.01	0.01	2.44	

1.2018	0.16	1.65	0.01	0.34	0.08	0.00	0.01	2.26	2.34
2.2018	0.16	1.65	0.01	0.32	0.05	0.00	0.01	2.20	
3.2018	0.16	1.50	0.01	0.34	0.08	0.01	0.01	2.10	
4.2018	0.20	1.88	0.01	0.17	0.08	0.04	0.00	2.38	
5.2018	0.06	2.33	0.00	0.05	0.06	0.05	0.00	2.54	
6.2018	0.06	2.56	0.00	0.07	0.06	0.04	0.00	2.78	
7.2018	0.11	2.19	0.01	0.13	0.04	0.02	0.00	2.50	
8.2018	0.06	2.13	0.00	0.16	0.04	0.02	0.00	2.41	
9.2018	0.09	1.94	0.01	0.25	0.06	0.01	0.00	2.36	
10.2018	0.12	1.71	0.01	0.38	0.07	0.00	0.01	2.30	
11.2018	0.12	1.57	0.01	0.29	0.04	0.02	0.01	2.07	
12.2018	0.15	1.60	0.01	0.36	0.06	0.01	0.01	2.20	

RE	Fossil Contribution [MJp/kWh]	EnR Contribution [MJp/kWh]	Nuclear Contribution [MJp/kWh]	STEP Contribution [MJp/kWh]	Other Contribution [MJp/kWh]	Swiss electricity [MJp/kWh]	Yearly impact [MJp/kWh]
1.2017	0.02	1.95	0.00	0.22	0.01	2.21	2.41
2.2017	0.02	1.94	0.01	0.12	0.01	2.10	
3.2017	0.01	2.00	0.01	0.13	0.01	2.17	
4.2017	0.01	1.96	0.01	0.16	0.01	2.14	
5.2017	0.01	2.14	0.01	0.20	0.00	2.36	
6.2017	0.01	2.49	0.00	0.28	0.00	2.78	
7.2017	0.01	2.23	0.01	0.22	0.01	2.47	
8.2017	0.00	2.34	0.01	0.26	0.00	2.61	

9.2017	0.01	2.36	0.01	0.22	0.00	2.59	
10.2017	0.01	2.38	0.00	0.14	0.01	2.54	
11.2017	0.01	2.27	0.00	0.18	0.01	2.47	
12.2017	0.01	2.23	0.01	0.19	0.01	2.44	
1.2018	0.01	2.08	0.01	0.16	0.01	2.26	2.34
2.2018	0.01	1.94	0.01	0.23	0.01	2.20	
3.2018	0.01	1.90	0.01	0.17	0.01	2.10	
4.2018	0.00	2.19	0.01	0.17	0.00	2.38	
5.2018	0.00	2.24	0.01	0.29	0.00	2.54	
6.2018	0.00	2.46	0.01	0.31	0.00	2.78	
7.2018	0.00	2.23	0.01	0.26	0.00	2.50	
8.2018	0.00	2.17	0.01	0.23	0.00	2.41	
9.2018	0.01	2.14	0.01	0.20	0.00	2.36	
10.2018	0.01	2.12	0.01	0.15	0.01	2.30	
11.2018	0.01	1.86	0.01	0.18	0.01	2.07	
12.2018	0.01	2.03	0.01	0.15	0.01	2.20	

ES	AT	CH	CZ	DE	FR	IT	Other	Swiss electricity	Yearly impact
1.2017	7.6	131.6	5.8	140.2	31.2	23.8	4.1	344.2	274.8
2.2017	8.3	141.4	7.3	147.6	43.2	1.3	4.1	353.2	
3.2017	8.4	142.6	7.7	101.5	33.9	2.3	2.6	298.9	

4.2017	5.8	162.9	7.8	66.6	30.0	16.8	1.8	291.7	
5.2017	2.7	148.4	4.0	51.8	21.6	13.6	1.3	243.3	
6.2017	2.8	127.8	2.9	47.9	13.3	16.0	1.3	211.9	
7.2017	2.7	140.0	2.9	59.0	23.5	3.8	1.9	233.9	
8.2017	4.4	135.0	4.3	49.6	18.8	3.5	0.5	216.2	
9.2017	4.9	129.1	6.2	79.9	23.6	2.6	0.9	247.2	
10.2017	6.8	121.2	7.7	112.0	26.8	3.0	2.1	279.6	
11.2017	8.3	113.9	7.8	131.9	21.3	5.4	3.2	291.9	
12.2017	7.4	127.4	6.2	117.8	25.0	4.0	3.4	291.1	
1.2018	7.8	136.2	4.5	82.4	32.0	1.1	1.9	265.9	257.2
2.2018	10.1	141.8	5.9	117.9	20.6	0.6	3.4	300.4	
3.2018	8.4	144.6	7.7	103.0	28.4	2.2	4.0	298.2	
4.2018	4.7	151.6	3.7	41.0	24.9	10.5	1.3	237.7	
5.2018	1.0	166.0	1.2	9.5	17.5	13.2	0.4	208.9	
6.2018	1.1	147.3	1.2	17.3	17.1	9.6	0.3	194.0	
7.2018	2.4	153.6	4.0	42.0	14.9	9.1	0.8	226.9	
8.2018	1.5	153.6	3.2	47.5	19.1	7.5	1.0	233.5	
9.2018	2.4	145.1	4.8	66.4	31.2	2.7	1.3	254.0	
10.2018	5.3	137.2	7.3	106.0	36.6	1.0	3.2	296.7	
11.2018	7.4	160.2	7.7	90.4	22.0	9.4	3.0	300.1	
12.2018	9.3	147.5	7.5	79.4	24.6	2.9	1.6	272.8	

ES	Fossil	EnR	Nuclear	STEP	Other	Swiss electricity	Yearly impact
1.2017	155.0	80.3	78.8	26.0	4.1	344.2	274.8
2.2017	139.4	97.8	96.4	15.5	4.1	353.2	
3.2017	96.9	72.4	110.7	16.4	2.6	298.9	
4.2017	77.9	69.2	124.4	18.5	1.8	291.7	
5.2017	56.9	50.8	111.0	23.3	1.3	243.3	
6.2017	53.1	54.8	71.3	31.5	1.3	211.9	
7.2017	53.8	51.2	101.9	25.0	1.9	233.9	
8.2017	44.2	48.8	93.5	29.2	0.5	216.2	
9.2017	72.1	67.1	81.4	25.7	0.9	247.2	
10.2017	98.0	86.7	75.5	17.4	2.1	279.6	
11.2017	122.3	75.7	69.5	21.1	3.2	291.9	
12.2017	102.2	81.5	81.2	22.8	3.4	291.1	
1.2018	68.8	68.7	107.3	19.2	1.9	265.9	257.2
2.2018	102.8	73.8	93.2	27.2	3.4	300.4	
3.2018	91.4	71.6	110.4	20.8	4.0	298.2	
4.2018	42.4	58.3	115.4	20.2	1.3	237.7	
5.2018	19.7	49.2	106.8	32.7	0.4	208.9	
6.2018	22.1	54.3	81.8	35.6	0.3	194.0	
7.2018	43.1	52.2	101.6	29.1	0.8	226.9	
8.2018	44.5	52.3	108.9	26.8	1.0	233.5	
9.2018	55.0	66.6	107.8	23.4	1.3	254.0	
10.2018	89.3	90.6	94.1	19.4	3.2	296.7	
11.2018	88.5	73.2	113.7	21.7	3.0	300.1	
12.2018	70.1	71.5	111.0	18.6	1.6	272.8	

Annex 4.3: Case studies description

The following section presents the monitoring plan of the case studies and the consumption profiles of the different scenarios.

Monitoring plan

Case studies 1 – 4

A two years (01/2016 – 01/2018) measurement campaign was set for the case studies, in order to collect the appropriate data for the energy needs of the project. The first case study was fully instrumented, i.e. measurements were taken, concerning the power of the HP, the boiler, the grid, the PV production, the flows and temperatures of the HP and the heating system. The three other case studies (CS2-CS4) were partially instrumented, i.e. no measurements were taken for the heat flow. Figure 89 presents the heating system of the buildings, as well as the monitoring pattern and the position of the transducers, while Table 31 shows the retained measurements for the project. Measurements were taken every 15 minutes.

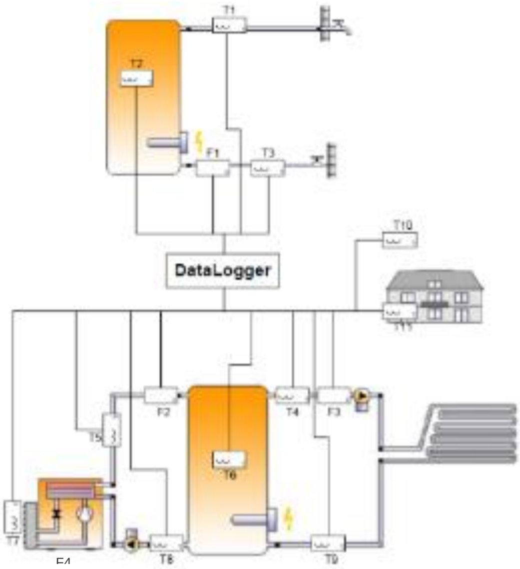


Figure 89: Monitoring pattern for CS1

Table 31: Technical characteristics of SFH case studies.

Transducer	Measurements
F1	Boiler power (kW)
F2	Heat pump flow (ml/sec)
F3	Space heating flow (ml/sec)
F4	Heat pump power (kW)
T5/T8	Heat pump temperature outlet/inlet (°C)
T4/T9	Space heating temperature outlet/inlet (°C)
T10	Irradiation with pyranometer
T11	Air temperature from weather station
PV	Electricity produced (kW)
Battery	Electricity stored (kW)

Case study 5

The fifth case study represents an MFH with 20 apartments. The measurement campaign started on 30.12.2015 and finished on 02.01.2018. Measurements were taken every hour, for the consumed energy of the 20 apartments and more specifically for the energy of the heating system (kWh), the total energy (kWh), the electricity (kWh) and the domestic hot water - DHW (L), see Figure 90 .

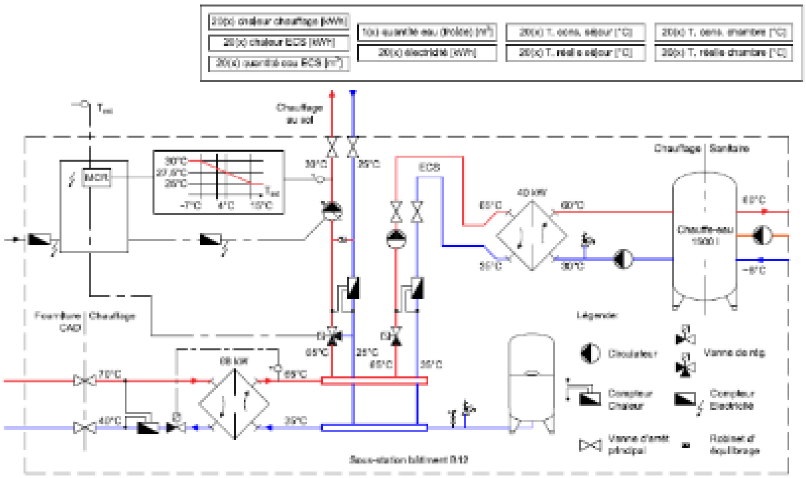


Figure 90: Technical system and monitoring pattern of case study 5.

Case study 6

This case study corresponds to an office building and measurements were taken every 11 minutes during one year (2018) for the electricity consumption (electricity consumed by the heat pump (kWh) not included), the electricity production of the PV (kWh) and the energy of the heating system (kWh). The heating system is shown in Figure 91.

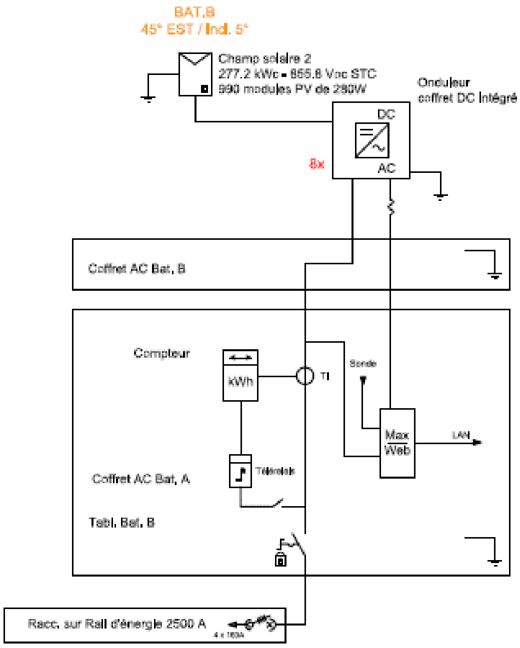


Figure 91: Technical system of case study 6.

Measured energy consumption of the all the case studies

Table 32, Table 33 and Table 34 present in detail the shares of the different energy uses, for all the case studies. The measured data of the case studies were aggregated, in order to calculate the daily profile of the electricity consumption (electricity supplied from the grid) and the PV production, which are presented in Figure 18, for the different domestic uses, i.e. DHW, space heating and the other domestic uses. The heat pump electricity consumption has a seasonal profile for all the case studies. The electricity for the DHW and other domestic uses is relatively stable intra- and inter- annually, for all the case studies, except for the second case study, for which a seasonal trend is observed for the DHW needs. The seasonality of the consumption and PV production is evident, with low electricity production during winter, while the opposite trend is observed during the summer months. The PV power production varies between zero to three kW per day, for this region and the specific installed PV power (between 6.6 and 10.7 kWp), while the small differences among the case studies derive from the different installed PV power. Table 32 presents in detail the shares of the different energy uses, as well as the part of the produced electricity that it is locally consumed and sent back to the grid. It can be seen that the heat pump electricity consumption represents approximately 40% to 50% of the total energy consumption of the buildings, for all the four case studies.

Table 32: Energy consumption and PV production of SFH case studies.

	Case study 1		Case study 2		Case study 3		Case study 4	
	2017	2018	2017	2018	2017	2018	2017	2018
Overall Energy consumption [kWh]	14160	14833	16875	18888	15326	15538	8522	7789
HP electricity consumption [kWh]	5408 (38%)	5581 (38%)	4484 (27%)	4382 (23%)	3610 (24%)	3886 (24%)	3924 (46%)	4383 (56%)
DHW electricity consumption [kWh]	1934 (14%)	1890 (12%)	7300 (43%)	8678 (46%)	2342 (15%)	2428 (16%)	1987 (23%)	1961 (25%)
Domestic appliances electricity consumption [kWh]	6817 (48%)	7361 (50%)	5130 (30%)	5828 (31%)	9373 (61%)	9281 (60%)	2611 (31%)	1434 (19%)
Photovoltaic production [kWh]	11160	10777	10993	11365	8426	8208	7489	7032
Share electricity sent to the grid [%]	64.8	58.2	74.5	71.2	56.3	50.6	69	75
Share electricity self-consumed [%]	35.2	41.8	25.5	28.8	43.7	49.4	31	25
Independency share [%]	27.8	30.4	16.6	17.3	24	26	27	23

The fifth case study corresponds to an MFH, for which the heating needs and the DHW are covered by district heating, while the electricity for the other domestic uses is provided by the grid. The energy consumption of the measured data for the years 2017 – 2019 is presented in Figure 19. Missing data were observed in the measurements. The procedure, already described in chapter 2, was followed for the missing data. In case of missing data for isolated hours, a linear interpolation was used, while in case of missing data for many consecutive hours, a typical day was used to fill the gap, which was defined based on the data before and after the period of the missing values.

Table 33: Energy consumption in [kWh/m^2] of CS5.

	2017	2018
Heat energy consumption	35.42	35.65
Electricity for other Domestic Uses	15.42	14.00
Energy for DHW	18.70	15.80

The data of the sixth case study (office building) correspond to measurements during the year 2018. Missing data were also found in the measurements and they were treated with the methodology that has been presented in chapter 2. A heat pump covers the heating needs, which is designed, according to the methodology, presented in chapter 2.

Table 34: Annual consumption of CS6.

	2018
Other Electricity Uses	54.50
HP Electricity	21.45
Grid Electricity	60.20
PV Production - Consumption	15.80

Consumption profiles of the alternative scenarios

Case studies 1 - 4

For these case studies, one alternative scenario was defined where the production of the PV installations was not taken into account. Thus, all electricity uses in the SFH buildings are covered by the grid. The energy consumption profiles of the buildings' consumption remain the same as the reference scenario, see Figure 18.

Case study 5

For this case study five more theoretical scenarios were considered, including a PV installation and a heat pump, with a constant or variable COP. They were designed, according to the methodology, as described in chapter 2. Their technical specifications, are presented in Table 35.

Table 35: Technical specifications of the theoretical systems used for the alternative scenarios; CS5.

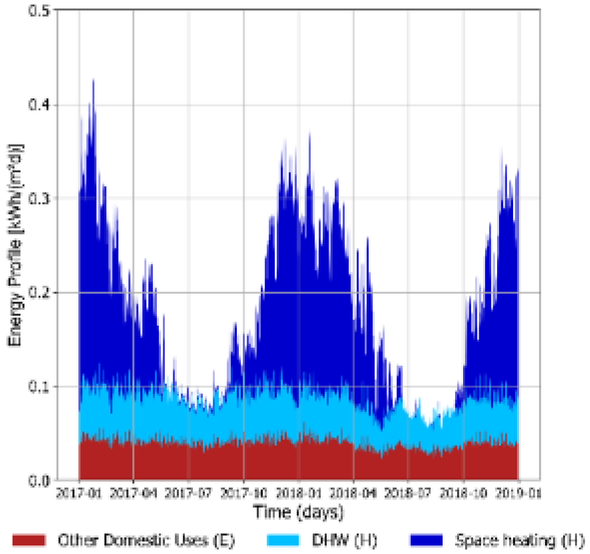
Technical system	Domestic needs	Technical specifications
PV installation		Orientation of the PV modules: SW, 86 polycrystalline PV modules 240 W (TSAM – 240 – PC – 05) with 15% efficiency and 250 Wc inverter.
Heat pump with variable COP	Heating + DHW	Design outdoor temperature: T_{ext} = -8°C Upper temperature limit for heating: $T_{up} = +18°C$ Condensation temperature and supply temperature: $T_{con,\ sup} = +55°C$
Heat pump with constant COP	Heating + DHW	$COP_{heating\&DHW}$ = 2.85 (average value of variable COP) Power=44.8kW Design outdoor temperature: T_{ext} = -8°C Upper temperature limit for heating: $T_{up} = +18°C$ Condensation temperature and supply temperature: $T_{con,\ sup} = +55°C$

The energy profiles of the different scenarios are presented in Figure 92. Scenario 5B includes the same technical systems as the reference scenario, i.e. district heating for space heating and DHW, while the electricity needs for all the other domestic uses are covered partially by the PV electricity production. The seasonality of the PV consumption can be identified, which is more prominent during the summer months. Approximately 60% of the annual electricity needs are covered by the PV installation, see Table 36.

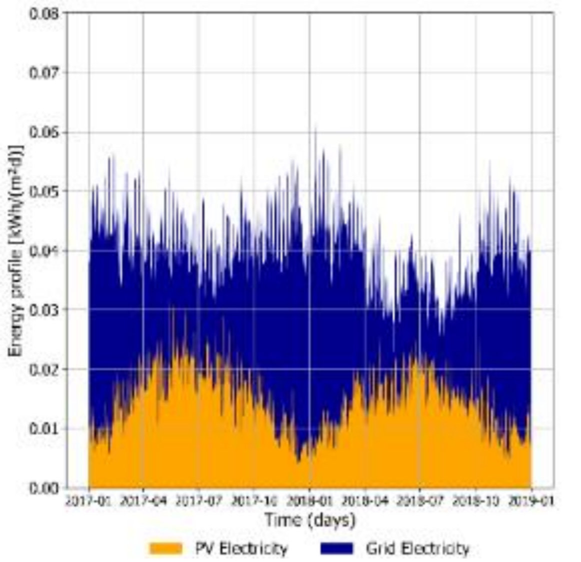
Scenarios CS5C and CS5D include a heat pump (with a constant and variable COP, respectively), in order to cover the space heating needs and the DHW. All the electricity needs are covered by the electricity coming from the grid. The annual electricity consumption of the heat pump with the variable COP (Scenario CS5D) for space heating is slightly higher than the one with the constant COP (Scenario CS5C). On the contrary, no significant difference was identified, concerning the electricity for the DHW, see Table 36.

Finally, the last scenarios CS5E and CS5F have the same configurations as the previous ones (heat pump with constant COP and variable COP respectively), while a PV installation is added to the system. The PV consumption is allocated proportionally to the energy needs of the building. As far as the scenario CS5E is concerned, in an annual basis, approximately 22% of the total electricity needs are covered by the PV production. For the scenario CS5F, approximately 20% of the total needs are covered by the PV. This small difference is derived by the slightly higher electricity needs of the heat pump, when a variable COP is considered,

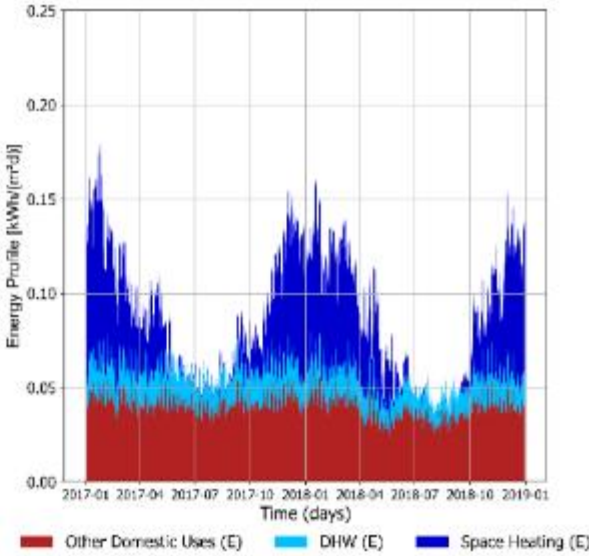
Reference Scenario



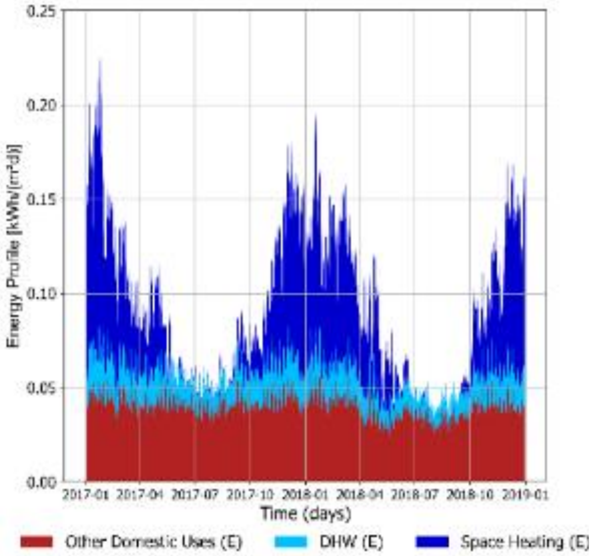
Scenario 5B



Scenario 5C



Scenario 5D



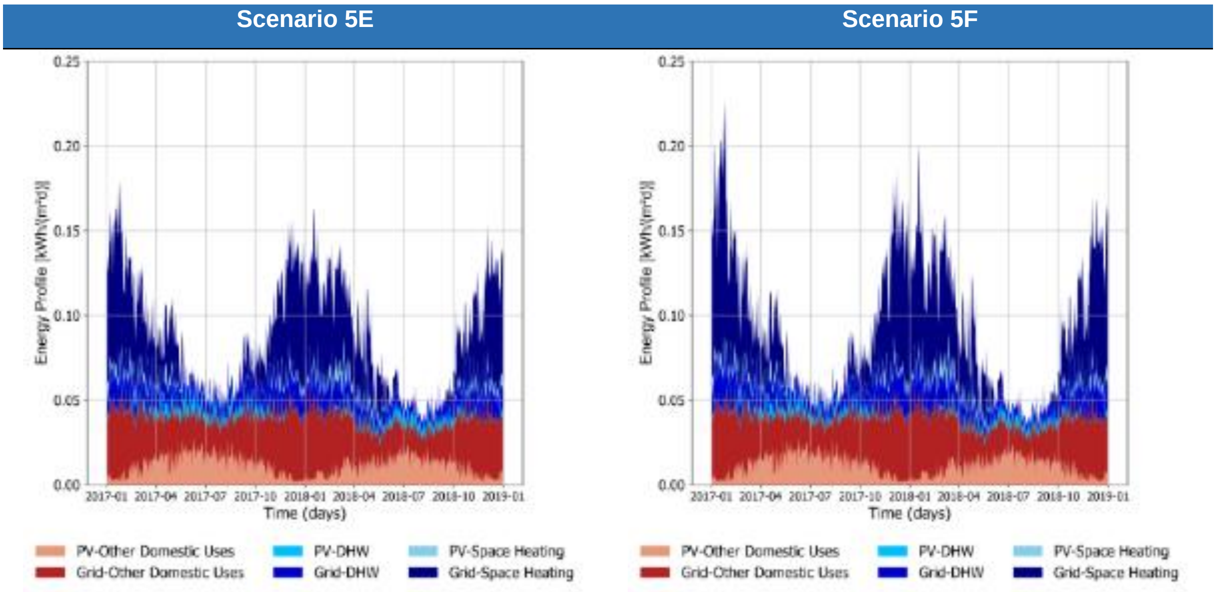


Figure 92: Energy profiles of the different scenarios; CS 5.

Table 36: Annual energy consumption [kWh/m²] of the scenarios; CS5.

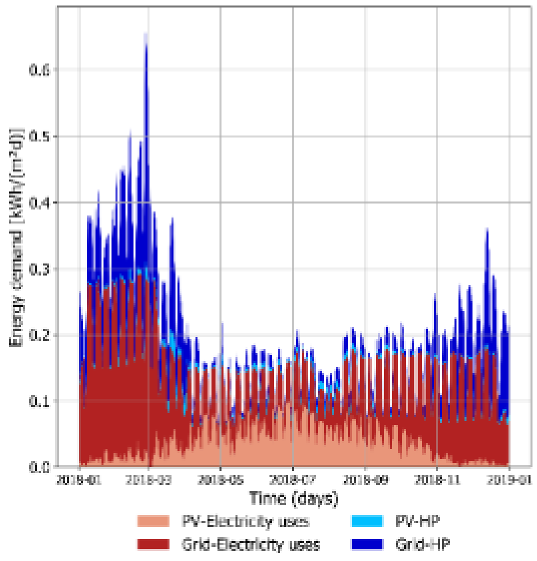
	Scenario 5B		Scenario 5C		Scenario 5D		Scenario 5E				Scenario 5F			
	2017	2018	2017	2018	2017	2018	2017		2018		2017		2018	
Electricity from grid	9.70	8.85	33.56	31.2	35.25	32.73	26.20		24.60		28.10		26.20	
PV electricity	5.74	5.14					7.30		6.60		7.15		6.50	
							PV	**Grid**	**PV**	**Grid**	**PV**	**Grid**	**PV**	**Grid**
Heat pump for space heating and DHW			11.90	11.90	13.50	13.33	1.04	10.8	1.21	10.7	1.05	12.5	1.24	12.1
Other Domestic Uses	15.1	14.0	15.42	14.00	15.42	14	4.5	10.92	4.00	10.00	4.50	10.92	4.00	10.00
DHW			6.24	5.30	6.33	5.40	1.74	4.5	1.40	3.90	1.61	4.72	1.30	4.10

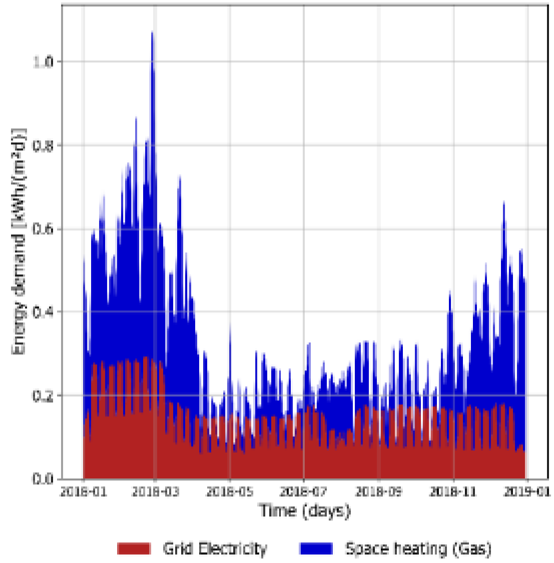
Case study 6

For the last case study, which corresponds to an office building, five more theoretical scenarios were considered as well, including using natural gas as an energy carrier for space heating, and different combinations using a heat pump and a PV installation. The annual consumption and the energy profiles of the different scenarios are presented in Table 37 and Figure 93, respectively. For the CS6B scenario the heat pump is substituted by natural gas, while the electricity uses are covered by the grid. As far as the CS6C scenario is concerned, the heating needs are covered by natural gas and a PV installation partially covers the needs for the electricity uses of the building, with a share of 28% on the total electricity needs, see Table 37.

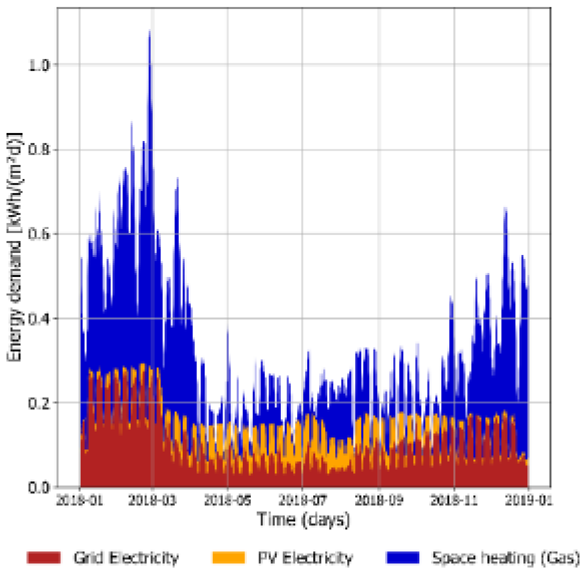
Concerning the scenarios CS6D and CS6E, they include a heat pump with a constant and variable COP, respectively and the needed electricity of the building is covered by the electricity from grid. Between, these two scenarios, the one with the variable COP, presents relatively higher energy needs, i.e. 19% than the one with the constant COP. Finally, the scenario 6F includes a PV installation with a constant COP heat pump. The PV consumption is proportionally allocated to the energy needs of the building. The electricity from the PV installation covers 22% of the total electricity needs of the building, i.e. heat pump and other electricity uses. For all scenarios, the energy needs present an intermittent profile because of the significant shift in energy use between working/off hours.

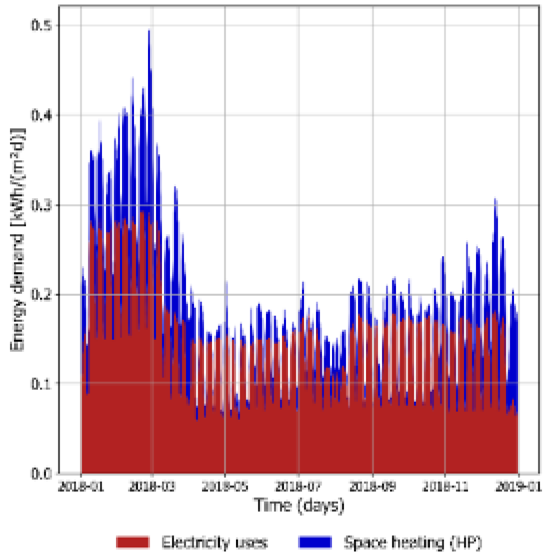
Reference Scenario	Scenario 6B





Scenario 6C	Scenario 6D





Scenario 6E	Scenario 6F

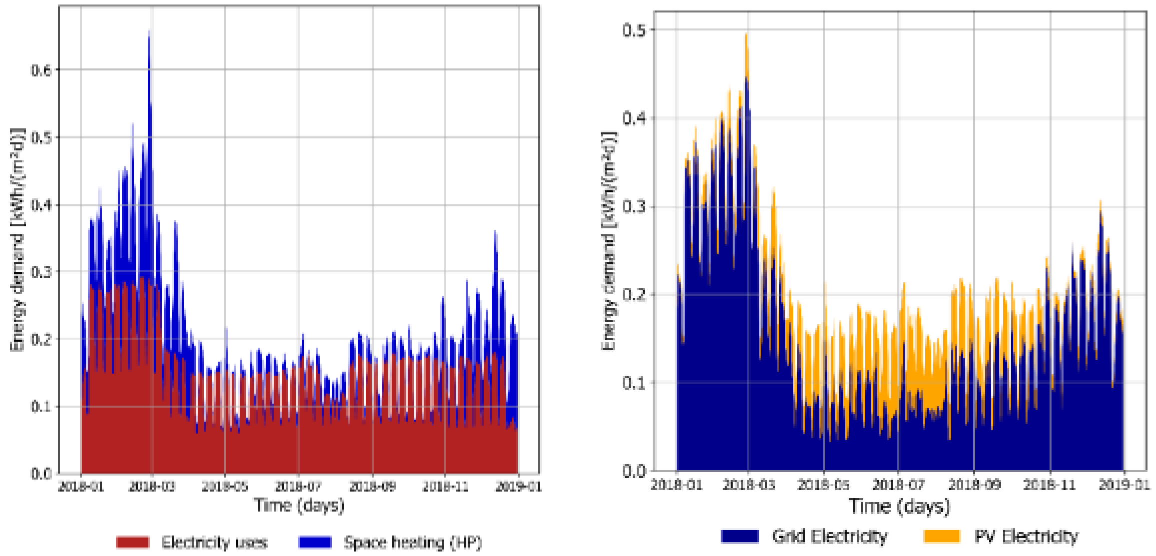


Figure 93: Energy profiles of the different scenarios; Case study 6.

Table 37: Annual energy consumption [kWh/m^2] of the scenarios; CS5.

Energy consumption [kWh/m^{2}y]	Scenario 6B	Scenario 6C	Scenario 6D	Scenario 6E	Scenario 6F
	2018	2018	2018	2018	2018
Other Electricity Uses	54.45	39.40	54.44	54.44	54.44
Natural gas	68.62	68.62			
Heat Pump			18.10	21.53	18.10
PV consumption		15.05			15.89

Annex 4: Environmental impacts of the case studies

The following section presents the results of the environmental impacts of the different case studies, under a daily time step, as well as their profile.

Environmental profiles of case studies 1 – 4

a) Case Study 1 – With and without PV

Two scenarios are considered, i.e. with and without PV installation. Produced PV electricity is partially consumed on site and partially injected to the grid (see Table 32). The electricity consumed on site is distributed proportionally to the electricity needs for each one of the different uses. The environmental impacts of the grid electricity for the different time resolutions were calculated and presented in the first part of WP4. Thus, taking into account the energy consumption of the building and the environmental impacts of the different energy carriers, the total impacts of the energy consumption of the building was calculated, using a script written in R. Table 38 shows the annual impacts of both scenarios, for all the different indicators and uses, under a daily time step calculation. For the scenario without the PV, the highest impact come from the electricity of the other domestic uses, for all the indicators. As far as te scenario with PV is concerned, the highest impact comes from the electricity of the space heating. This is the case for all indicators. Comparing the two scenarios, the one with the PV installation has approximately 10% lower GHGe than without the PV. For the other indicators, i.e. the NRE, RE and UBP, this percentage is approximately 17%, 28% and 11%, respectively. In total, the PV electricity covers approximately 30% of the energy needs of the building, which correspond to almost 17% of the total GHGe, 16% of the total NRE or 19% of the total UBP.

Table 38: Environmental impacts (per m^2 of ERA) of the CS1, without PV (upper table) and with PV (lower table).

	CS1 – Without PV: Daily time step			
	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	4,164	1,2	4,33	**9,694**
NRE [MJ/(m2y)]	52,61	18,7	69,63	**140,94**
RE [MJ/(m2y)]	134,1	46,5	172,13	**352,73**
UBP [ecopoints/(m2y)]	6387,43	2053,5	7511,96	**15952,89**

	CS1 – With PV: Daily time step						
	Space heating		DHW		Other domestic uses		Sum
	Grid	PV	Grid	PV	Grid	PV	
GHG [kgCO2eq/(m2y)]	3,81	0,163	0,88	0,206	2,66	1,097	**8,816**
NRE [MJ/(m2y)]	48,125	2,07	12,81	2,6	38,25	13,84	**117,695**
RE [MJ/(m2y)]	122,46	0,36	32,05	0,45	95,41	2,4	**253,13**
UBP [ecopoints/(m2y)]	5843,99	296,7	1451,25	374,27	4339,37	1992,62	**14298,2**

b) Case Study 2 – With and without PV

The second case study was studied for the two alternatives, as before, i.e. with and without PV. As it was the case for the previous scenario, the electricity produced on site is proportionally allocated to the electricity needs of the different uses, while part of the produced electricity is reinjected back to the grid. The results of the analysis are presented in Table 39, under a daily time step. For this case study, when no PV installation is taken into account, the highest impacts for the GHGe come from the electricity for the DHW, which correspond to 47% of the total environmental impacts. As far as the other indicators are concerned, this percentage is approximately 45%. For the scenario with the PV installation, the highest share on the total GHGe comes also from the electricity consumed for the DHW and it remains almost the same (45% of the total GHGe). Comparing the two scenarios, the scenario with the PV installation presents approximately 6% lower GHGe than the one without the PV. The PV benefit is approximately, 10%, 17% and 7%, for the NRE, RE and UBP, respectively. In total, the PV electricity covers almost 17% of the energy needs of the building, which correspond to approximately 9%, for the GHGe and the NRE, and 10% for the UBP indicator.

Table 39: Environmental impacts (per m^2 of ERA) of the CS1, without PV (lower table) and withPV (upper table).

	Daily time step			
	HP	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	3,01	5,3	3,14	**11,45**
NRE [MJ/(m2y)]	38,55	69,14	48,44	**156,13**
RE [MJ/(m2y)]	97,47	175,61	120,63	**393,71**
UBP [ecopoints/(m2y)]	4643,51	8283,37	5338,55	**18265,43**

	Daily time step						
	Space heating		DHW		Other domestic uses		
	Grid	PV	Grid	PV	Grid	PV	Sum
GHG [kgCO2eq/(m2y)]	2,77	0,12	4,9	0,23	2,18	0,6	**10,8**
NRE [MJ/(m2y)]	35,18	1,5	62,79	2,86	31,31	7,45	**141,09**
RE [MJ/(m2y)]	88,9	0,26	158,97	0,5	78,4	1,3	**328,33**
UBP [ecopoints/(m2y)]	4253,53	215,57	7531,65	411,74	3564,46	1073,13	**17050,08**

Figure 94 shows the GHGe under a daily time step for the CS2, without PV. It can be noticed that the impacts of the heat pump and the DHW follow the energy consumption profile. There is a pronounced intra-annual seasonality, with lower impacts during the summer months and higher impacts during the winter months. There is also a moderate inter-annually seasonality. The slightly lower GHGe of 2018 is explained by the fact that during this year, the electricity imports diminished and consequently the GHGe (less imports imply a lower GHGe impact). In addition, there is an intra-annual seasonality of the electricity impacts for the other domestic uses. As already mentioned, this behavior can be explained by the lower imports of electricity in summer and consequently lower GHGe.

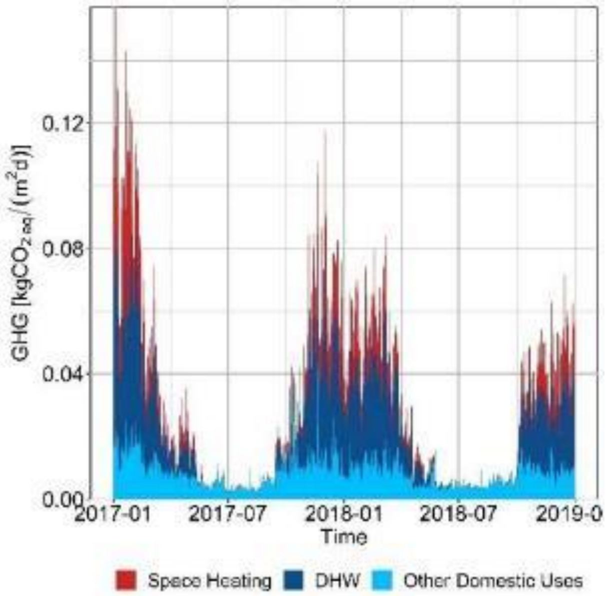


Figure 94: GHG emissions of the CS2 without PV.

Figure 95 shows the GHGe of the scenario with the PV installation. The GHGe of the grid electricity have the same profile as the one for the case without the PV installation. Concerning the PV impacts, they follow the energy production profile of the PV electricity and consequently they show an intra-annual seasonality, with higher impacts during summer and lower impacts in the winter period. There are three peaks of the GHGe (two positives and one negative), all observed in summer. The positive peaks correspond to an increased electricity production, due to a high solar radiance (see Figure 18), while the negative one corresponds probably to an error of the measurement system.

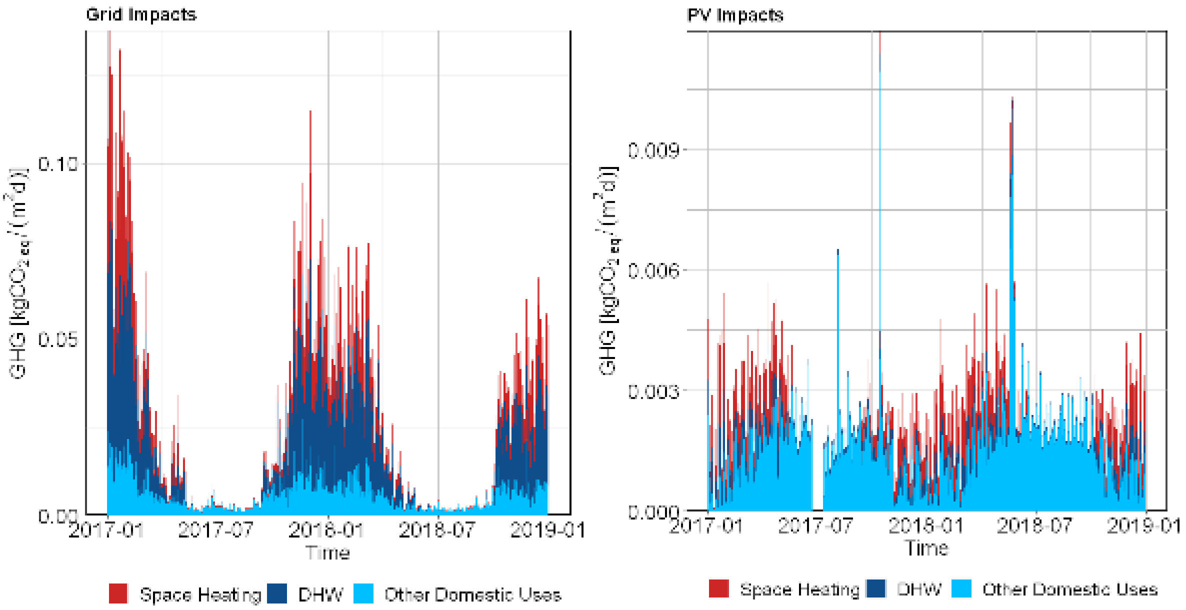


Figure 95: GHG emissions of the CS2 with PV.

c) Case Study 3 – With and without PV

The GHGe of the third case study under a daily profile are presented in Table 40. For this case study and the scenario without the PV installation, the electricity of the other domestic uses presents the highest GHG impacts on the total GHGe of the building (approximately 58%). Comparing this scenario to the scenario with the PV installation, the latter presents approximately 5% lower GHGe for the daily time step. As far as the other indicators are concerned, this difference is approximately 24% and 5% for the RE and the UBP indicator, while no particular benefit can be observed for the NRE indicator. For the scenario with PV installation, the impacts of the grid electricity for the other domestic uses correspond approximately to 45% of the total GHGe, while the electricity produced on site correspond approximately to 13%. In total, the PV electricity covers almost 25% of the energy needs of the building, which correspond to approximately 19%, 17% and 20% of the GHGe, NRE and UBP, respectively.

Table 40: Environmental impacts (per m^2 of ERA) of the CS3, without PV (upper table) and with PV (lower table).

	Daily time step			
	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	4,59	2,48	9,7	**16,77**
NRE [MJ/(m2y)]	59,44	38,62	125,27	**223,33**
RE [MJ/(m2y)]	152,27	96,24	373,14	**621,65**
UBP [ecopoints/(m2y)]	7176,68	4241,4	16459,56	**27877,64**

	Daily time step						
	Space heating		DHW		Other domestic uses		
	Grid	PV	Grid	PV	Grid	PV	Sum
GHG [kgCO2eq/(m2y)]	4,07	0,32	1,85	0,53	7,2	2,1	**16,07**
NRE [MJ/(m2y)]	52,7	4,06	27,1	6,7	106,5	26,4	**223,46**
RE [MJ/(m2y)]	134,86	0,7	67,9	1,16	262,89	4,57	**472,08**
UBP [ecopoints/(m2y)]	6365,22	583,3	3032,32	965,37	11841	3793,44	**26580,65**

Figure 96 presents the daily profile of the GHGe of the building. The GHGe of the electricity for the heat space heating follows the energy consumption profile, with a high intra-annual seasonality. The GHGe of the DHW and the electricity for the other domestic uses, follow a seasonal profile unlike that of the energy consumption. As already explained, this difference come from the fact that during the summer months the GHGe of the grid electricity are lower, due to the reduced electricity imports (mainly from Germany). In addition, there is an inter-annual seasonality, concerning the GHGe of the space heating. This is explained by the fact that in 2018, the electricity imports diminished and consequently the GHGe (less imports imply a lower GHGe impact). Figure 97 presents the GHGe of the scenario with the PV installation. The grid electricity impacts do not present any particular difference from the scenario without the PV installation. As far as the GHGe of the PV installation, they follow the electricity production (see Figure 18), with an intra-annual seasonality, due to the increased solar radiation of the summer months. The highest part of the GHGe for both scenarios, come from the electricity for the other domestic uses, as already explained.

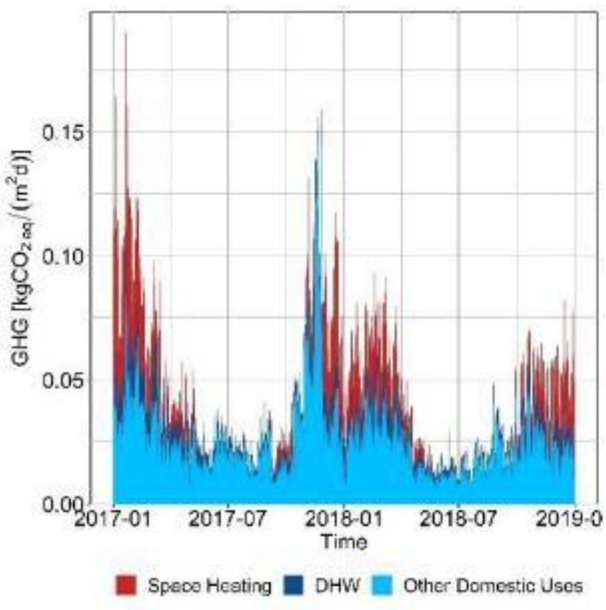


Figure 96: GHG emissions of the CS3 without PV.

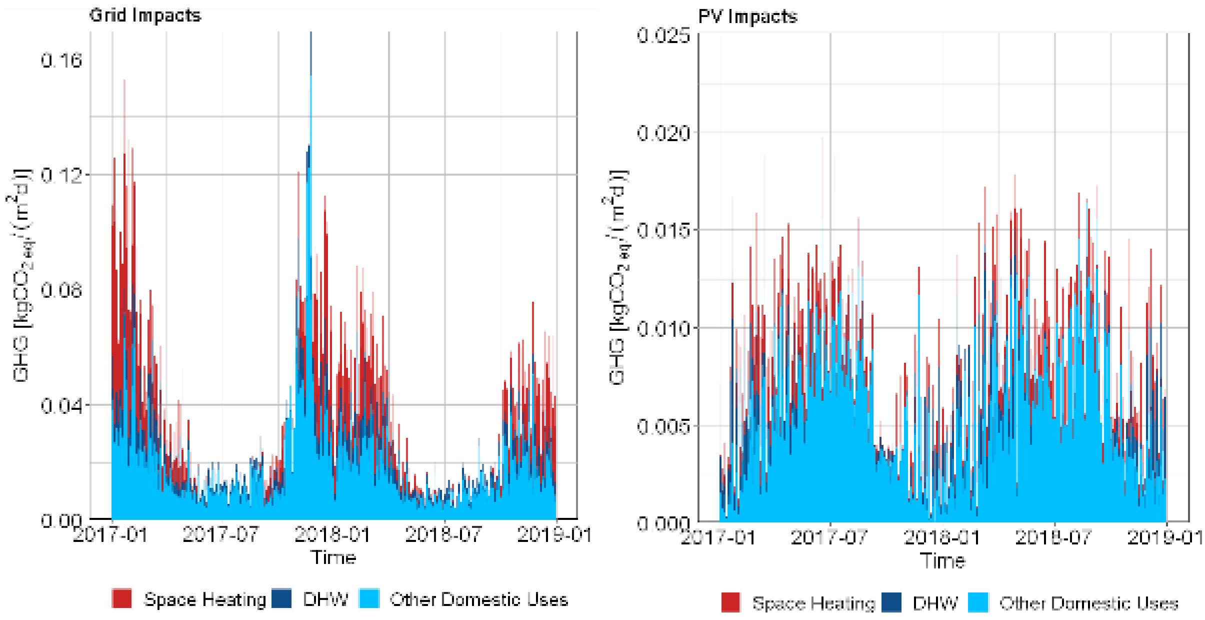


Figure 97: GHG emissions of the CS3 with PV.

d) Case Study 4 – With and Without PV

The same scenarios were studied for the fourth case study, too. Table 41 presents the GHGe under a daily time step for the two scenarios. For this case study and the scenario without the PV installation, the electricity for the space heating contributes the most to the total building impacts, with a share of approximately 50%, for all the indicators. For the scenario with the PV installation, approximately 25% of the electricity needs are covered by the electricity produced on site, which accounts for approximately 20% of the total impacts for all the indicators. Comparing the two scenarios, the total GHGe are approximately 3% lower for the case with the PV installation. As far as the other indicators are concerned this difference is approximately 9% and 3% for the NRE and UBP respectively.

Table 41: Environmental impacts (per m^2 of ERA) of the CS4, without PV (upper table) and withPV (lower table).

	Daily time step			
	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	5,8	2,4	2,51	**10,71**
NRE [MJ/(m2y)]	76,1	36,82	37,93	**150,85**
RE [MJ/(m2y)]	192,63	91,6	93,5	**377,73**
UBP [ecopoints/(m2y)]	9054,88	4051,14	4164,85	**17270,87**

	Daily time step						
	Space heating		DHW		Other domestic uses		
	Grid	PV	Grid	PV	Grid	PV	Sum
GHG [kgCO2eq/(m2y)]	5,1	0,54	1,57	0,75	1,66	0,77	**10,39**
NRE [MJ/(m2y)]	66,27	6,74	22,62	9,5	23,32	9,75	**138,2**
RE [MJ/(m2y)]	167,54	1,17	56,75	1,65	57,83	1,69	**286,63**
UBP [ecopoints/(m2y)]	7911,46	971,24	2571,58	1367,63	2649,38	1403,1	**16874,39**

Figure 98 shows the GHGe, of the CS4, without the PV installation, under a daily time step. As already mentioned, the highest share of the GHGe, come from the electricity of the space heating. Its profile follows the energy consumption profile, i.e. intra-annual fluctuation, with high seasonality. The GHGe of the other usages do not follow the energy consumption profile and they show an intra-annual fluctuation, which is less pronounced than that of the GHGe of the space heating. It should be noticed that there is a pronounced inter-annual fluctuation of the GHGe, as far as the electricity for the space heating is concerned. As already mentioned, this is explained by the fact that in 2018, the electricity imports diminished and consequently the GHGe (less imports imply a lower GHGe impact). Figure 99 shows the GHGe for the scenario with the PV installation. The GHGe of the electricity coming from the grid, are similar with the scenario without the PV. The GHGe of the PV installation follow the electricity production of the PV and thus they show a high intra-annual seasonality, i.e. higher impacts during the summer months and lower impacts during the winter period.

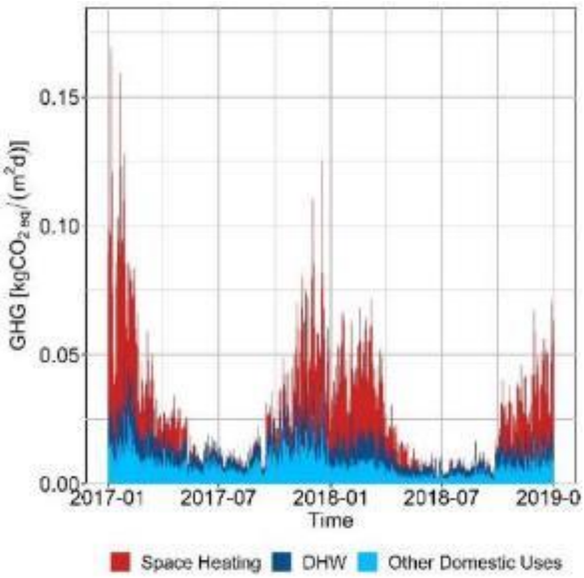


Figure 98: GHG emissions of the CS4 without PV.

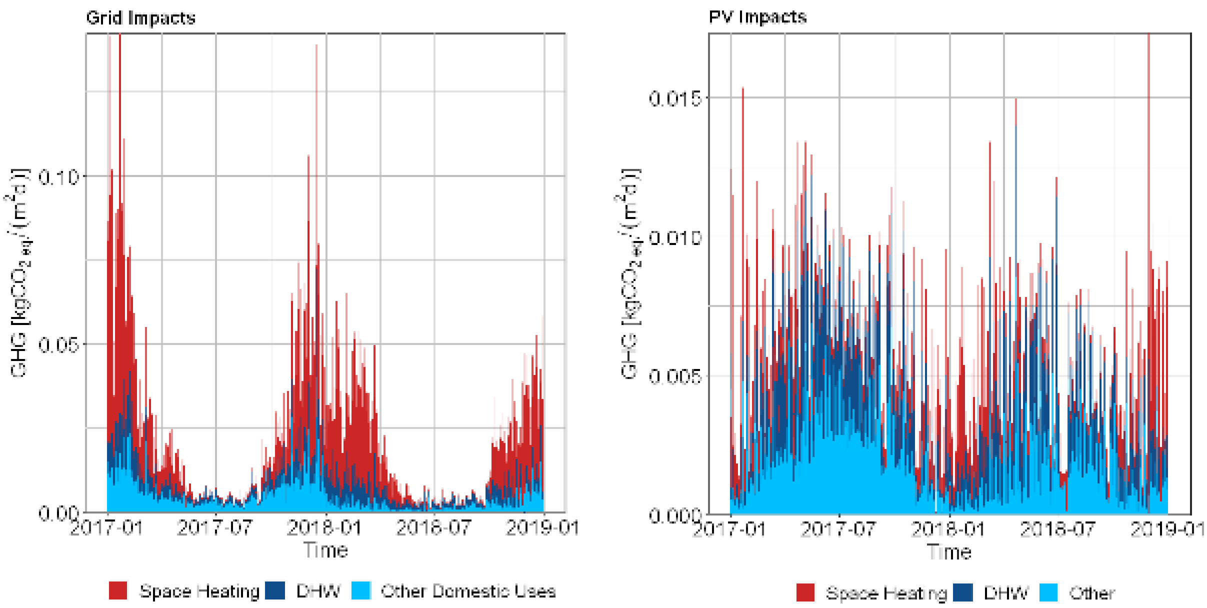


Figure 99: GHG emissions of the CS4 with PV.

Environmental profiles of CS5

a) Reference scenario

Concerning the reference scenario, the energy carrier for the heating needs and the DHW are covered by district heating and for the other domestic uses by the grid electricity. The Ecoinvent database v3.4 was used for the environmental impact of the district heating, which corresponds to a mean value of different energy sources (94% of waste heating). Taking into account the energy consumption of the building and the environmental impacts of the different energy carriers, the total impacts of the energy consumption of the building was calculated, using a script written in Python.

Table 42 presents the annual results of the two years period, for the daily aggregation of the environmental impacts of the grid electricity profile. For the GHGe, NRE and UBP indicators, the impacts of the space heating represent the highest share of the total building impacts, e.g. 57% for the GHGe. As far as the RE indicator is concerned, the electricity of the other domestic uses represents approximately 96% for total environmental impacts. This trend can be explained by the fact that the grid electricity uses a significant share of renewable energy sources compared to the other non-electricity covered needs.

Table 42: Environmental impacts (per m^2 of ERA) of the reference scenario of CS5.

	Daily time step			
	Other Domestic Uses	DHW	Space Heating	Sum
GHG [kgCO2eq/(m2y)]	2.3	4.34	8.95	**15.59**
NRE [MJ/(m2y)]	87.95	73.48	151.39	**312.82**
RE [MJ/(m2y)]	35.73	0.49	1	**37.22**
UBP [ecopoints/(m2y)]	3895.89	2657.03	5474.14	**12027.06**

The environmental impact profiles on a daily basis, for the examined period are presented in Figure 100. For the GHGe, NRE and UBP indicators, the impacts of the heating needs and the DHW follow the energy consumption of the building, see Figure 19. The impacts of the heating needs exhibit high seasonality, due to the energy peaks of the winter period. This is valid for both of the years in question. Concerning, the impacts of the DHW, they remain relatively stable intra- and inter -annually, not only because of the stable trend of the energy profile, but also because of the constant environmental impacts of the district heating throughout the examined period. On the contrary, this is not the case for the impacts of the other domestic uses, for which the energy profile follows a relatively stable trend, as well. The grid electricity impacts fluctuate inter- and intra- annually. During the summer period, the electricity imports, which are responsible for the highest share of the environmental impact of the Swiss grid electricity, diminish and thus the impacts of the other domestic uses diminish, as well. In addition, in 2018, the grid electricity imports diminished, because of the higher nuclear production in Switzerland, which results in inter-annual fluctuation of the electricity for the other domestic uses. This fluctuation of the other domestic uses is more prominent for the GHGe and UBP indicators, while it is not the case for the NRE and RE. As far as the RE indicator is concerned, it is mainly the impacts of the other domestic uses that represent the highest share on the total impacts of the building, because of the used renewable energy sources for the grid electricity.

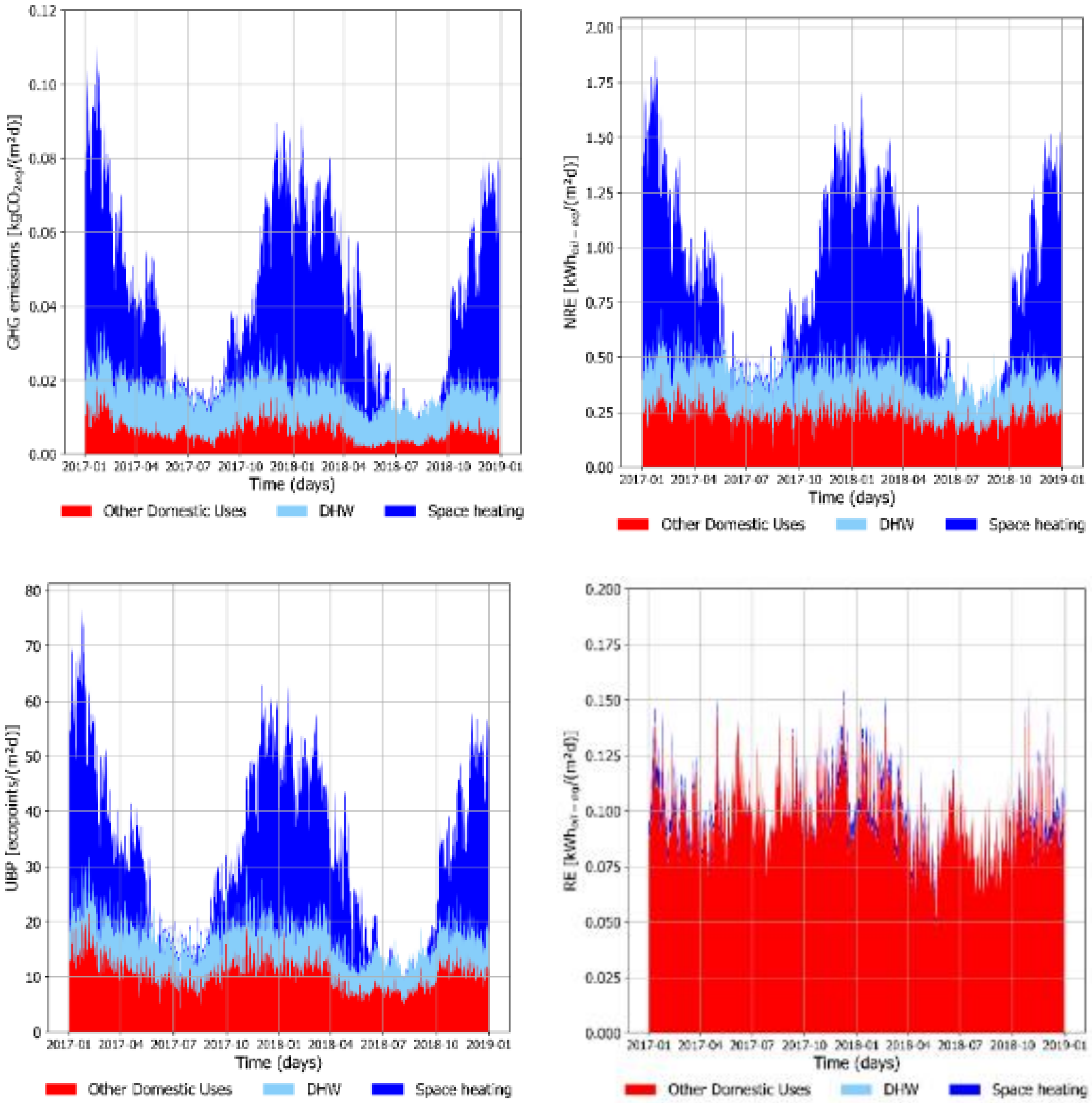


Figure 100: Environmental impacts of total energy consumption of CS5, evaluated by GHGe, NRE, RE and UBP indicators.

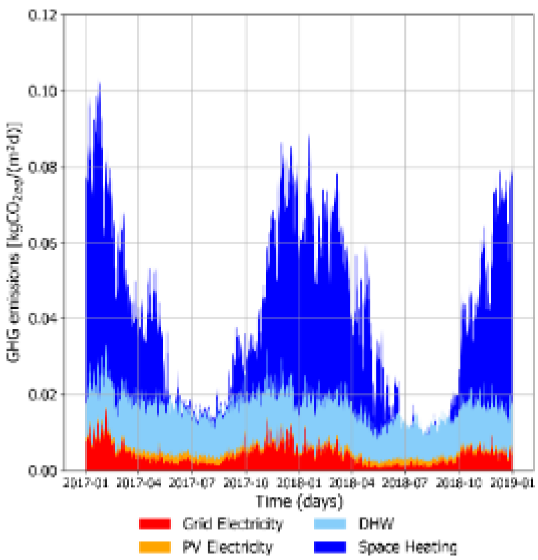
b) CS5B

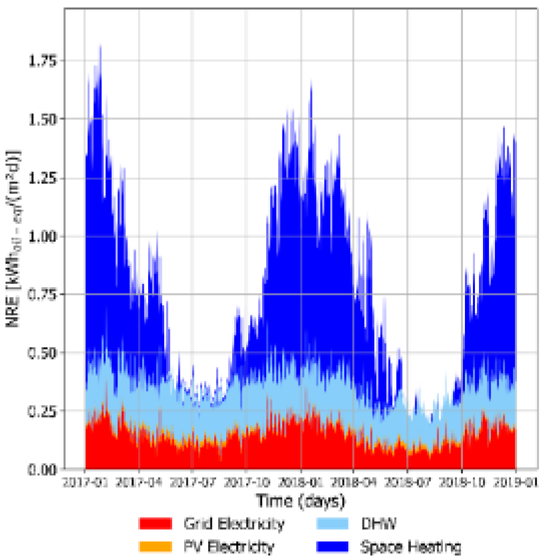
This scenario includes the same system configuration, like the reference scenario, with an additional PV installation. . The total PV electricity production is used on site and no injection to the grid is planned. The environmental impacts of the PV installation and its electricity production are calculated following the methodology, presented in chapter 2. The total environmental impacts on annual basis for the daily aggregation of the grid environmental impacts are presented in Table 43. The PV electricity impacts of the GHGe represent 23% of the electricity impacts and 3% of the total building impact. As far as the NRE and UBP are concerned, the PV electricity impacts represents 2% and 7% of the total impacts respectively. Comparing this scenario with the reference one, the environmental gain is approximately 2% because of the PV installation, for the GHGe. As far as the NRE and the UBP are concerned, this gain is 8% and 5%, respectively.

Figure 101 presents the daily environmental impact of this scenario for the two examined years. As far as the heating needs and the DHW, the environmental impacts follow the energy consumption profile, i.e. high seasonality of the impacts of the heating needs and stable profile for the DHW. The impacts of the other domestic uses, covered by the electricity grid, follow a seasonal trend, i.e. higher impacts during the winter period and lower impacts during the summer period, for both examined years. This fact is explained by the seasonality of the impacts of the grid electricity, due to the reduced imports in summer, (mainly from Germany that uses non-renewable sources of energy) and the PV installation that partially covers the electricity needs in summer. Furthermore, , the PV impacts follow a seasonal profile and are linked mainly to the summer months, since more electricity is produced, as it is shown in the GHGe, NRE and UBP indicator. The impact of the PV installation, is more pronounced for the case of the RE indicator, since this indicator shows the part of impacts coming from renewable energy sources.

Table 43: Environmental impacts (per m^2 of ERA) of the CS5B scenario.

	Daily step time step				
	Other domestic uses		Space heating	DHW	Sum
	PV	Grid			
GHG [kgCO2eq/(m2y)]	0.45	1.52	8.95	4.34	**15,26**
NRE [MJ/(m2y)]	5.94	55.46	151.38	73.48	**286,26**
RE [MJ/(m2y)]	24.06	22.42	1	0.49	**47,97**
UBP [ecopoints/(m2y)]	839.54	2503.77	5474.14	2657.029	**11474,48**





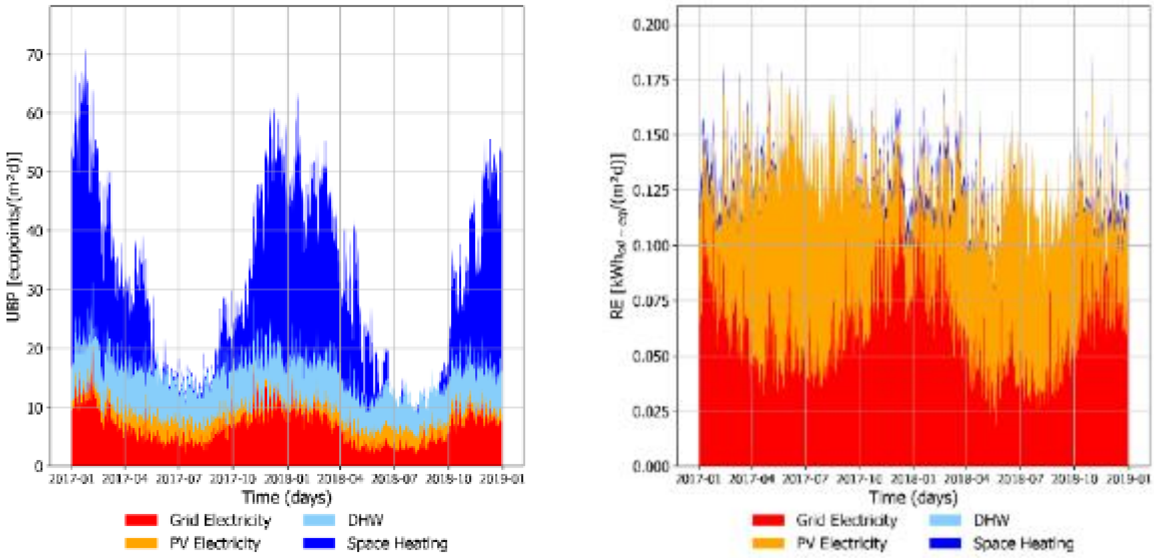


Figure 101: Environmental impacts of total energy consumption of Case study 5B, evaluated by GHGe, NRE, RE and UBP indicators.

c) CS5C

In the following scenario, a heat pump was considered for the space heating and the DHW. A constant COP was defined as the average of the variable COP, calculated using the methodology in chapter 2. Table 44 presents the total annual environmental impacts, for the the daily aggregation of the impact data. The space heating is responsible for 45% of the GHGe, while for the case of the NRE and the UBP indicator, the highest share comes from the electricity for the other domestic uses, with a share of 41% and 45% respectively. Comparing this scenario with the reference one (district heating), it can be concluded that the heat pump solution presents 60% less GHGe. As far as the NRE and the UBP are concerned, this gain is approximately 40% and 30% respectively.

Table 44: Environmental impacts (per m^2 of ERA) of the CS5C scenario.

	Daily time step			
	Other Domestic Uses	DHW	Space Heating	Sum
GHG [kgCO2eq/(m2y)]	2.3	1.3	2.95	**6.55**
NRE [MJ/(m2y)]	87.95	34.56	72.02	**194.53**
RE [MJ/(m2y)]	35.73	13.99	28.22	**77.94**
UBP [ecopoints/(m2y)]	3895.89	1745.60	3803.48	**9444.80**

Figure 102 presents the daily profile of the environmental impacts for this scenario. The electricity impacts of the space heating follow the energy profile (see Figure 92). An intra-annual seasonality is observed, i.e. higher impacts during the winter period, because of the increased heating needs and consequently the increased electricity imports from the neighboring countries, mainly from Germany. In addition, the impact profile of the other domestic uses shows a seasonal trend as well, because of the electricity imports, during the winter. This tendency is more pronounced for the GHGe and the UBP indicators, while for the NRE indicator, the profile for the other domestic uses is relatively stable. Concerning the profile of the DHW, it is relatively stable throughout the year, for all the indicators.

Furthermore, there is an inter-annual seasonality, exhibited by all the four indicators, while it is more pronounced for the GHGe. Lower impacts are observed for the winter and the summer period of the year 2018.

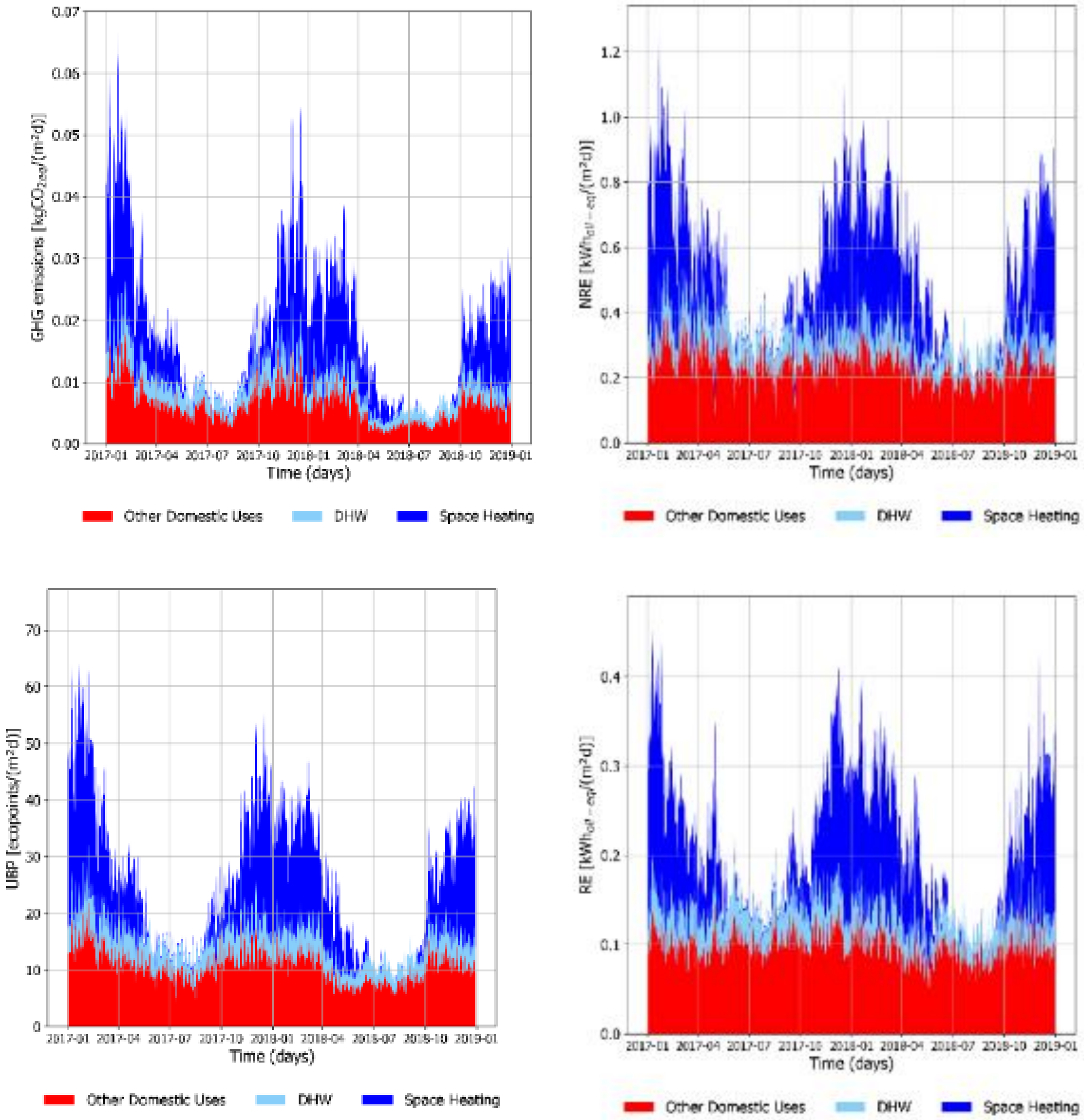


Figure 102: Environmental impacts of total energy consumption of Case study 5C, evaluated by GHGe, NRE, RE and UBP indicators.

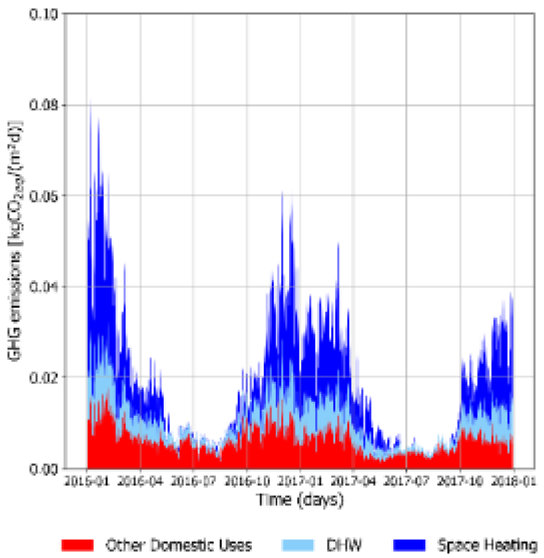
d) CS5D

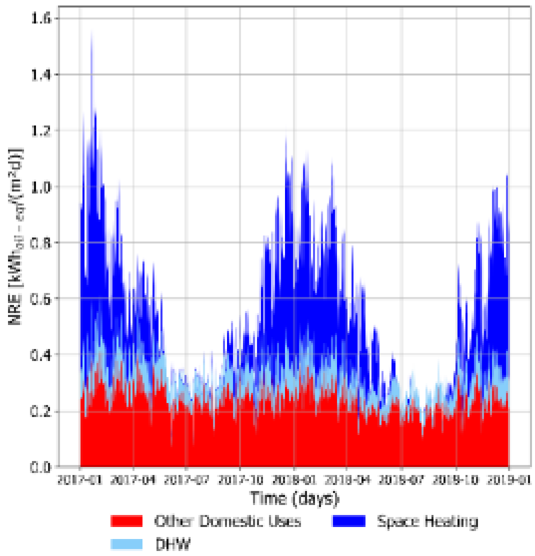
In this scenario, a variable hourly COP is considered for the heat pump, while all the other assumptions remain the same as in the scenario CS5C. Table 45 summarizes the total annual impacts for the daily aggregation environmental impacts. As expected, by considering a variable COP for the heat pump, the environmental impacts slightly increase. By comparing this scenario with the previous one (constant COP), the variable COP is responsible for a 5% increase of the total GHGe for the case of the daily step. More specifically, separately for the space heating, there is a 10%, for the GHGe. As far as the total NRE and UBP are concerned, there is a 5% increase because of the variable COP.

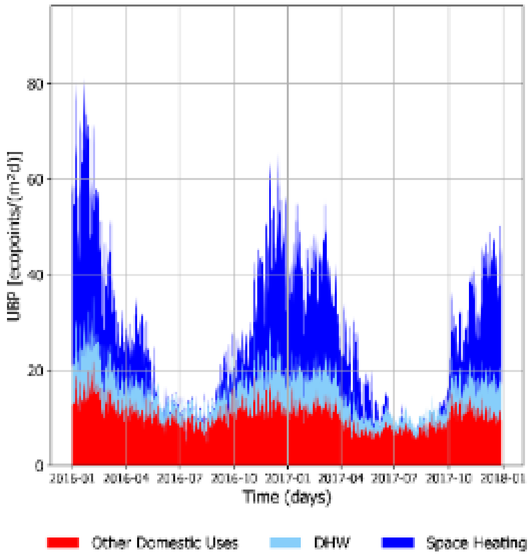
Table 45: Environmental impacts (per m^2 of ERA) of the CS5D scenario.

	Daily time step			
	Other Domestic Uses	DHW	Space Heating	Sum
GHG [kgCO2eq/(m2y)]	2.3	1.34	3.25	**6.89**
NRE [MJ/(m2y)]	87.95	35.3	81.4	**204.65**
RE [MJ/(m2y)]	35.73	14.2	31.92	**81.85**
UBP [ecopoints/(m2y)]	3895.89	2015.89	4257.56	**10169.34**

Figure 103 presents the daily impact profile of this scenario. The GHGe of the space heating and the other domestic uses follow the energy consumption profile of the building, i.e. there is a seasonal trend, with higher impacts during the winter and lower impacts during the summer months. It is interesting to note that for this scenario the impacts of the DHW fluctuate intra- and inter-annually. This tendency is more prominent for the GHGe and it is explained by the variable COP of the heat pump and the variable environmental impacts of the grid electricity. It is always during the summer months that the impacts are the lowest, because of the reduced electricity imports.







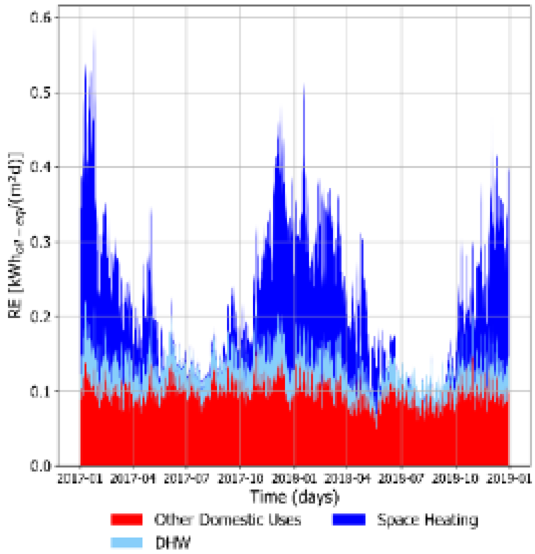


Figure 103: Environmental impacts of total energy consumption of case study 5D, evaluated by GHGe, NRE, RE and UBP indicators.

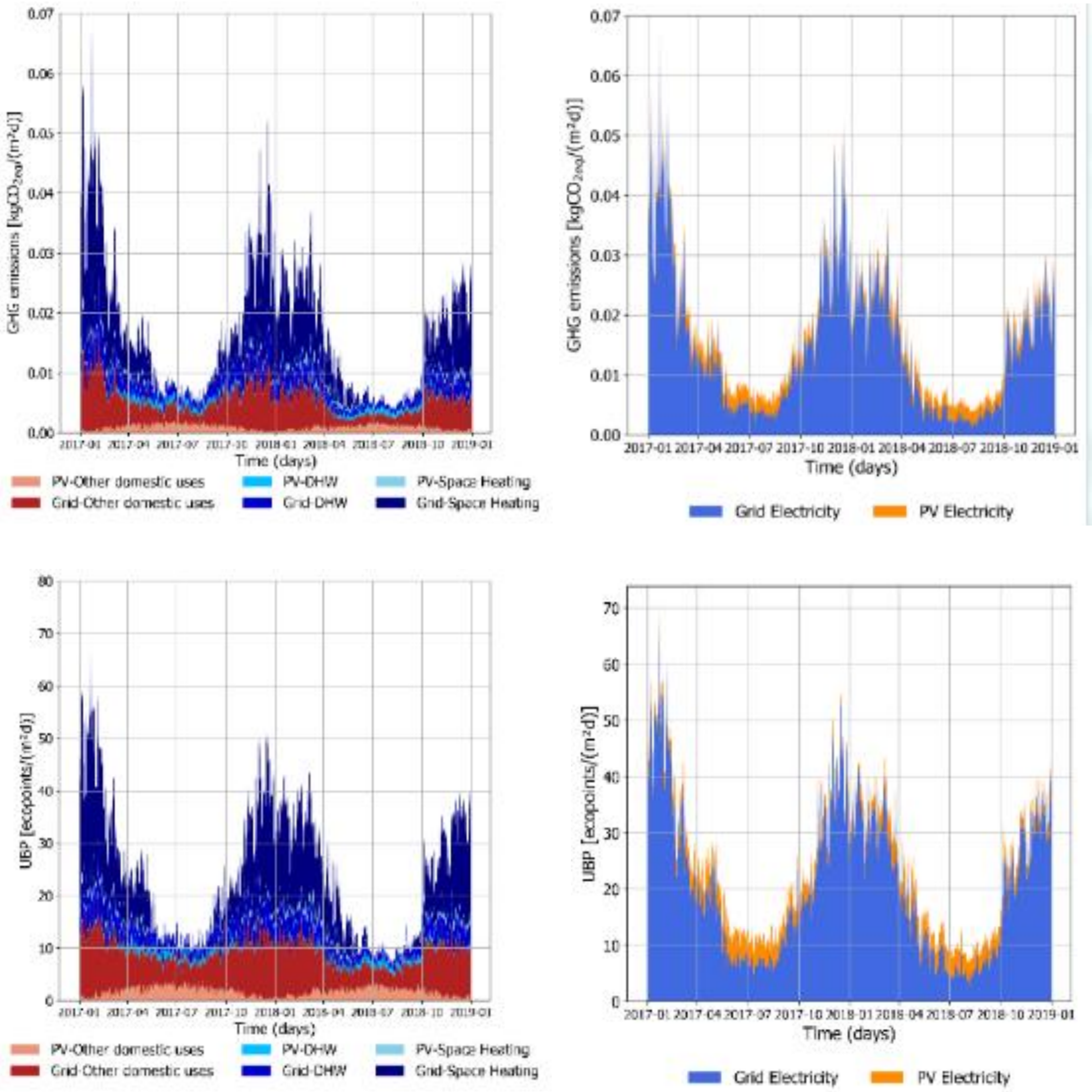
e) CS5E

The following scenario includes the same technical systems as the CS5C scenario, with an additional PV installation. Table 46 presents the total impacts of the case study, using a daily time step. The PV and the grid electricity impacts are presented separately, for the different energy uses. The PV electricity is allocated proportionally according to each one of the different uses and it covers approximately the 22% of the total electricity consumption of the building. The PV impacts represent 13% of the total GHGe of the building, while the rest are coming from the grid. For the NRE and UBP indicators the PV impacts represent 5% and 14% respectively of the building. The present configuration of the technical systems (PV and heat pump) presents the most favorable solution in terms of the environmental impacts. Comparing this scenario, with the reference one, the total GHGe impacts are 60% lower than those of the reference scenario. For the NRE and the UBP indicators these differences are less important, i.e. 18% and 8% respectively. Comparing this scenario, with CS5C scenario (that has no PV installation), there is approximately 6% gain on the total GHG, because of the PV installation. For the NRE and the UBP, this gain is approximately 18% and 8%, respectively.

Table 46: Environmental impacts (per m^2 of ERA) of the CS5E scenario.

	Daily time step								
	Grid	PV	Other Domestic Uses		DHW		Space heating		Sum
			Grid	PV	Grid	PV	Grid	PV	
GHG [kgCO2eq/(m2y)]	5.36	0.76	1.71	0.35	1.00	0.24	2.70	0.17	**6.12**
NRE [MJ/(m2y)]	153	7.6	62.65	4.65	25.16	1.74	65.17	1.24	**160.6**
RE [MJ/(m2y)]	30.7	60.96	25.31	18.78	10.12	7.00	25.56	5.00	**91.6**
UBP [ecopoints/(m2y)]	7564.6	1170.3	2827.74	654.97	1290.28	300.78	214.54	3446.58	**8734.9**

Figure 104 shows the daily environmental profiles of the four studied indicators. The impacts of all the different uses for all the indicators follow a seasonal profile, as it was the case for the previous scenarios, as well. The electricity produced by the PV installation, reduces the impacts of the electricity grid, mainly during the summer months.



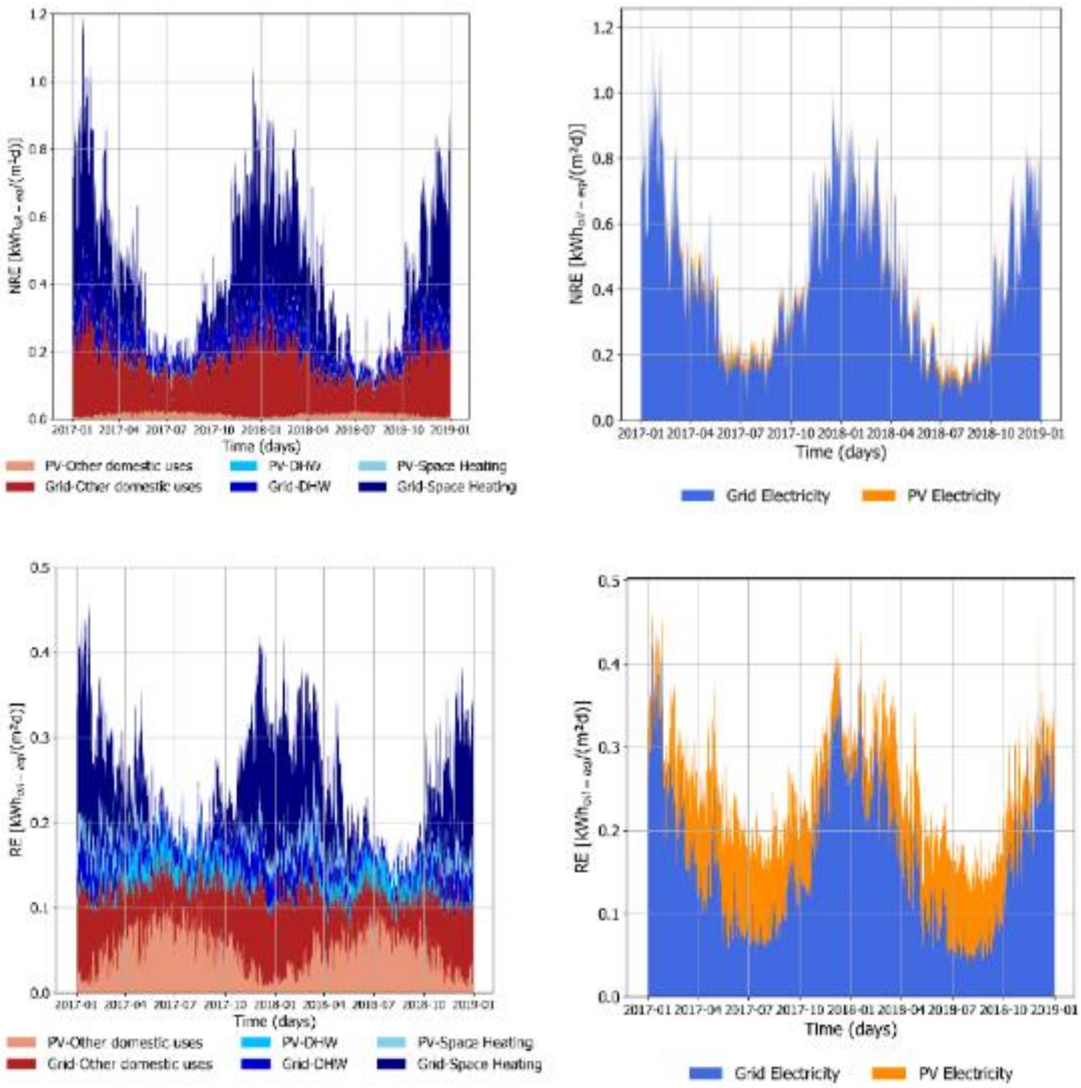


Figure 104: Environmental impacts of total energy consumption of Case study 5E, evaluated by GHGe, NRE, RE and UBP indicators.

f) CS5F

This scenario includes the same assumptions, concerning the technical systems as the CS5E, except for the fact that a variable COP is considered for the heat pump. Table 47 presents the total impacts for this scenario, for the daily time step. The PV electricity production was allocated proportionally to the energy needs for every usage, as previously. As expected the impacts are slightly higher than the case of the constant COP, i.e. approximately 6% for all the indicators. However, the solution that combines the PV and heat pump still remains the most favorable one, in terms of environmental impacts. Comparing this scenario with scenario CS5D (that has no PV installation), there is approximately 6% gain, because of the PV installation. The environmental impact profiles of this scenario exhibit similar tendency as those of the scenario CS5E.

Table 47: Environmental impacts (per m^2 of ERA) of the CS5F scenario.

	Daily time step								
	Grid	PV	Other Domestic Uses		DHW		Space heating		Sum
			Grid	PV	Grid	PV	Grid	PV	
GHG [kgCO2eq/(m2y)]	5.74	0.75	1.72	0.35	1.03	0.22	3.00	0.17	**6.47**
NRE [MJ/(m2y)]	163.62	7.51	62.68	4.63	26.52	1.61	74.42	1.26	**171.13**
RE [MJ/(m2y)]	30.24	65.16	25.31	18.75	10.64	6.43	29.1	5.1	**95.39**
UBP [ecopoints/(m2y)]	8098.2	1153.90	2830.92	654.20	1363.73	280.27	3903.58	214.91	**9247.60**

Environmental profiles of CS6

a) Reference scenario

The reference scenario includes a heat pump (variable COP) for the space heating and the DHW. The energy needs for the heat pump and the other domestic uses are covered by the grid and partially by a PV installation. The produced electricity is consumed on site and no electricity is sent back to the grid. Table 48 presents the annual energy impacts of the reference scenario, for a daily time step. The PV consumption corresponds approximately to 21% of the total energy consumption of the building and its impact to 11% of the total GHGe of the building. As far as the NRE and the UBP is concerned the PV impacts correspond approximately to 4% and 11%, of the total impacts respectively.

Table 48: Environmental impacts (per m^2 of ERA) of the reference scenario of CS6.

	Daily time step				
	Other domestic uses		Space heating & DHW (HP)		Sum
	PV	Grid	PV	Grid	
GHG [kgCO2eq/(m2y)]	0.898	5.867	0.32	4.36	**11.45**
NRE [MJ/(m2y)]	11.67	241.45	1.85	115.1	**370.07**
RE [MJ/(m2y)]	54.37	99.27	8.57	46.62	**208.83**
UBP [ecopoints/(m2y)]	1692.54	10555.37	352.1	5819.48	**18419.49**

b) CS6B

The second scenario includes natural gas as the energy carrier for space heating and the DHW, while the electricity for the other domestic uses is provided by the grid. Table 49 presents the environmental impacts on a daily time step. 70% of the total GHGe come from the space heating and the DHW, while the rest come from the electricity of the other domestic uses. As far as the other indicators are concerned, 54% and 58% come from the electricity of the other domestic uses for the NRE and the UBP, respectively.

Table 49: Environmental impacts (per m^2 of ERA) of the CS6B scenario.

	Daily time step		
	Other domestic uses	Space heating & DHW (Natural gas)	Sum
GHG [kgCO2eq/(m2y)]	7.4	16.1	**23.5**
NRE [MJ/(m2y)]	321.27	271.56	**592.83**
RE [MJ/(m2y)]	133.28	1.74	**135.02**
UBP [ecopoints/(m2y)]	13768.11	9845.22	**23613.33**

Figure 105 presents the daily profile of the GHGe for both uses. The impacts of the space heating follow the energy consumption profile, while it is not the case for the impacts of the other domestic uses. However, the intermittent trend is clearly recognizable, for both energy uses. The lower impacts during the summer months of the electricity for the other domestic uses, derive from the fact that during the summer months, the impacts of the grid electricity diminish, since the electricity imports diminish, too. As already explained, the highest percentage of the imports come from Germany, which use a high percentage of non-renewable energy sources.

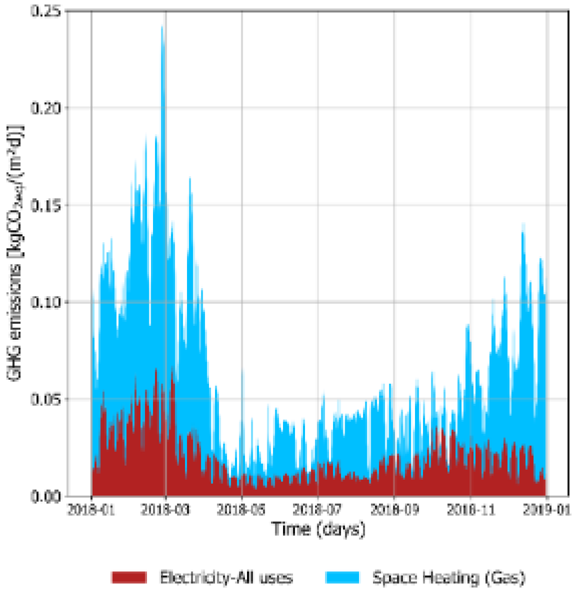


Figure 105: GHG emissions for the different uses of the CS6B scenario.

c) CS6C

The CS6C scenario includes the same technical systems as the previous scenario, with the difference that a PV installation is added. Like in the reference scenario, the produced electricity is consumed on site, with no injection to the grid. The PV electricity corresponds approximately to 17% of the electricity needs of the building and its impact to 4% of the total GHGe, see Table 50. Comparing this scenario with the previous one, i.e. with no PV installation, there is a 3% environmental gain for the GHGe, when a PV installation is considered. As far as the other indicators are concerned, the PV gain is 13% and 7% for the NRE and the UBP, respectively. Comparing this scenario with the reference one, the GHGe are 100% higher than those of the reference scenario. As far as the other indicators are concerned, this difference is 40% and 80% for the NRE and UBP, respectively. Thus, the heat pump solution with the PV installation is proved to be a better solution than the natural gas, for all the environmental indicators.

Table 50: Environmental impacts (per m^2 of ERA) of the CS6C scenario.

	Daily time step			
	Other domestic uses		Space heating & DHW (natural gas)	Sum
	Grid electricity	PV electricity		
GHG [kgCO2eq/(m2y)]	5.66	0.99	16.1	**22.75**
NRE [MJ/(m2y)]	232.94	12.9	271.56	**517.4**
RE [MJ/(m2y)]	95.79	60.1	1.74	**157.63**
UBP [ecopoints/(m2y)]	10185.52	1871.03	9845.22	**21901.77**

Figure 106 shows the daily GHGe for the different uses of the building. Concerning the space heating, no difference is to be noticed with the previous scenario. The electricity impacts of the other domestic uses do not follow the electricity consumption scenario and they present an intra-annual fluctuation, i.e. lower impacts during the summer months. This fact can be explained, by the fact that part of electricity is covered by the PV installation and that during the summer months, the electricity imports diminish and consequently the environmental impacts. In addition, the intermittent trend is obvious for both energy uses.

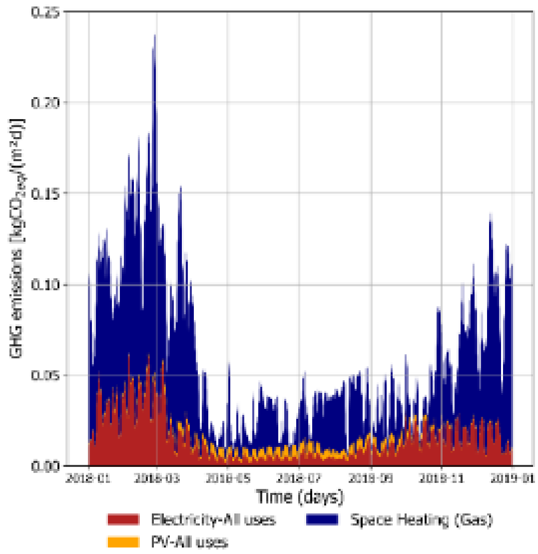


Figure 106: GHG emissions for the different uses of the CS6C scenario.

d) CS6D

This scenario includes a heat pump (constant COP) for the space heating and the DHW and all the electricity needs are covered by the grid. Table 51 includes the impacts of this scenario, using a daily time step. 40% of the GHGe of the total building come from the heat pump. Comparing this scenario with the reference one, i.e. with PV installation, there is approximately 1.5% increase of the GHGe, 16% for the NRE and 5% for the UBP indicators, because of the absence of the PV installation.

Table 51: Environmental impacts (per m^2 of ERA) of the CS6D scenario.

	Daily time step		
	Other domestic uses	Space heating & DHW (heat pump)	Sum
GHG [kgCO2eq/(m2y)]	7.4	4.2	**11.6**
NRE [MJ/(m2y)]	321.27	107.19	**428.46**
RE [MJ/(m2y)]	133.28	43.68	**176.96**
UBP [ecopoints/(m2y)]	13768.11	5466.37	**19234.48**

Figure 107 shows the GHG for the different uses, under a daily time step. The impacts of the heat pump follow the energy consumption profile. The impacts of the domestic uses show a less prominent seasonality. Both profiles present the intermittent trend exhibited because of the occupant profile. In addition, during the summer months and because of the lower electricity imports, the electricity impacts are lower than during the winter months, as already explained.

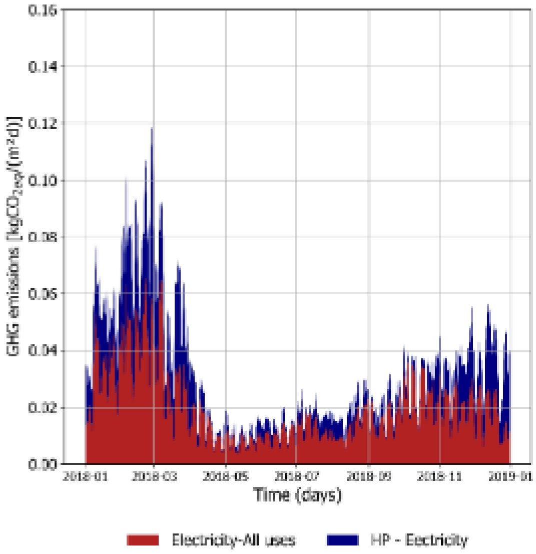


Figure 107: GHG emissions for the different uses of the CS6D scenario.

e) CS6E

This scenario includes the same technical systems as the previous scenario, with the difference that a variable COP is considered for the heat pump. Table 52 presents the total impacts of the building, under a daily time step. The GHGe of the heat pump represent again the 40% of the total GHGe of the building, as it was the case for the previous scenario. Comparing this scenario with the previous one, there is a 5% increase of the total GHGe. This small increase is due to the variable COP of the heat pump. For the NRE and the UBP, this increase is approximately 5%, as well.

Table 52: Environmental impacts (per m^2 of ERA) of the CS6E scenario.

	Daily time step		
	Other domestic uses	Space heating & DHW (heat pump)	Sum
GHG [kgCO2eq/(m2y)]	7.4	4.8	**12.2**
NRE [MJ/(m2y)]	321.27	127.75	**449.02**
RE [MJ/(m2y)]	133.28	51.84	**185.12**
UBP [ecopoints/(m2y)]	13768.11	6433.1	**20201.21**

Figure 108 shows the GHGe of all the different uses. As it was the case for the previous scenario, the impacts of the heat pump electricity follow the energy consumption profile and they are slightly higher because of the variable COP of the heat pump. The impacts of the other domestic uses have the same profile as in the previous scenario.

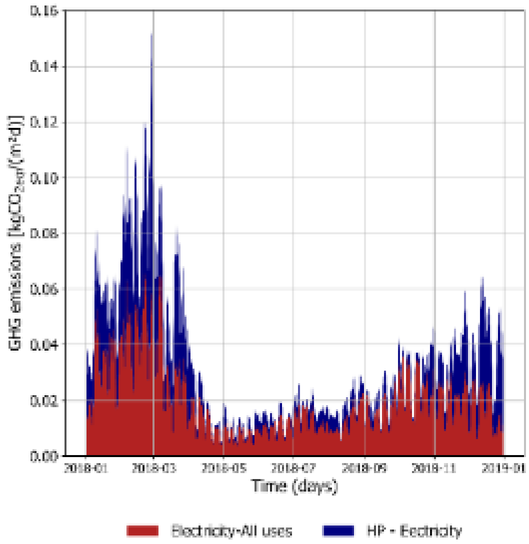


Figure 108: GHG emissions for the different uses of the CS6E scenario.

f) CS6F

This last scenario includes the same technical system as the reference scenario, with the difference that the heat pump is considered with a constant COP. Table 53 shows the impacts for all the different indicators, under a daily time step. Comparing this scenario with the reference one, it can be noticed that the heat pump with a variable COP presents 6% higher GHGe, NRE and UBP total impacts. The GHGe of the heat pump with a constant COP are approximately 15% lower than those with a variable COP. For the NRE and the UBP indicators, the constant COP results to a 18% and 17% lower impacts, respectively.

Table 53: Environmental impacts (per m^2 of ERA) of the CS6F scenario.

	Daily time step				
	Other domestic uses		Space heating & DHW (HP)		
	PV	Grid	PV	Grid	Sum
GHG [kgCO2eq/(m2y)]	0.9	5.85	0.336	3.72	**10.81**
NRE [MJ/(m2y)]	11.68	241.34	1.94	93.9	**348.86**
RE [MJ/(m2y)]	54.42	99.26	9.01	38.15	**200.84**
UBP [ecopoints/(m2y)]	1694.12	10546.71	371.1	4819.7	**17431.63**

Figure 109 presents the daily GHGe of the different uses. No difference can be noticed between this profile and the one for the reference scenarios.

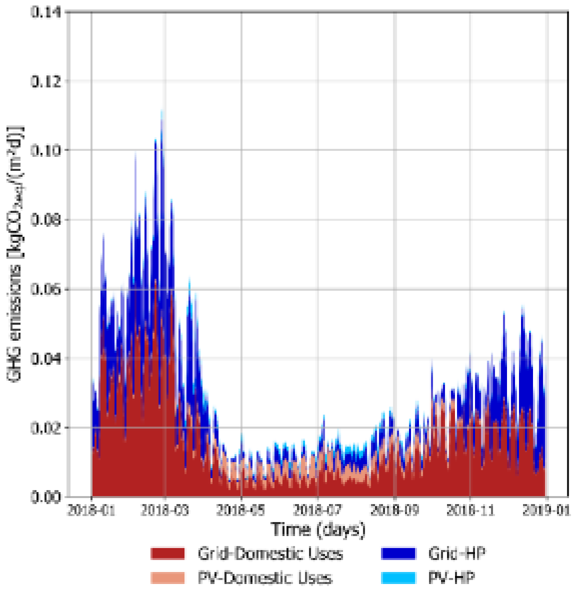


Figure 109: GHG emissions for the different uses of the CS6F scenario.

Annex 4.5: Time step influence

Time step influence of case studies 1 – 4

This section presents the influence of the time step on the environmental impacts of the case studies and the different scenarios. For each case study and scenario, the environmental impacts of the four considered time steps are presented, i.e. annual, monthly, daily and hourly time step.

a) Case Study 1 – With and without PV

Table 54 and Table 32 present the environmental impacts for the four time steps, of the two studied alternatives; with and without PV, respectively. Looking at the results for the case without PV, the higher the time resolution, the higher the environmental impacts of the building, e.g. evaluated by the GHGe. The difference between the two extreme time steps is approximately 9%, for the total GHGe. As far as the other indicators are concerned, this difference is 3% and 4% for the NRE and the UBP, respectively. When looking only at the GHGe of the electricity for the heating needs, this difference is approximately 27%, while for the other domestic uses this difference is approximately 3%. It can be noticed, thus, that the influence of the time resolution is more important for energy consumption profiles that present significant seasonality, as it is the case for the heating needs.

The results for the scenario with the PV, show that there is approximately 16% difference between the annual and the hourly time steps for the total GHGe. For the other indicators, this difference is 4% and 7% for the NRE and the UBP, respectively. For this scenario, too, the higher the time resolution, the higher the environmental electricity impacts of the building. It can be noticed that this difference is approximately 28%, for the grid electricity of the heating needs. Comparing the two scenarios, it can be observed that the influence of the time resolution is higher for the scenario with the PV installation. On the contrary, looking only at the space heating needs, the impact of the time resolution is similar for both scenarios.

Comparing the two examined scenarios for the hourly time step, i.e. with and without PV, it can be observed that there is approximately 8% gain because of the PV installation, in terms of GHGe for the hourly time step. For the other indicators, this gain is approximately 18% and 10% for the NRE and the UBP.

Table 54: Environmental impacts (per m² of ERA), for the four time steps CS1 – Without PV.

	Annual time step				Monthly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	3,53	1,23	4,54	**9,3**	3,94	1,17	4,2	**9,31**
NRE [MJ/(m2y)]	53,47	18,62	68,99	**141,08**	53,55	19	71	**143,55**
RE [MJ/(m2y)]	134,92	46,95	174,1	**355,97**	131,39	45,24	166,73	**343,36**
UBP [ecopoints/(m2y)]	5929,79	2065,89	7643,43	**15639,11**	5849,55	1965,15	7225,6	**15040,3**

	Daily time step				Hourly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	4,164	1,2	4,33	**9,694**	4,47	1,23	4,4	**10,1**
NRE [MJ/(m2y)]	52,61	18,7	69,63	**140,94**	49,52	18,56	69,5	**137,58**
RE [MJ/(m2y)]	134,1	46,5	172,13	**352,73**	146,44	47,4	174,5	**368,34**
UBP [ecopoints/(m2y)]	6387,43	2053,5	7511,96	**15952,89**	6627,74	2062,4	7494,32	**16184,46**

Table 55: Environmental impacts (per m² of ERA), for the four time steps CS1 – With PV.

	Annual time step							Monthly time step			
	PV			Grid							
	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG	0,163	0,206	1,097	3,23	0,85	2,52	**8,066**	3,763	1,056	3,657	**8,476**
NRE	2,07	2,6	13,84	48,8	12,83	38,23	**118,37**	51,04	15,62	52,77	**119,43**
RE	0,36	0,45	2,4	123,1	32,36	96,44	**255,11**	120,22	31,82	95,423	**247,463**
UBP	296,7	374,3	1992,6	5414,5	1423,0	4241,4	**13742,46**	5639,06	1748,312	6080,56	**13467,932**

	Daily time step				Hourly time step						
					PV			Grid			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	Sum
GHG	3,973	1,086	3,757	**8,816**	0,16	0,21	1,10	4,13	0,93	2,77	**9,30**
NRE	50,195	15,41	52,09	**117,7**	2,07	2,60	13,84	45,05	12,45	37,00	**113,01**
RE	122,82	32,5	97,81	**253,13**	0,36	0,45	2,40	134,27	33,58	100,94	**272,00**
UBP	6140,69	1825,5	6331,99	**14298**	296,7	374,27	1992,62	6084,3	1479,7	4415,35	**14643,00**

b) Case Study 2 – With and without PV

Table 56 and Table 57 present the results for the different time steps for the two scenarios of the second case study. For the case without the PV, the higher the time resolution, the higher the environmental impacts of the building. Looking at this scenario, the difference of the total GHGe between the annual and the hourly time step is approximately 17%. For the other indicators, this difference is 5% and 7% for the NRE and the UBP, respectively. This difference is more pronounced, when comparing the GHGe of the space heating and the DHW separately, i.e. 27% and 23%, respectively between the annual and the hourly time step. It should be noted that for this case study, the time step influence is more prominent than the first case study, because of the high seasonality, exhibited by the energy consumption profiles of the electricity for the space heating and the DHW, as well.

For the scenario with the PV installation, the difference between the annual and the hourly time step, is approximately 20% for the total GHGe. As far as the other indicators are concerned, the time step difference is 6% and 9% for the NRE and the UBP, respectively. Looking separately the GHGe of the electricity for the space heating and the DHW, it is noted that the time step difference is approximately 26%. As it has already been explained, the higher the seasonality of the energy consumption profile and consequently the profile of the GHGe, the higher the impact of the time step, on the results of the GHGe. Comparing the two scenarios for the hourly time step, the PV gain is approximately 6%, for the GHG and the UBP indicators. Concerning the NRE the PV gain is 10%, because of the PV installation.

Table 56: Environmental impacts (per m^2 of ERA), for the four time steps CS2 – Without PV.

	Annual time step				Monthly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	2,58	4,58	3,16	**10,32**	2,86	5,09	3,03	**10,98**
NRE [MJ/(m2y)]	39,04	70,12	48,23	**157,39**	39,21	70,1	49,33	**158,64**
RE [MJ/(m2y)]	98,47	177,12	121,76	**397,35**	95,63	173,17	117,24	**386,04**
UBP [ecopoints/(m2y)]	4333,27	7757,85	5339,51	**17430,63**	4264,26	7698,316	5105,11	**17067,686**

	Daily time step				Hourly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	3,01	5,3	3,14	**11,45**	3,26	5,63	3,2	**12,09**
NRE [MJ/(m2y)]	38,55	69,14	48,44	**156,13**	36,39	65,7	47,82	**149,91**
RE [MJ/(m2y)]	97,47	175,61	120,63	**393,71**	106,31	190,1	123,72	**420,13**
UBP [ecopoints/(m2y)]	4643,51	8283,37	5338,55	**18265,43**	4810,77	8539,36	5364,4	**18714,53**

Table 57: Environmental impacts (per m² of ERA), for the four time steps CS2 – With PV.

	Annual time step							Monthly time step			
	PV			Grid							
	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG	0,12	0,23	0,6	2,35	4,15	2,1	**9,55**	2,75	4,89	2,69	**10,33**
NRE	1,5	2,86	7,45	35,56	63,6	31,4	**142,37**	37,23	66,42	39,33	**142,98**
RE	0,56	0,5	1,3	89,7	160,43	79,1	**331,59**	87,53	157,65	77,79	**322,97**
UBP	215,57	411,74	1073,13	3947,73	7026,57	3474,18	**16148,92**	4113	7409,06	4436,57	**15958,63**

	Daily time step				Hourly time step						
					PV			Grid			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	Sum
GHG	2,89	5,13	2,78	**10,8**	0,12	0,23	0,6	2,99	5,17	2,3	**11,41**
NRE	36,68	65,65	38,76	**141,09**	1,5	2,86	7,45	33,026	59,31	30,23	**134,376**
RE	89,16	159,47	79,7	**328,33**	0,56	0,5	1,3	97,51	173,14	82,88	**355,89**
UBP	4469,1	7943,39	4637,59	**17050,08**	215,57	411,74	1073,13	4421,71	7791,1	3633,66	**17546,91**

c) Case Study 3 – With and without PV

The same procedure was followed for this case study. Table 58 and Table 59 present the results for the different time steps for the scenario without PV and the one with the PV installation, respectively. For the first scenario, the difference between the annual and the hourly time step is 5%, while for the second scenario, this difference is 9%, for the GHGe. For the NRE and the UBP, the time step difference for the scenario without PV installation is approximately 2%, while for the scenario with PV installation is approximately 4%. Looking only at the GHGe of the electricity for the heating needs the time step influence is approximately 24% for both scenarios. It can be observed that for this case study too, the high seasonality of the energy consumption profile, results to a higher impact of the time resolution. In addition, the GHGe of the scenario with the PV installation is more sensitive to the time resolution. Comparing the two scenarios, with and without PV, for the hourly time step, the PV gain is approximately 4% for the GHGe. For the NRE and the UBP, the PV gain is approximately 12% and 4% respectively.

Table 58: Environmental impacts (per m² of ERA), for the four time steps CS3 – Without PV.

	Annual time step				Monthly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	3,97	2,54	9,95	**16,46**	4,4	2,4	9,42	**16,22**
NRE [MJ/(m2y)]	60,46	38,48	150,5	**249,44**	60,34	39,34	154,87	**254,55**
RE [MJ/(m2y)]	152,6	97,1	379,6	**629,3**	149,85	93,51	362,45	**605,81**
UBP [ecopoints/(m2y)]	6700,3	4266,69	16699,21	**27666,2**	6625,48	4059,62	15789,6	**26474,7**

	Daily time step				Hourly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	4,59	2,48	9,7	**16,77**	4,9	2,51	9,8	**17,21**
NRE [MJ/(m2y)]	59,44	38,62	125,27	**223,33**	56,2	38,37	150,43	**245**
RE [MJ/(m2y)]	152,27	96,24	373,14	**621,65**	165,78	98,43	383,82	**648,03**
UBP [ecopoints/(m2y)]	7176,68	4241,4	16459,56	**27877,64**	7423,94	4246,49	16520,2	**28190,63**

Table 59: Environmental impacts (per m^2 of ERA), for the four time steps CS3 – With PV.

	Annual time step								Monthly time step			
	PV				Grid							
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG	0,32	0,53	2,1	2,95	3,52	1,8	7	**15,27**	4,19	2,29	9,1	**15,58**
NRE	4,05	6,71	26,34	37,1	53,55	27,15	106	**223,8**	57,61	34,38	135,09	**227,1**
RE	0,7	1,16	4,56	6,42	135,04	68,5	267,41	**477,3**	133,28	67,31	260,4	**461**
UBP	583,3	965	3793	5342	5934	3008	11778	**26062**	6453	3856	15037	**25347**

	Daily time step				Hourly time step						
					PV			Grid			Sum
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	
GHG	4,39	2,38	9,3	**16,07**	0,32	0,53	2,1	4,39	1,87	7,42	**16,63**
NRE	56,76	33,8	132,9	**223,46**	4,06	6,71	26,4	49,6	26,6	103,83	**217,2**
RE	135,56	69,06	267,46	**472,08**	0,7	1,16	4,57	147,57	71,01	276,1	**501,11**
UBP	6948,52	3997,69	15634,44	**26580,65**	583,3	965,37	3793,44	6609,2	3071,345	12012,15	**27034,805**

d) Case Study 4 – With and without PV

The results of the time step influence for the fourth case study are presented in Table 60 and Table 61. As far as the scenario without the PV installation is concerned, the GHGe of the hourly time step are 10% higher than those for the annual time step. For the NRE and the UBP, this difference is 3% and 4%, respectively. Looking only at the GHGe of the electricity for space heating, the difference between the two time steps is approximately 20%. For the scenario with the PV installation, the total GHGe between the annual and the hourly time step present a 13% difference. Comparing the two scenarios, with and without the PV installation, for the hourly time step, the PV gain is approximately 3%, 9% and 2% for the GHGe, NRE and UBP, respectively.

Table 60: Environmental impacts (per m² of ERA), for the four time steps CS4 – Without PV.

	Annual time step				Monthly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	5,06	2,42	2,58	**10,06**	5,5	2,3	2,4	**10,2**
NRE [MJ/(m2y)]	77	36,63	37,62	**151,25**	77,36	37,57	38,89	**153,82**
RE [MJ/(m2y)]	194,4	92,4	94,5	**381,3**	189,07	88,5	89,73	**367,3**
UBP [ecopoints/(m2y)]	8528,15	4064,5	4210,8	**16803,45**	8379,92	3852,12	3904,2	**16136,24**

	Daily time step				Hourly time step			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG [kgCO2eq/(m2y)]	5,8	2,4	2,51	**10,71**	6,17	2,39	2,5	**11,06**
NRE [MJ/(m2y)]	76,1	36,82	37,93	**150,85**	72,13	37,02	38,12	**147,27**
RE [MJ/(m2y)]	192,63	91,6	93,5	**377,73**	208,97	92,79	94,31	**396,07**
UBP [ecopoints/(m2y)]	9054,88	4051,14	4164,85	**17270,87**	9352,92	4023,91	4127,9	**17504,73**

Table 61: Environmental impacts (per m² of ERA), for the four time steps CS4 – With PV.

	Annual time step							Monthly time step			
	PV			Grid							
	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Sum
GHG	0,54	0,75	0,77	4,4	1,5	1,6	**9,56**	5,36	2,26	2,34	**9,96**
NRE	6,75	9,5	9,75	66,92	22,65	23,27	**138,84**	74,06	32,54	33,6	**140,2**
RE	1,17	1,65	1,69	168,94	57,19	58,44	**289,08**	165,57	56,89	57,66	**280,12**
UBP	971,24	1367,63	1403,1	7412,55	2506,65	2607,4	**16268,57**	8275,18	3797,19	3861,75	**15934,12**

	Daily time step				Hourly time step						
					PV			Grid			
	Space heating	DHW	Other domestic uses	Sum	Space heating	DHW	Other domestic uses	Space heating	DHW	Other domestic uses	Sum
GHG	5,64	2,32	2,43	**10,39**	0,54	0,75	0,77	5,46	1,6	1,67	**10,79**
NRE	73,01	32,12	33,07	**138,2**	6,75	9,5	9,75	62,27	22,3	22,99	**133,56**
RE	168,71	58,4	59,52	**286,63**	1,17	1,65	1,69	183,27	59,14	59,94	**306,86**
UBP	8882,7	3939,21	4052,48	**16874,39**	971,24	1367,63	1403,1	8214,93	2586,56	2658,44	**17201,9**

Time step influence of CS5

a) Reference Scenario

Table 62 is a compendious table of the four considered time steps and for the four examined indicators, of the fifth case study. For the reference scenario, the energy needs for the DHW and the space heating are covered with natural gas and grid electricity covers the needs for the other domestic uses. As it can be seen from the results, no significant difference is noticed for the different time steps. Between the annual and the hourly time step there is approximately 0.4% difference, for the GHGe. For the NRE and UBP indicators, this difference is 0.2% and 0.4%, respectively. This insignificant difference comes mainly from the fact that only the impacts of the electricity for the other domestic uses, are considered dynamically, while the impacts of the natural gas are considered as constant. Furthermore, the GHGe of the electricity for the other domestic uses correspond approximately to 15% of the annual GHGe and thus the impact of the dynamic consideration of the electricity is trivialized.

Table 62: Environmental impacts (per m^2 of ERA), for the four time steps of the reference scenario of the CS5.

	Annual			Sum	Monthly			Sum
	Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
GHG [kgCO2eq/(m2y)]	2.36	4.34	8.95	**15.65**	2.23	4.34	8.95	**15.52**
NRE [MJ/(m2y)]	89.27	73.48	151.39	**314.14**	85.28	73.48	151.39	**310.15**
RE [MJ/(m2y)]	35.41	0.49	1	**36.9**	36.42	0.49	1	**37.91**
UBP [ecopoints/(m2y)]	3934.58	2657.03	5474.14	**12065.75**	3713.58	2657.03	5474.14	**11844.75**

	Daily			Sum	Hourly			Sum
	Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
GHG [kgCO2eq/(m2y)]	2.3	4.34	8.95	**15.59**	2.3	4.34	8.95	**15.59**
NRE [MJ/(m2y)]	87.95	73.48	151.39	**312.82**	89.83	73.49	151.39	**314.7**
RE [MJ/(m2y)]	35.73	0.49	1	**37.22**	35.61	0.49	1	**37.1**
UBP [ecopoints/(m2y)]	3895.89	2657.03	5474.14	**12027.06**	3884.44	2657.029	5474.14	**12015.609**

b) CS5B

This scenario includes the same technical configuration as the previous scenario, with the difference that a PV installation is added to the building. Thus, part of the electricity of the other domestic uses is covered by electricity produced on site. Table 63 presents the environmental impacts of the four time steps. Looking the results between the annual and the hourly time step, there is a 0.45% difference between these two scenarios, for the GHGe. Almost the same difference is observed for the other indicators, i.e. 0.6% and 0.4% for the NRE and UBP, respectively. As it has already been explained for the previous scenario, this insignificant difference derives from the fact that only a small part of the impact of the energy needs of the building is considered dynamically, i.e. the electricity for the other domestic uses, which corresponds to 15% of the total GHGe.

Table 63: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS5B.

	Annual					Monthly				
	Other domestic uses		Space heating	DHW	Sum	Other domestic uses		Space heating	DHW	Sum
	PV	Grid				PV	Grid			
GHG [kgCO2eq/(m2y)]	0.45	1.48	8.95	4.34	**15.22**	0.453	1.46	8.95	4.34	**15.203**
NRE [MJ/(m2y)]	5.95	56.26	151.39	73.48	**287.08**	5.95	54.04	151.39	73.48	**284.86**
RE [MJ/(m2y)]	24.06	22.32	1	0.49	**47.87**	24.06	22.82	1	0.49	**48.37**
UBP [ecopoints/(m2y)]	839.54	2479.26	5474.12	2657.029	**11449.949**	839.54	2369.18	5474.14	2657.03	**11339.89**

	Daily					Hourly				
	Other domestic uses		Space heating	DHW	Sum	Other domestic uses		Space heating	DHW	Sum
	PV	Grid				PV	Grid			
GHG [kgCO2eq/(m2y)]	0.45	1.52	8.95	4.34	**15.26**	0.45	1.55	8.95	4.34	**15.29**
NRE [MJ/(m2y)]	5.94	55.46	151.38	73.48	**286.26**	5.95	58	151.39	73.48	**288.82**
RE [MJ/(m2y)]	24.06	22.42	1	0.49	**47.97**	24.06	21.96	1	0.49	**47.51**
UBP [ecopoints/(m2y)]	839.54	2503.77	5474.14	2657.029	**11474.479**	839.54	2524.34	5474.14	2654.03	**11492.05**

c) CS5C

This scenario includes a heat pump (constant COP) for the heating needs and the DHW. All the electricity is provided by the grid. Table 64 shows the results for the different time steps. Looking at the results, it can be seen that the higher the time resolution, the higher the impacts of the building. However, comparing the annual and the hourly time step, the difference is still insignificant (5%), when considering the total GHGe. The time step difference for the NRE and the UBP indicators, is approximately 2%. It should be noted though, that the impacts of the electricity for the other domestic uses and the DHW do not exhibit a high seasonality, as already discussed in the previous section, and this is the reason why their impacts for the different time steps is insignificant. In other words, when calculating the impacts for a constant energy profile, with a dynamic electricity impact profile, the effects of the dynamic consideration of the electricity impact profile are trivialized. On the contrary, when looking at the electricity needs for the space heating between the annual and the hourly time step, there is a 14% difference for the GHGe, which derives from the fact that both the electricity consumption and the impacts of the heating needs exhibit a pronounced intra-annual fluctuation.

Table 64: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS5C.

	Annual			Sum	Monthly			Sum
	Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
GHG [kgCO2eq/(m2y)]	2.36	1.32	2.7	**6.38**	2.23	1.27	2.85	**6.35**
NRE [MJ/(m2y)]	89.26	35.02	72.2	**196.48**	85.276	33.44	70.56	**189.276**
RE [MJ/(m2y)]	35.41	13.9	28.6	**77.91**	36.42	14.27	28.7	**79.39**
UBP [ecopoints/(m2y)]	3934.6	1755.8	3606.8	**9297.2**	3713.6	1667.4	3555.79	**8936.79**

	Daily			Sum	Hourly			Sum
	Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
GHG [kgCO2eq/(m2y)]	2.3	1.3	2.95	**6.55**	2.3	1.3	3.07	**6.67**
NRE [MJ/(m2y)]	87.95	34.56	72.02	**194.53**	89.83	35.25	77.42	**202.5**
RE [MJ/(m2y)]	35.73	13.99	28.22	**77.94**	35.61	14.04	26.94	**76.59**
UBP [ecopoints/(m2y)]	3895.89	1744.97	3801.93	**9442.79**	3884.44	1730.7	3896.85	**9511.99**

d) CS5D

This scenario has the same technical configuration, as the previous one, with the difference that a variable COP is considered for the heat pump. Table 65 presents the results for the different time steps and the different indicators. When looking at the GHGe, the highest difference can be observed between the annual and the hourly time step, i.e. approximately 6%. Looking at the other indicators, this difference is approximately 1% and 3% for the NRE and the UBP. Furthermore, looking at the GHGe of the electricity for the space heating, the highest difference can be observed between the annual and the hourly time resolution, i.e. approximately 16%. It should be noted, though that this difference derives also from the fact that an hourly COP for the heat pump was considered. Comparing the scenarios CS5C and CS5D, the impact of the variable hourly COP, is approximately 5.5% on the total hourly GHGe.

Table 65: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS5D.

	Annual			Sum	Monthly			Sum
	Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
GHG [kgCO2eq/(m2y)]	2.36	1.34	2.94	**6.64**	2,23	1,3	3,14	**6,67**
NRE [MJ/(m2y)]	89.27	35.66	81.64	**206.57**	85,27	34,15	79,75	**199,17**
RE [MJ/(m2y)]	35.41	14.13	32.32	**81.86**	36,42	14,5	32,45	**83,37**
UBP [ecopoints/(m2y)]	3934.6	1783.97	4023.72	**9742.29**	3713,6	1703	3968	**9384,6**

	Daily			Sum	Hourly			Sum
	Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
GHG [kgCO2eq/(m2y)]	2,3	1,34	3,25	**6,89**	2.3	1.34	3.4	**7.04**
NRE [MJ/(m2y)]	87,95	35,3	81,4	**204,65**	89.83	31.16	87.72	**208.71**
RE [MJ/(m2y)]	35,73	14,2	31,92	**81,85**	35.61	14.21	30.42	**80.24**
UBP [ecopoints/(m2y)]	3895,89	1790	4257,56	**9943,45**	3884.44	1780.03	4370.8	**10035.27**

e) CS5E

This scenario includes the same technical systems as the scenario CS5C with an additional PV installation. Table 66 presents the results of the different time steps. The highest difference can be observed between the annual and the hourly time step, i.e. 7%, for the total GHGe. Looking at the other indicators, the time step difference is 5% and 4% for the NRE and the UBP, respectively. The same difference for the total GHGe impacts of the grid electricity for the space heating is 14%, for the GHGe. Comparing this scenario with the scenario CS5C, it is observed that the influence of the time step is minimized for the scenario CS5E, since part of the electricity is provided by the PV installation. The environmental impact of the latter is not calculated within a dynamic framework, as it is the case for the electricity provided by the grid.

Table 66: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS5E.

	Annual					Sum	Monthly					Sum
	Grid	PV	Other Domestic Uses	DHW	Space heating		Grid	PV	Other Domestic Uses	DHW	Space heating	
GHG	5.07	0.76	2.03	1.19	2.61	**5.83**	5.18	0.76	2	1.2	2.78	**5.98**
NRE	154.34	7.6	68.25	27.2	66.61	**162.06**	149.38	7.6	65.67	26.2	65.12	**156.99**
RE	30.69	61.14	44	17	30.83	**91.83**	30.69	62.05	44.52	17.26	30.95	**92.73**
UBP	7342.0	1170.3	3454.0	1577	3481.4	**8512.3**	7121.8	1170	3330.0	1526.1	3436.0	**8292.0**

	Daily					Sum	Hourly					Sum
	Grid	PV	Other Domestic Uses	DHW	Space heating		Grid	PV	Other Domestic Uses	DHW	Space heating	
GHG	5.36	0.76	2.1	1.22	2.8	**6.12**	5.52	0.76	2.1	1.21	2.96	**6.27**
NRE	153	7.6	67.29	26.9	66.41	**160.6**	161.84	7.6	70.01	27.89	71.56	**169.46**
RE	30.7	60.96	44.08	17	30.52	**91.6**	30.7	59.21	43.67	17	29.25	**89.92**
UBP	7565	1170	3482.7	1591.1	3661.1	**8734.9**	7672.7	1170.3	3499.6	1588.1	3755.3	**8843.0**

f) CS5F

The final scenario includes the same system configuration, as the previous one, with the difference that a variable COP is defined for the heat pump. Table 67 presents the results for the different time resolutions. As it was the case for the previous scenario, the highest difference of the time step can be observed between the annual and the hourly time step, i.e. approximately 7% for the GHGe. The time step difference for the NRE and the UBP is 5% and 4%, respectively. When looking only at the grid electricity for the space heating, this difference is slightly higher, i.e. approximately 11%, for the reasons, already explained for the scenario CS5D. Finally, the same conclusion, as before, can be drawn, when comparing this scenario and the scenario CS5D; the influence of the time step for the CS5F scenario is minimized, since part of the electricity is provided by the PV.

Table 67: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS5F.

	Annual					Sum	Monthly					Sum
	Grid	PV	Other Domestic Uses	DHW	Space heating		Grid	PV	Other Domestic Uses	DHW	Space heating	
GHG	5.47	0.75	2.03	1.23	2.96	**6,22**	6.22	5.56	0.75	2	1.23	**6,29**
NRE	165.1	7.47	68.18	28.44	75.95	**172,57**	172.57	159.88	7.47	65.71	27.44	**167,36**
RE	30.23	65.39	43.96	17.06	34.62	**95,64**	95.64	30.23	66.27	44.51	17.26	**96,52**
UBP	7879.8	1154.5	3454.4	1622.7	3953.5	**9030,7**	9030.7	7608.4	1154.2	3331.5	1570.4	**8758,2**

	Daily					Sum	Hourly					Sum
	Grid	PV	Other Domestic Uses	DHW	Space heating		Grid	PV	Other Domestic Uses	DHW	Space heating	
GHG	5.74	0.75	2.08	1.25	3.14	**6,47**	5,9	0,75	2,1	1,26	3,29	**6,65**
NRE	163.66	7.47	67.32	28.13	75.68	**171,13**	173,63	7,48	70,07	29,31	81,72	**181,1**
RE	30.23	65.16	44.06	17.07	34.26	**95,39**	30,23	63,13	43,62	16,98	32,78	**93,38**
UBP	8098.2	1153.9	3485.1	1644.0	4118.5	**9247,6**	8220,3	1152,9	3502,5	1645,1	4225,7	**9373,3**

Time step influence of CS6

a) Reference scenario

The reference scenario of the sixth case study includes a heat pump (variable COP) for the heating needs and a PV installation, which covers part of the electricity needs. Table 68 presents the results for the four time steps and the four studied indicators. It can be noticed that the higher the time resolution, the higher the environmental impacts. Comparing the total GHGe between the annual and the hourly time step, there is approximately 9% difference on the total GHGe, (approximately 8% for the grid electricity of the heat pump). For the other indicators, this difference is 6% and 4% for the NRE and the UBP, respectively. The same difference is observed for the GHGe of the domestic uses and the heating needs. This case study corresponds to an office building and the energy consumption of all the electricity uses fluctuate during the time, not only because of the different seasons (winter vs summer), but also because of the dynamic occupancy profile.

Table 68: Environmental impacts (per m^2 of ERA), for the four time steps of the reference scenario of the CS6.

	Annual time step					Monthly time step				
	PV	Grid	Space heating (HP)	Domestic uses	Sum	PV	Grid	Space heating (HP)	Domestic uses	Sum
GHG [kgCO2eq/(m2y)]	1.22	9.92	4.6	6.53	**11.13**	1.22	10.5	4.78	6.95	**11.73**
NRE [MJ/(m2y)]	13.51	368.42	120.45	261.5	**381.95**	13.51	370.1	121.74	261.87	**383.61**
RE [MJ/(m2y)]	62.94	143.84	54.88	151.91	**206.79**	62.94	142.21	54	151.2	**205.2**
UBP [ecopoints/(m2y)]	2045.38	16235.78	6105.34	12175.81	**18281.15**	2045.41	16583.17	6159.66	12468.92	**18628.58**

	Daily time step					Hourly time step				
	Domestic uses		Space heating (HP)		Sum	PV	Grid	Space heating (HP)	Domestic uses	Sum
	PV	Grid	PV	Grid						
GHG [kgCO2eq/(m2y)]	0.898	5.867	0.32	4.36	**11.45**	1.22	10.86	4.97	7.11	**12.08**
NRE [MJ/(m2y)]	11.67	241.45	1.85	115.1	**370.07**	13.51	392.55	131.05	275.01	**406.06**
RE [MJ/(m2y)]	54.37	99.27	8.57	46.62	**208.83**	62.94	138.13	51.76	149.32	**201.08**
UBP [ecopoints/(m2y)]	1692.54	10555.37	352.1	5819.48	**18419.49**	2048.44	16915.95	6423.05	12541.34	**18964.39**

b) CS6B

For this scenario the heating needs are covered by natural gas and the domestic uses by the electricity from the grid. The results of the different time steps are presented in Table 69. Comparing between the annual and the hourly time step, there is 1% for the GHGe. For the other indicators, this difference is less than 1.5%. The dynamic effect of the electricity profile is trivialized, since the space heating needs are covered by natural gas.

Table 69: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS6B.

	Annual time step			Monthly time step		
	Domestic uses	Space heating (Natural gas)	Sum	Domestic uses	Space heating (Natural gas)	Sum
GHG [kgCO2eq/(m2y)]	7.52	16.1	**23.62**	7.7	16.1	**23.8**
NRE [MJ/(m2y)]	333.1	271.56	**604.66**	332.64	271.56	**604.2**
RE [MJ/(m2y)]	130.055	1.74	**131.795**	130	1.74	**131.74**
UBP [ecopoints/(m2y)]	13978.05	9845.22	**23823.27**	14276.14	9845.22	**24121.36**

	Daily time step			Hourly time step		
	Domestic uses	Space heating (Natural gas)	Sum	Domestic uses	Space heating (Natural gas)	Sum
GHG [kgCO2eq/(m2y)]	7.4	16.1	**23.5**	7.72	16.1	**23.82**
NRE [MJ/(m2y)]	321.27	271.56	**592.83**	340.56	271.56	**612.12**
RE [MJ/(m2y)]	133.28	1.74	**135.02**	130.01	1.74	**131.75**
UBP [ecopoints/(m2y)]	13768.11	9845.22	**23613.33**	13992.022	9845.22	**23837.242**

c) CS6C

This scenario includes the same technical systems as the previous, with the difference that part of the electricity needs is covered by a PV installation. Comparing the GHGe between the annual and the hourly time step, there is a slightly difference (approximately 3%). For the other indicators, the time step difference is approximately 3%, as well, see Table 70.

Table 70 : Environmental impacts (per m2 of ERA), for the four time steps of the scenario CS6C.

	Annual time step				Monthly time step			
	Grid Electricity	PV Electricity	Space heating (Natural gas)	Sum	Grid Electricity	PV Electricity	Space heating (Natural gas)	Sum
GHG	5.4	0.99	16.1	**22.49**	5.84	0.99	16.1	**22.93**
NRE	241.04	12.9	271.56	**525.5**	241.35	12.9	271.56	**525.81**
RE	94.11	60.1	1.74	**155.95**	93.41	60.1	1.74	**155.25**
UBP	10114.71	1871.03	9845.22	**21830.96**	10398.56	1871.03	9845.22	**22114.81**

	Daily time step				Hourly time step			
	Grid Electricity	PV Electricity	Space heating (Natural gas)	Sum	Grid Electricity	PV Electricity	Space heating (Natural gas)	Sum
GHG	5.66	0.99	16.1	**22.75**	6	0.99	16.1	**23.09**
NRE	232.94	12.9	271.56	**517.4**	254.42	12.9	271.56	**538.88**
RE	95.79	60.1	1.74	**157.63**	91.49	60.1	1.74	**153.33**
UBP	10185.52	1871.03	9845.22	**21901.77**	10476.75	1871.03	9845.22	**22193**

d) CS6D

The following scenario includes a heat pump (constant COP) for the heating needs and the electricity from grid covers the other domestic uses. Comparing the total GHGe results between the annual and hourly time step, there is a 5% difference, which remains still insignificant. For the other indicators, the time step difference is still insignificant, i.e. 3% and 1.5% for the NRE and the UBP indicators. Comparing the electricity for the space heating, the difference between the annual and the hourly time step is Table 71.

Table 71 : Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS6D.

	Annual time step			Monthly time step		
	Domestic uses	Space heating (HP)	Sum	Domestic uses	Space heating (HP)	Sum
GHG [kgCO2eq/(m2y)]	7.51	4	**11.51**	7.7	4.26	**11.96**
NRE [MJ/(m2y)]	333.1	110.73	**443.83**	332.65	111.8	**444.45**
RE [MJ/(m2y)]	130.06	43.22	**173.28**	13	42.6	**55.6**
UBP [ecopoints/(m2y)]	13978.05	5370.1	**19348.15**	14276.14	5503.25	**19779.39**

	Daily time step			Hourly time step		
	Domestic uses	Space heating (HP)	Sum	Domestic uses	Space heating (HP)	Sum
GHG [kgCO2eq/(m2y)]	7.4	4.2	**11.6**	7.71	4.42	**12.13**
NRE [MJ/(m2y)]	321.27	107.19	**428.46**	340.56	118.4	**458.96**
RE [MJ/(m2y)]	133.28	43.68	**176.96**	130.01	41.06	**171.07**
UBP [ecopoints/(m2y)]	13768.11	5466.37	**19234.48**	13992.02	5664.1	**19656.12**

e) CS6E

This scenario is directly comparable with the previous one and the reference scenario. The CS6E scenario includes a heat pump (variable COP) for the heating needs and no PV installation. The higher the time resolution, the higher the total GHGe of the building, but still this difference remains trivial, i.e. approximately 7%, see . For the other indicators, the time step difference is 4% and 2% for the NRE and the UBP, respectively. Looking at the difference between the annual and the hourly time step for the electricity of the space heating, there is a 15% for the GHGe. The influence of the time step is slightly higher than the previous scenario, because of the fact that a variable COP was taken into account for this scenario. Comparing, this scenario with the reference one, it can be observed that there is no particular difference, concerning the time step, with or without PV.

Table 72: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS6E.

	Annual time step			Monthly time step		
	Domestic uses	Space heating (HP)	Sum	Domestic uses	Space heating (HP)	Sum
GHG [kgCO2eq/(m2y)]	7.51	4.47	**11.98**	7.7	4.86	**12.56**
NRE [MJ/(m2y)]	333.1	131.72	**464.82**	332.65	132.98	**465.63**
RE [MJ/(m2y)]	130.06	51.43	**181.49**	130	50.55	**180.55**
UBP [ecopoints/(m2y)]	13978.04	6252	**20230.04**	14276.14	6422.4	**20698.54**

	Daily time step			Hourly time step		
	Domestic uses	Space heating (HP)	Sum	Domestic uses	Space heating (HP)	Sum
GHG [kgCO2eq/(m2y)]	7.4	4.8	**12.2**	7.72	5.12	**12.84**
NRE [MJ/(m2y)]	321.27	127.75	**449.02**	340.56	142.11	**482.67**
RE [MJ/(m2y)]	133.28	51.84	**185.12**	133.28	51.85	**185.13**
UBP [ecopoints/(m2y)]	13768.11	6433.1	**20201.21**	13992.02	6691.21	**20683.23**

f) CS6F

The final scenario includes the same system configuration as the reference scenario, with the difference that the heat pump is considered with a constant COP. The difference of the GHGe between the annual and the hourly time step is approximately 10% and it remains at the same level, as for the reference scenario, see . For the NRE and the UBP, the time step difference is 6% and 4%, respectively. Looking only at the GHGe of the electricity of the space heating, there is a 12% between the annual and the hourly time step.

Table 73: Environmental impacts (per m^2 of ERA), for the four time steps of the scenario CS6F

	Annual					**Monthly**				
	Grid	**PV**	**Domestic uses**	**HP**	**Sum**	**Grid**	**PV**	**Domestic uses**	**HP**	**Sum**
GHG	9.14	1.23	6.54	3.83	**10.37**	9.82	1.23	6.95	4.11	**11.06**
NRE	346.64	13.62	261.43	98.85	**360.28**	348.21	13.62	261.8	100.04	**361.84**
RE	135.34	63.44	151.93	46.85	**198.78**	133.92	63.44	151.21	46.14	**197.35**
UBP	15180.1	2065.2	12174.13	5071.2	**17245.33**	15601.95	2065.22	12465.7	5201.47	**17667.17**

	Daily					**Hourly**				
	Domestic uses		**PAC**		**Sum**	**Grid**	**PV**	**Domestic uses**	**HP**	**Sum**
	PV	**Grid**	**PV**	**Grid**						
GHG	0.9	5.85	0.336	3.72	**10.81**	10.15	1.24	7.1	4.3	**11.4**
NRE	11.68	241.34	1.94	93.9	**348.86**	368.21	13.62	274.86	107	**381.86**
RE	54.42	99.26	9.01	38.15	**200.84**	130.4	63.44	149.4	44.47	**193.87**
UBP	1694.12	10546.71	371.1	4819.7	**17431.63**	15861.35	2065.22	12533.55	5393.02	**17926.57**

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Summary graphs for RE and UBP indicators

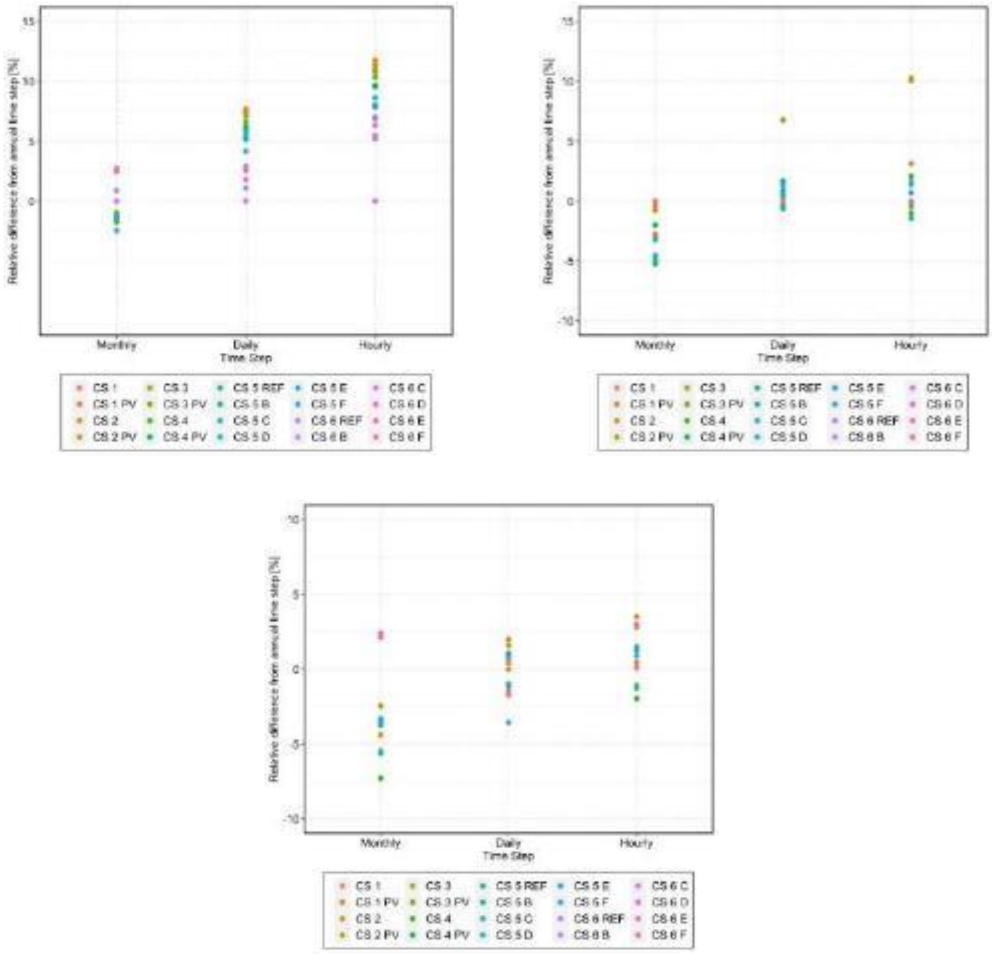

Figure 110: Relative difference from the annual time step, of all the scenarios for the UBP of the space heating (top-left) and DHW (top-right) and other domestic uses (center-down).

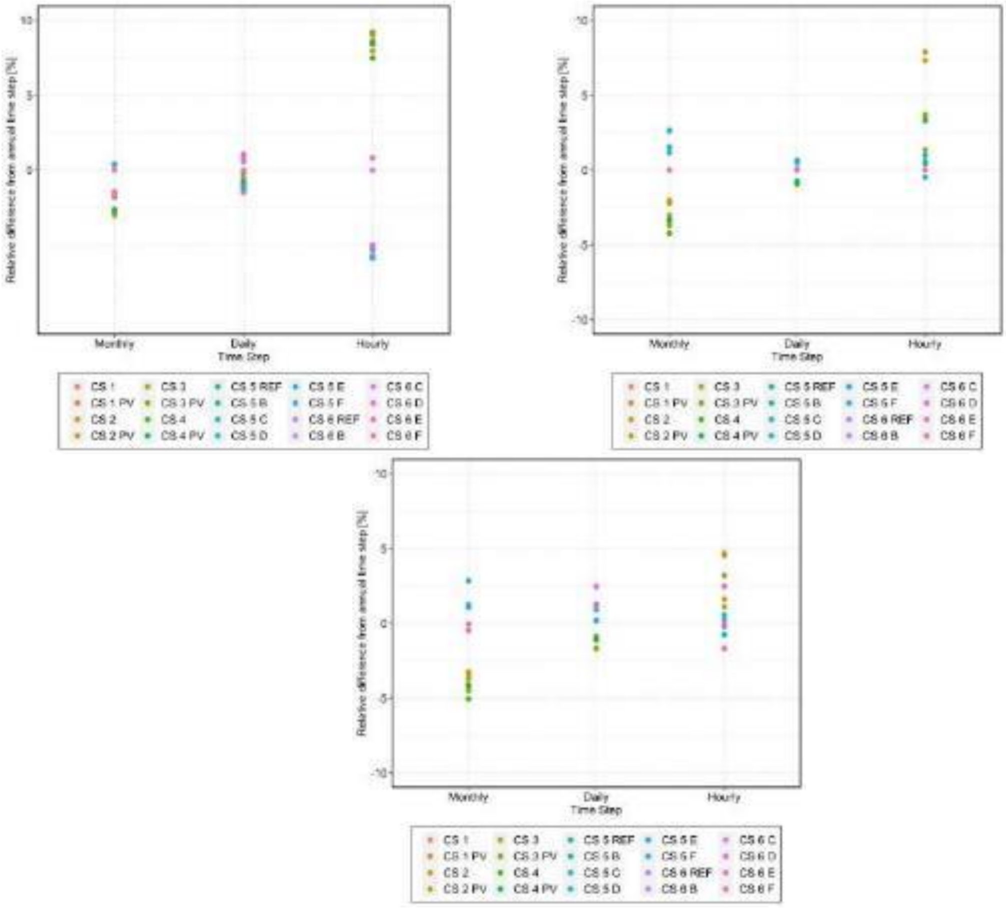

Figure 111: Relative difference from the annual time step, of all the scenarios for the NRE of the space heating (top-left) and DHW (top-right) and other domestic uses (center-down).

Annex 4.6: Summary tables of the results

Table 74: Compendious table of the results of the sixth case studies, for the NRE.

Case studies	**CS 1-4**			**CS5**				**CS6**			
	Energy consumption profile	**Time step Influence**	**PV gain**	**Energy consumption profile**	**Impact of COP**	**Time Step Influence**	**PV gain**	**Energy consumption profile**	**Impact of COP**	**Time Step Influence**	**PV gain**
Space Heating	Seasonal	On average 7% between the yearly and annual time step, for the. (With and Without PV)	Hourly time step: 4%-5%	Seasonal		Between annual and hourly 7%-8%	Hourly time step: 7%-8%	Seasonal and intermittent use		**Without PV**:7%-8% **With PV** : 8%-9%	Hourly time step:8%-9%
DHW	Stable and seasonal only for the CS2	**Without PV:** 2% **With PV** :3%	Hourly time step:5%-19%	Stable		Between annual and hourly 0%-12%	Hourly time step : 6%-20%				
Other domestic Uses	Stable	**Without PV:** 1% **With PV**: 2%	Hourly time step : 13%-26%	Stable		Between annual and hourly 1%-3%	Hourly time step: 22%-28%	Moderate seasonality and intermittent use		**Without PV** hourly time step: 2% **With PV** for hourly time step : 5%	Hourly time step:13%-21%

case studies	CS1 - 4				CS5					CS6				
	Energy consumption profile	**General trend of the impacts**	**Time step influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time step influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time step influence**	**PV gain**
Total impacts without PV installation			Between annual and hourly time step: 2%-5%	Hourly time step: 9%-18%			3 % for the hourly time step	0%-3 % for the hourly time step	Hourly time step:8%-16%			Hourly time step:5%	between annual and hourly time step: 2%-4%	Hourly time step: 12%-17%
Total impacts with PV installation			Between annual and hourly time step: 3%-6%				7% for the hourly time step	1%-5% for the hourly time step				Hourly time step:6%	between annual and hourly time step: 2%-6%	

Table 75: Compendious table of the results of the sixth case studies, for the RE.

Case studies	CS 1-4			CS5				CS6			
	Energy consumption profile	**Time step Influence**	**PV gain**	**Energy consumption profile**	**Impact of COP**	**Time Step Influence**	**PV gain**	**Energy consumption profile**	**Impact of COP**	**Time Step Influence**	**PV gain**
Space Heating	Seasonal	On average 8.5% between the yearly and annual time step, for the. (With and Without PV)	Hourly time step: 8%-11%	Seasonal		Between annual and hourly:5%-6%	Hourly time step:8%	Seasonal and intermittent use		**Without PV**: 1%-5% **With PV** : 5%-6%	Hourly time step: 1%-8%
DHW	Stable and seasonal only for the CS2	**Without PV: 2.5%** **With PV :5%**	Hourly time step: 9%-34%	Stable		Between annual and hourly:1%	Hourly time step :19%-21%				
Other domestic Uses	Stable	**Without PV:** 1% **With PV**:4 %	Hourly time step :26%-41%	Stable		Between annual and hourly:1%	Hourly time step: 22%-29%	Moderate seasonality and intermittent use		**Without PV** hourly time step: 1%-2% **With PV** for hourly time step :2%	Hourly time step: 9%-16%

case studies	CS1 - 4				CS5					CS6				
	Energy consumption profile	**General trend of the impacts**	**Time step influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time step influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time step influence**	**PV gain**
Total impacts without PV installation			Between annual and hourly time step: 3%-6%	Hourly time step: 15%-22%			for the hourly time step:5%	for the hourly time step:1%-2%	Hourly time step: 16%-28%			Hourly time step:8%	between annual and hourly time step: 1%-2%	Hourly time step: 9%-16%
Total impacts with PV installation			Between annual and hourly time step: 5%-7%				for the hourly time step:4%	for the hourly time step:1%-2%				Hourly time step: 4%	between annual and hourly time step:2%-3%	

Table 76: Compendious table of the results of the sixth case studies, for the UBP.

Case studies	**CS 1-4**			**CS5**				**CS6**			
	Energy consumption profile	**Time step Influence**	**PV gain**	**Energy consumption profile**	**Impact of COP**	**Time Step Influence**	**PV gain**	**Energy consumption profile**	**Impact of COP**	**Time Step Influence**	**PV gain**
Space Heating	Seasonal	On average 11% between the yearly and annual time step, for the. (With and Without PV)	Hourly time step:2%-4%	Seasonal		Between annual and hourly:8%-9%	Hourly time step:3%-4%	Seasonal and intermittent use		**Without PV**: 5%-7% **With PV** : 5%-6%	Hourly time step:4%-5%
DHW	Stable and seasonal only for the CS2	**Without PV: 3% With PV :4%**	Hourly time step:2%-10%	Stable		Between annual and hourly:0%-2%	Hourly time step : 8%				
Other domestic Uses	Stable	**Without PV:** 1% **With PV**:2 %	Hourly time step :2%-15%	Stable		Between annual and hourly:1%	Hourly time step:10%-13%	Moderate seasonality and intermittent use		**Without PV** hourly time step: 1% **With PV** for hourly time step : 3%	Hourly time step: 7%-10%

case studies	CS1 - 4				CS5					CS6				
	Energy consumption profile	**General trend of the impacts**	**Time step influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time step influence**	**PV gain**	**Energy consumption profile**	**General trend of the impacts**	**Impact of COP**	**Time step influence**	**PV gain**
Total impacts without PV installation			Between annual and hourly time step: 2%-7%	Hourly time step: 2%-10%			for the hourly time step: 5%	for the hourly time step: 1%-3%	Hourly time step: 4%-7%			Hourly time step:5%	between annual and hourly time step: 2%-7%	Hourly time step:7%-9%
Total impacts with PV installation			Between annual and hourly time step: 4%-9%				for the hourly time step : 6%	for the hourly time step : 1%-4%				Hourly time step:6%	between annual and hourly time step: 2%-4%	

Chapter 4 – Part B: Annexes

Environmental impact of micro cogeneration

The annexes present the following elements:

- Details on the environmental impact calculation assumptions and models for the heat and electricity production of the micro-CHP units
- Results and discussions regarding the heat and electricity impact of the micro-CHP units compared to electricity from grid and traditional gas boiler
- Description of the case studies
- Detailed results of the case studies

Environmental impact assumptions and models

System boundaries

The process chain to calculate the environmental impacts of a building energy demand (heat + electricity) with a micro-cogeneration is presented in Figure 112. Two technologies have been considered for cogeneration, combustion based and fuel cells units.

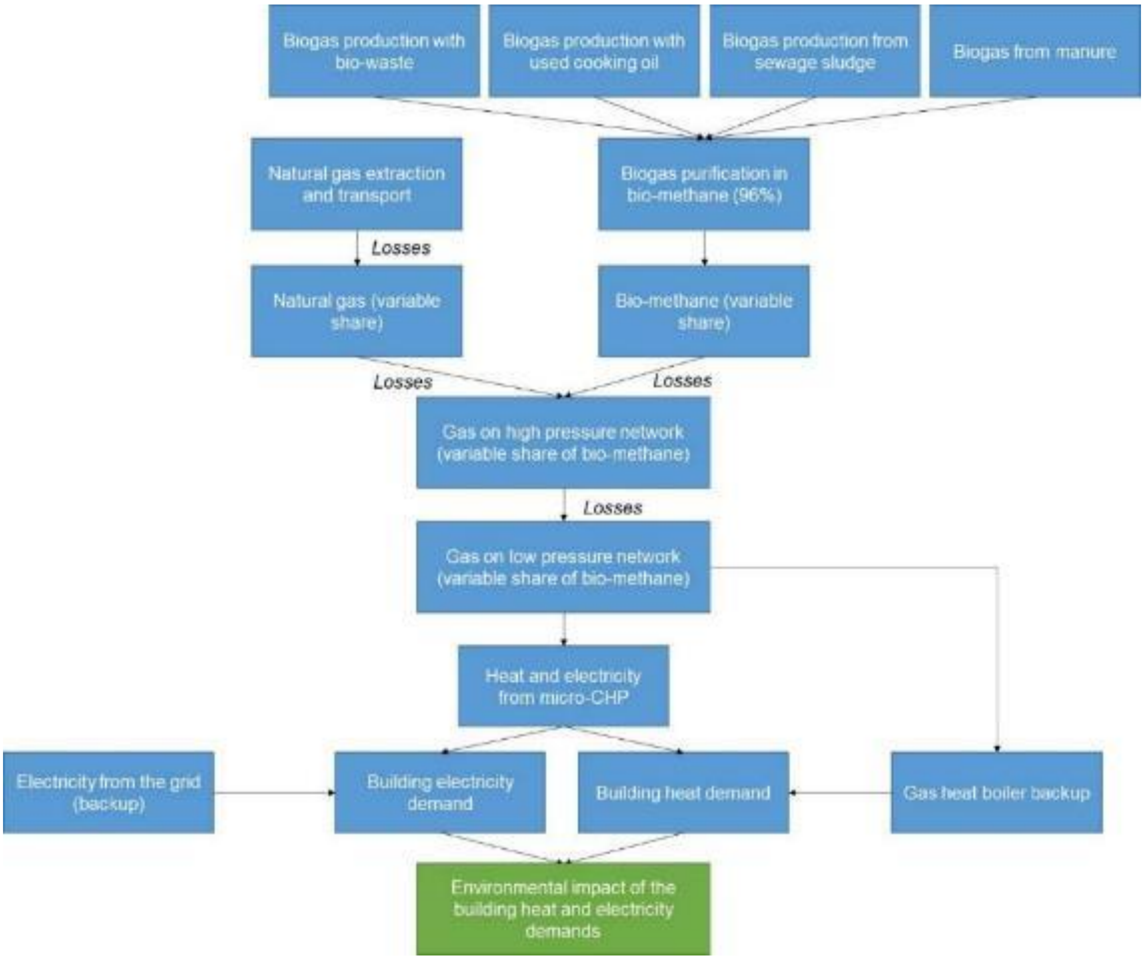

Figure 112 Model used to calculate the environmental impact of building's heat and electricity demands with micro-CHP

The biogas inventories are taken from ecoinvent V3.4. Within this database, the biogas is obtained by anaerobic digestion with four different substrates (in Switzerland), manure, biowaste, sewage sludge or used vegetable cooking oil. The biogas has then to be purified via a Pressure Swing Adsorption (PSA) process, in order a 96% pure bio-methane per volume that can be injected to the gas grid. The gas grid operates with fossil gas and different shares of bio-methane. The gas grid has two levels, i.e. high pressure and low pressure. The conversion from high to low pressure implies losses. At the building level, the low pressure gas network provides the necessary gas for the operation of the micro-CHP. As already mentioned in the chapter 2, the micro-CHP unit is not monovalent. There is a backup system for heat production, which relies on gas. For the electricity, when the micro-CHP can not cover 100% of the needs, the grid covers the difference between the electricity needs and the decentralized production.

Thereby, in order to calculate the environmental impacts of a building, equipped with a micro-CHP, it is necessary to consider the environmental impacts of the:

- biogas
- bio-methane production
- fossil gas supply
- distribution from high to low pressure
- electricity from the grid (relying on the EcoDynBat results)
- heat production with the backup unit
- heat/electricity production of the micro-CHP unit, considering its technical performances.

The following sections introduce the modeling choices for the aforementioned processes

Modeling assumptions of the environmental impacts of heat and electricity produced by a micro-CHP unit

The developed model for the impacts calculation of the micro-CHP, within the EcoDynBat project, relies on the ecoinvent 3.4 database. However, the inventories have been adjusted to the EcoDynBat scope and project needs. The main assumptions for each step of the process chain are introduced below. At the end of this chapter, the used ecoinvent inventories are summarized.

Biogas production

Within ecoinvent there are four biogas substrates in Switzerland, i.e. manure, biowaste, sewage sludge or used vegetable cooking oil. Ecoinvent defines a different impact calculation for each substrate. For the sewage sludge and bio-waste substrates, the biogas production is considered as a waste treatment. Therefore, there is no impact allocated to the biogas production. For these substrates, the impact of the biogas production is allocated to the process that has generated the waste for the biogas production. Thereby, producing 1m^3 of biogas with these substrates has a zero impact.

Conversely, for the manure and vegetable cooking oil production chain, the substrates are considered as recyclable. Therefore, according to the allocation method used in ecoinvent, the environmental impacts of the biogas production encompass the direct and indirect emissions related to the biogas production.

Thereby, based on this allocation assumption, the environmental impact of the biogas production (per m^3) is highly variable, see Table 77.

Table 77 Environmental impacts of biogas production according to ecoinvent, considering the four existing substrate for the production in Switzerland

	Biogas from manure	Biogas from biowaste	Biogas from sewage sludge	Biogas from used vegetable cooking oil
Climate change [kg CO_2 eq/m^3]	1.92	0.00	0.00	0.36
NRE [MJp/m^3]	5.47	0.00	0.00	5.25
RE [MJp/m^3]	1.66	0.00	0.00	1.65
ES [UBP/m^3]	11420	0.00	0.00	336

The assumption “waste treatment” versus “recyclable product” strongly influences the environmental impacts. Although the ecoinvent assumption is valid and coherent with the overall database structure, one can argue about the choice relative to the biogas production obtained with recyclable substrate. Indeed, manure and vegetable cooking oil are substrates that they could be also considered, as waste to be treated. For example, the manure is waste from farming, which is mostly stored in open-field and then spread in the field. If not treated in a biogas plant, the emissions (methane, carbon dioxide, etc.) are therefore emitted directly in the air, having a direct impact.

This modelling assumption is an important topic in the LCA field and this is not the purpose of the EcoDynBat project to solve the question. Nevertheless, within the project, it has been decided to use the two modelling assumptions (i.e. minimum and maximum biogas impacts) for the biogas production. Thereby, in the project, there will be two unitary impacts for the biogas production:

- If the biogas production is considered as a waste treatment, it has a null impact (per m^3);
- If the biogas production is considered as a recyclable product, its impacts are calculated from ecoinvent, using manure as substrate for the production (per m^3).

Bio-methane production from biogas

According to the ecoinvent database, related to biogas modelling, the biogas is composed of 67% of methane. While this biogas can be directly used with centralized cogeneration units, it can not be directly used in the gas network. It has first to be purified in order to reach a methane content of 96% in volume.

Within ecoinvent, there is a process modelled for the purification. This purification is performed by Pressure Swing Adsorption (PSA). This dataset from ecoinvent, and its related environmental impacts, is considered in the EcoDynBat project.

Gas network (high and low pressure)

Once the bio-methane is produced, it has to be distributed via the gas network. The gas network operates at high and low pressures. The conversion from high to low pressure implies losses. The ecoinvent dataset has been used for modelling the gas network at both pressures. Within the ecoinvent inventory, the leakage rate is 0.72% for the conversion from high to low pressure.

Within the EcoDynBat project, the gas network has been assumed to operate with different share of bio-methane. In the project, four shares have been considered, 0% bio-methane (i.e all the grid operate with 100% fossil fuel gas), 10%, 20%, and 100% bio-methane.

Heat and electricity from micro-CHP

For the EcoDynBat project, two micro-CHP technologies have been considered, namely, combustion based and fuel cell based. The following chapter summarizes the modelling assumptions for the environmental impacts.

Combustion-CHP

In the ecoinvent database, there are two inventories for the modeling of the micro-CHP environmental impacts, i.e. one for the heat production and one for the electricity production. The details, regarding the hypothesis can be found in the ecoinvent report related to CHP[12].

The inventories consider a system model of a 2kW electrical power, operating with natural gas. The electrical and thermal efficiency are 25% (on LHW) and 65%, respectively. The database uses an exergy allocation, in order to calculate the impact of both the produced heat and electricity. The exergy factor for the electricity is 1, while the heat is 0.139, considering a thermodynamic mean temperature of 67°C and an ambient temperature of 20°C. The direct emissions are based on multiple literature sources, which can be found in the ecoinvent report[13].

Within EcoDynBat, the exergy allocations followed the ecoinvent assumption. Nevertheless, the factors have been adjusted according the technical characteristics of the real micro-CHP units. Thereby, the thermal efficiency has been set at 75.9% (High Heating value, HHV) and the electric efficiency set at 32.1% (HHV). While in ecoinvent the unit operates with natural gas, in EcoDynBat a variable share of bio-methane has been considered. The direct emissions have been adjusted, according to the bio-methane share, for each EcoDynBat configuration. For example, in case that ecoinvent assumes a certain amount of CO_2 (fossil), emitted by the cogeneration unit, EcoDynBat calculated the CO_2 amount, as a function of the bio-methane share (i.e if 20% bio-methane share in the gas supply mix, 20% of the

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[12] T. Heck, 2007, ecoinvent report No.6-XIV: “Wärme-Kraft-Köplung”

[13] R. Dones, C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Röder, M. Faist Emmenegger, R. Frischknecht, N. Jungbluth, M. Tuchschmid , , ecoinvent report No.5 “Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries”, p.155,

ecoinvent emissions were set as biogenic and 80% as fossil). The emissions have be defined linearly, considering the ecoinvent initial assumption and the EcoDynBat efficiencies.

Fuel-cells CHP

The ecoinvent database models the environmental impacts of heat and electricity produced by Polymer Electrolyte Membrane fuel-cells (PEM). The fuel cell is already modeled to operate with 100% bio-methane (96% volume CH_4). The details regarding the modelling assumptions can be found in the ecoinvent report[14]. As it was the case for the combustion-based units, the exergy allocation has been considered for the fuel cells. The inventories related to heat and electricity production have been considered in the EcoDynBat project. Nevertheless, the electrical efficiency has been adjusted to the EcoDynBat values (33%) and the thermal efficiency has been set to 55%.

Since the EcoDynBat project considers different bio-methane shares for the gas supply, the direct emissions (taken from the ecoinvent inventories) have been adjusted, according to the bio-methane and natural gas shares. For example, in the ecoinvent inventory, when a specific amount for biogenic CH_4 was emitted to produced 1kWh of electricity, this amount was proportionally attributed to fossil CH_4 and biogenic CH_4, according to the bio-methane share, in the gas network.

Backup of heat production and electricity needs

Since the micro-CHP systems are bivalent, there is a need for a backup boiler to cover the building heat demand that cannot be covered by the cogeneration units. This backup boiler is connected to the same gas network as the CHP.

The considered backup is a gas boiler, using the same amount of bio-methane, as the micro-CHP. The ecoinvent inventory (see specific name below, Table 15) has been considered and the direct emissions, as well as the impact of the gas has been adjusted, according to the bio-methane share, as for the heat and electricity inventories of the micro-CHP.

The micro-CHP cannot provide 100% of the electricity needs. The backup is ensured by the Swiss electricity grid. The impacts are taken from the EcoDynBat results presented in the chapter 4-a.

Ecoinvent inventories used in the EcoDynBat WP4b

A summary of the ecoinvent inventories, adjusted according to the needs of the project is given in the Table 78

[14] A. Primas, Basler&Hofmann, 2007, ecoinvent report No.20 "Life Cycle Inventories of new-CHP systems"

	Ecoinvent V3.4 process name	Comment
Biogas production	Biogas {CH}| anaerobic digestion of manure | Cut-off, U	Consider here the production model according to ecoinvent for which the input material is considered as a recyclable product. Therefore the biogas production has an impact ⇨ Biogas based on a recyclable product
	Biogas {CH}| treatment of sewage sludge by anaerobic digestion | Cut-off, U	Consider here the production model according to ecoinvent for which the input material is considered as a waste. Therefore the biogas production has NO impact ⇨ Biogas based on a waste product (i.e treatment)
Biogas purification to bio-methane	Methane, 96% by volume {CH}| biogas purification to methane 96 vol-% | Cut-off, U	Biogas purification at 96% volume of methane to be injected in the gas network
High pressure transport	Methane, 96% by volume, from biogas, high pressure, at user {CH}| production | Cut-off, U	Consider the leakage for distribution at high pressure
Low pressure transport	Methane, 96% by volume, from biogas, low pressure, at user {CH}| production | Cut-off, U	Consider the leakage from high to low pressure and the distribution losses
Heat backup	Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating | Cut-off, U	Modulating condensing gas boiler, efficiency on LHV = 108% The impacts are calculated according to the bio-methane share in the gas network
Natural gas supply	Natural gas, low pressure {CH}|market for| Cut-off, U	According to ecoinvent the natural gas in Switzerland is provided at 37% by the Netherland, 26% by Norway, 25% by Russia (the remaining by DE, DZ, UK)
Electricity from the grid	Data From EcoDynBat	Based on the EcoDynBat data
Heat produced from micro-CHP	- Fuel-cell: Heat, future {CH}| biogas, burned in polymer electrolyte membrane fuel cell 2kWe, future | Cut-off, U - Combustion CHP: Heat, central or small-scale, natural gas {CH}| heat and power co-generation, natural gas, mini-plant 2KW electrical | Cut-off, U	Energetic efficiency for combustion CHP and fuel cells from the EcoDynBat assumptions (see above). Exergy allocation. Direct emissions adjusted as a function of the bio-methane share in the gas network
Electricity produced from micro-CHP	- Fuel-cell: Electricity, low voltage {CH}| biogas, burned in polymer electrolyte membrane fuel cell 2kWe, future | Cut-off, U ecoinvent - Combustion-CHP: Electricity, low voltage {CH}| heat and power co-generation, natural gas, mini-plant 2KW electrical | Cut-off, U	

Table 78 Summary of the inventories used for the environmental impact calculation of heat and electricity produced by micro-CHP (combustion & fuel cells)

Environmental impact assessment

Gas boiler backup impacts

The results of the environmental impact of the heat produced by a condensing boiler, with a variable share of bio-methane, are presented in Table 79.

Table 79 Environmental impacts for the heat backup system, as a function of the bio-methane share and biogas modelling assumption

			Heat from gas (backup)	
			Recyclable	Waste
0% bio-methane	Climate change	[kg CO_2 eq/kWh]	0.252	0.252
	NRE	[MJp/kWh]	4.260	4.260
	RE	[MJp/kWh]	0.028	0.028
	ES	[UBP/kWh]	154	154
10% bio-methane	Climate change	[kg CO_2 eq/kWh]	0.264	0.236
	NRE	[MJp/kWh]	3.964	3.885
	RE	[MJp/kWh]	0.064	0.040
	ES	[UBP/kWh]	311	146
20% bio-methane	Climate change	[kg CO_2 eq/kWh]	0.275	0.220
	NRE	[MJp/kWh]	3.669	3.510
	RE	[MJp/kWh]	0.100	0.052
	ES	[UBP/kWh]	469	138
100% bio-methane	Climate change	[kg CO_2 eq/kWh]	0.370	0.091
	NRE	[MJp/kWh]	1.301	0.509
	RE	[MJp/kWh]	0.384	0.144
	ES	[UBP/kWh]	1727	73

The environmental impacts of the heat produced, by a condensing gas boiler, varies significantly, according to the share of bio-methane and the biogas modeling choice, i.e. a recyclable product or a waste treatment. The latter is clearly the most influencing parameter.

Indeed, for the case with 100% bio-methane, the climate change impact varies from 91 to 370 g CO_2 eq/kWh of useful heat. The environmental impacts (ecological scarcity and climate change) of the heat produced with bio-methane are higher than the heat produced by 100% of fossil natural gas (0% of bio-methane in the table).

Using the bio-methane, when considering the initial substrate as a recyclable product (manure for example), should be avoided, especially when there is an interest of minimizing the climate change and ecological scarcity. On the contrary, considering biogas as a waste treatment presents an interesting solution, in order to reduce the environmental impacts as compared to fossil fuel solutions. It is not the purpose of the EcoDynBat project to discuss which allocation procedure has to be preferred. However, based on the above results, it appears necessary to discuss this specific point and test these two model choices for the LCA calculations, since this assumption leads to completely opposite results.

Micro-CHP heat and electricity impacts

Based on the assumptions and models presented, the environmental impacts of the heat and electricity produced by the micro-CHP units are calculated. The results are given in Table 80 and Figure 113.

Table 80 Environmental impacts of heat and electricity produced by micro-CHP (combustion and fuel cell), - EcoDynBat assumptions.

		Fuel cell heat		Fuel cell electricity		MicroCHP heat		MicroCHP electricity	
		Waste	Recyclable	Waste	Recyclable	Waste	Recyclable	Waste	Recyclable
0% bio-methane	Climate change [kg CO_2 eq/kWh]	0.068	0.068	0.454	0.454	0.107	0.107	0.922	0.922
	Non-renew. E [MJp/kWh]	1.18	1.18	7.96	7.96	1.77	1.77	15.01	15.01
	Renew-E [MJp/kWh]	0.014	0.014	0.045	0.045	0.004	0.004	0.033	0.033
	Ecological scarcity [UBP/kWh]	54	54	307	307	66	66	562	562
10% bio-methane	Climate change [kg CO_2 eq/kWh]	0.065	0.072	0.428	0.479	0.096	0.107	0.697	0.776
	Non-renew. E [MJp/kWh]	1.09	1.11	7.33	7.47	1.52	1.55	11.02	11.25
	Renew-E [MJp/kWh]	0.017	0.023	0.066	0.110	0.009	0.018	0.063	0.131
	Ecological scarcity [UBP/kWh]	52	94	294	596	60	125	433	905
20% bio-methane	Climate change [kg CO_2 eq/kWh]	0.061	0.075	0.401	0.503	0.090	0.112	0.649	0.81
	Non-renew. E [MJp/kWh]	0.99	1.03	6.64	6.93	1.37	1.44	9.96	10.41
	Renew-E [MJp/kWh]	0.020	0.032	0.087	0.175	0.013	0.032	0.096	0.232
	Ecological scarcity [UBP/kWh]	50	133	280	885	57	186	409	1352
100% bio-méthane	Climate change [kg CO_2 eq/kWh]	0.031	0.101	0.188	0.697	0.039	0.148	0.283	1.076
	Non-renew. E [MJp/kWh]	0.24	0.44	1.15	2.60	0.20	0.51	1.41	3.67

	Renew-E [MJp/kWh]	0.043	0.103	0.256	0.695	0.050	0.144	0.359	1.042
	Ecological scarcity [UBP/kWh]	35	450	171	3197	31	680	224	4934

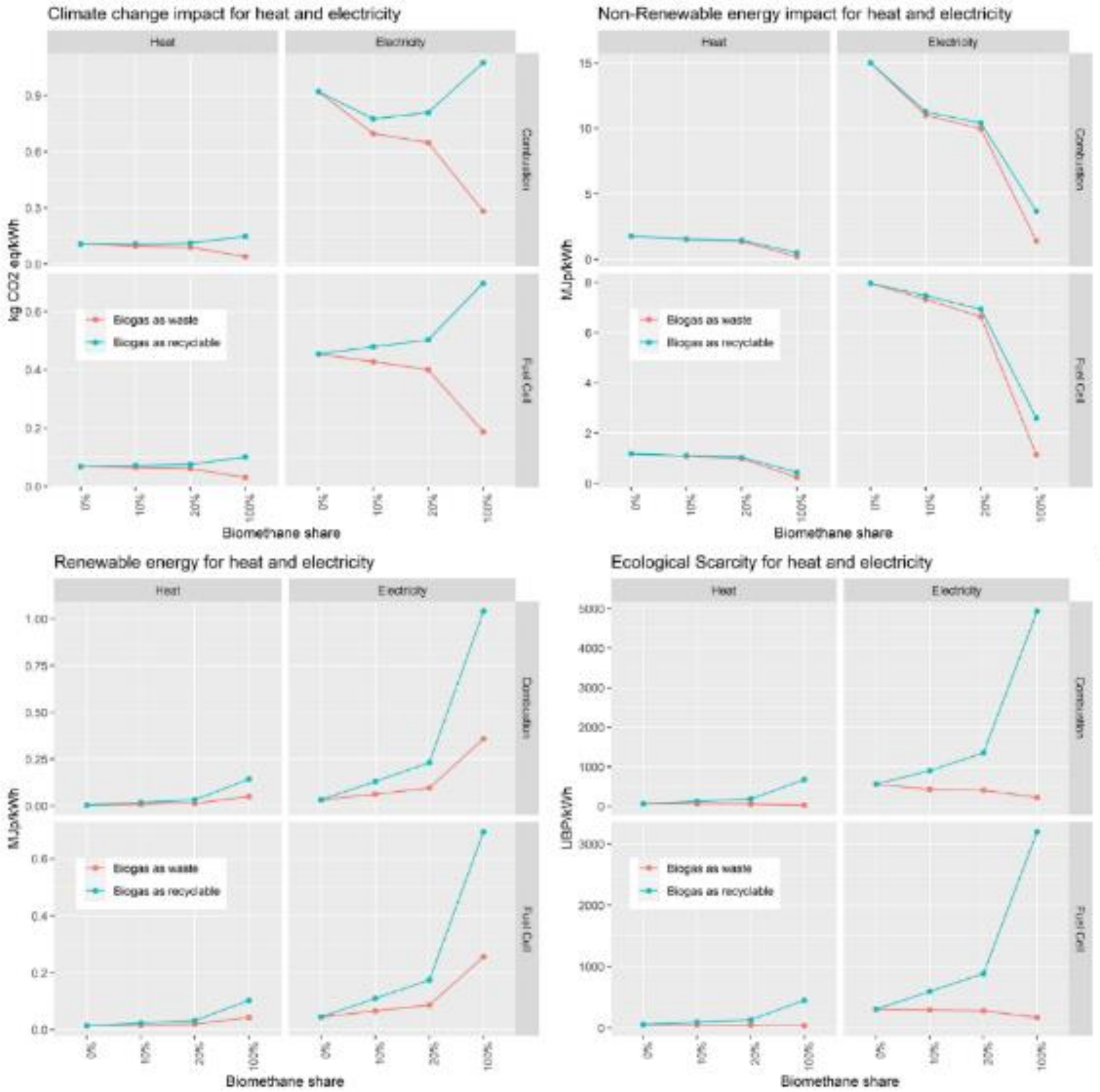


Figure 113 Environmental impacts of heat and electricity, produced by the micro-CHP (combustion and fuel cell), according to the EcoDynBat assumptions

As it was the case for the backup boiler, the environmental impacts of the heat and electricity, produced by the combustion or fuel cell micro-CHP, are driven by the allocation choice of the biogas production. If the substrate used for the biogas is considered as a recyclable product, therefore, the impacts are very high for the climate change and ecological scarcity indicators. The higher the bio-methane share is, the higher these indicators are. For example, for the configuration of a combustion based micro-CHP with 100% of bio-methane (considered as a recyclable product), the climate change impact of the produced electricity is 1.076kg CO_2 eq/kWh. On the contrary, when assuming the biogas as a waste treatment, the climate change impact of electricity is 0.283kg CO_2 eq/kWh. For the option “biogas as waste treatment”, the environmental impacts decrease, with the increasing bio-methane share (apart for the renewable indicator, since the share of renewable energy increases). The heat impacts are significantly lower, than the impact of a traditional condensing boiler (see previous chapter). The electricity impacts vary from 188 g CO_2 eq/kWh (electricity produced by a fuel cell micro-CHP with 100% bio-methane) to 697 g CO_2 eq/kWh (electricity produced by a combustion micro-CHP with 10% bio-methane).

In order to evaluate the potential gain of the micro-CHP, its impacts are compared to those of the Swiss grid electricity, see Figure 114. To do so, the environmental impact of the micro-CHP are plotted for each bio-methane share (horizontal lines) and the ordered impacts of the grid electricity are also displayed. The impacts concern the case that the biogas is issued for the waste treatment. Regarding the climate change impact, the impacts overcome the maximum grid impact, for all the scenarios that have a bio-methane share equal or lower than 20%, for the combustion micro-CHP. For all the other scenarios, the higher the bio-methane share, the larger the time period that the micro-CHP impacts remain below the impacts of the grid electricity. For example, the electricity from a fuel cell with 100% of bio-methane has lower impact than that of the grid electricity, for 28.5 % of the time, while the impacts of the electricity from a combustion based CHP, with 100% of bio-methane, remains 9 % of the time, lower than those of the grid electricity.

Regarding the NRE indicator, the impacts overcome the electricity grid impact only for the case when there is no bio-methane in the gas network. With 10% and 20% of bio-methane, the impacts of the combustion based CHP heat lie in the upper range of the grid distribution. On the contrary, the electricity from both technologies with 100% bio-methane has an impact below that of the Swiss mix, since it is 100% renewable. The results for the RE indicator are reversed. The higher the bio-methane share is for each micro-CHP technology, the higher the RE impacts are. Nevertheless, it should be noted that the micro-CHP impacts are far below the grid impacts, showing that the grid electricity has a higher content of renewable sources. Finally, regarding the ecological scarcity, the higher the bio-methane share is, the larger the time-period that the impacts are below the impacts of the grid electricity, as it is the case for all the indicators. For the combustion micro-CHP, low bio-methane shares imply an impact in the upper range of the Swiss consumed electricity. It is interesting to note that for all the indicators the higher the bio-methane share the lower are the impacts and that the impacts of the fuel cell micro-CHP are always lower than those of the combustion micro-CHP.

Thus, using a micro-CHP and considering the biogas as a product obtained from waste treatment, presents a favorable solution, compared to the grid electricity, but not always. There are times that the grid has very low impacts, i.e. mostly when Switzerland imports less. Nevertheless, considering the impact of the heat (see Table 80), it appears that using a micro-CHP with a high bio-methane share is an interesting solution, in terms of environmental impacts as compared to a gas boiler, for the heating needs.

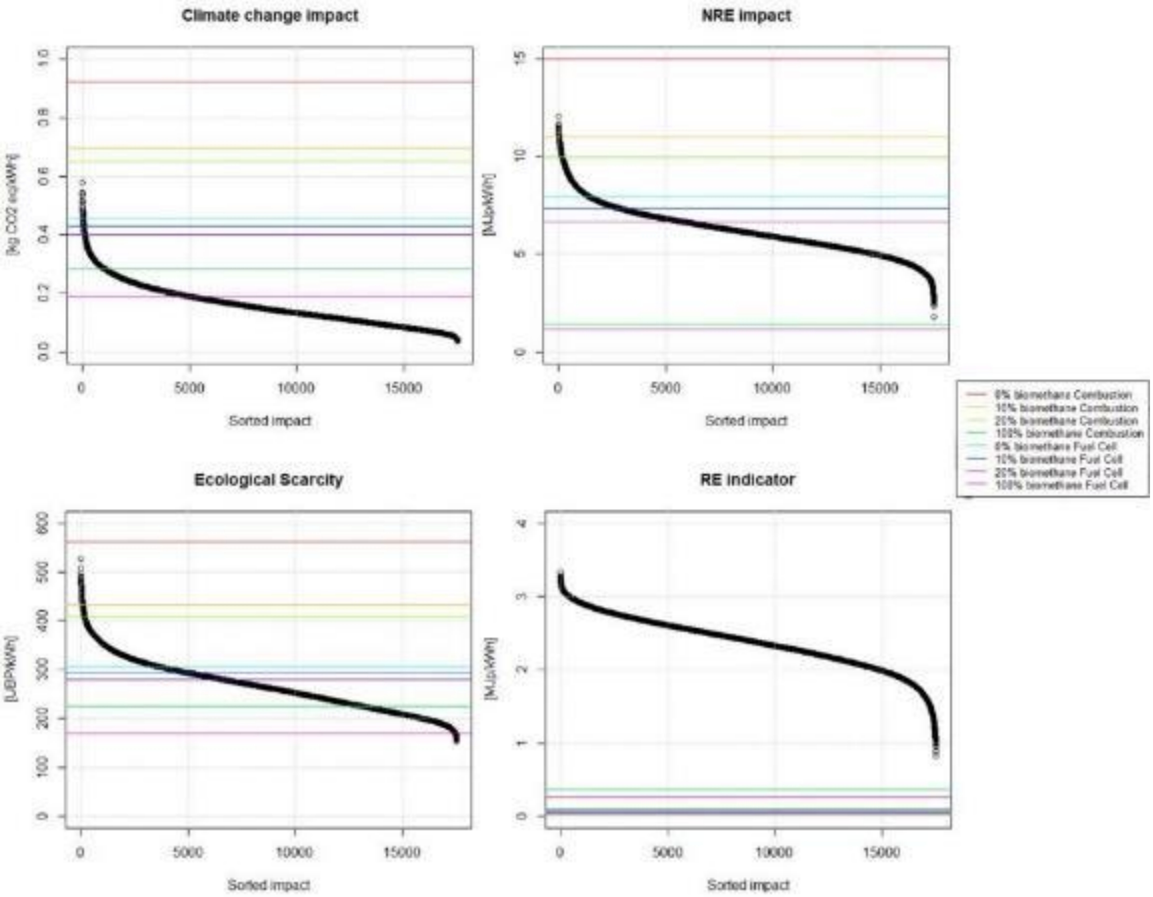


Figure 114 Impact of electricity produced by micro-CHP (combustion and fuel cell) with the assumption "biogas from waste)

The environmental impacts of the electricity, produced by the two considered micro-CHP technologies are also displayed in Figure 115, for the assumption “biogas as a recyclable product”.

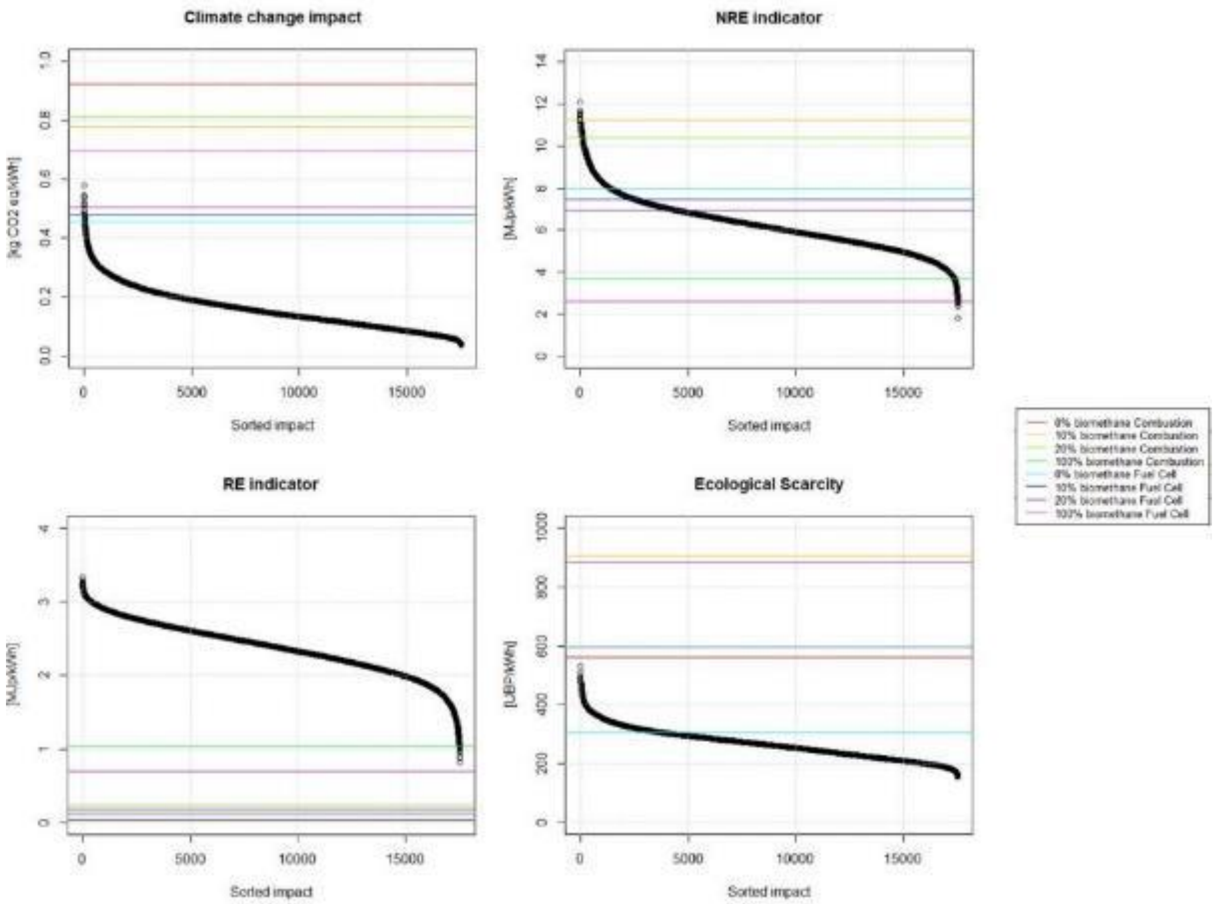


Figure 115 Impact of electricity produced by micro-CHP (combustion and fuel cell) with the assumption "biogas from recyclable product".

Note: the impact lines for 100% bio-methane is too high to be plotted in the same graph, it is therefore not displayed here

The results of Figure 115 are completely different, from the results of biogas issued from waste treatment. For the climate change and the ecological scarcity impact categories, the higher the bio-methane share is, the higher the impacts are. In other words, with this assumption, adding bio-methane in the gas network implies a higher impact. It would be therefore more interesting to use micro-CHP with 100% fossil fuel natural gas. Considering the NRE indicator, it appears that the impacts of the bio-methane solutions are between the upper and lower limit of those of the grid electricity, while the fuel cell technology present the most favorable solution. For the RE indicator, logically, the higher the bio-methane share is, the higher the impact. However, for the case of 100% of bio-methane, the impacts are in the lower range of the Swiss electricity mix.

The heat impacts produced by the micro-CHP technology have been compared to the heat produced by a gas boiler. The results for the different bio-methane shares and two biogas modelling choices (waste or recyclable) are displayed in Figure 116.

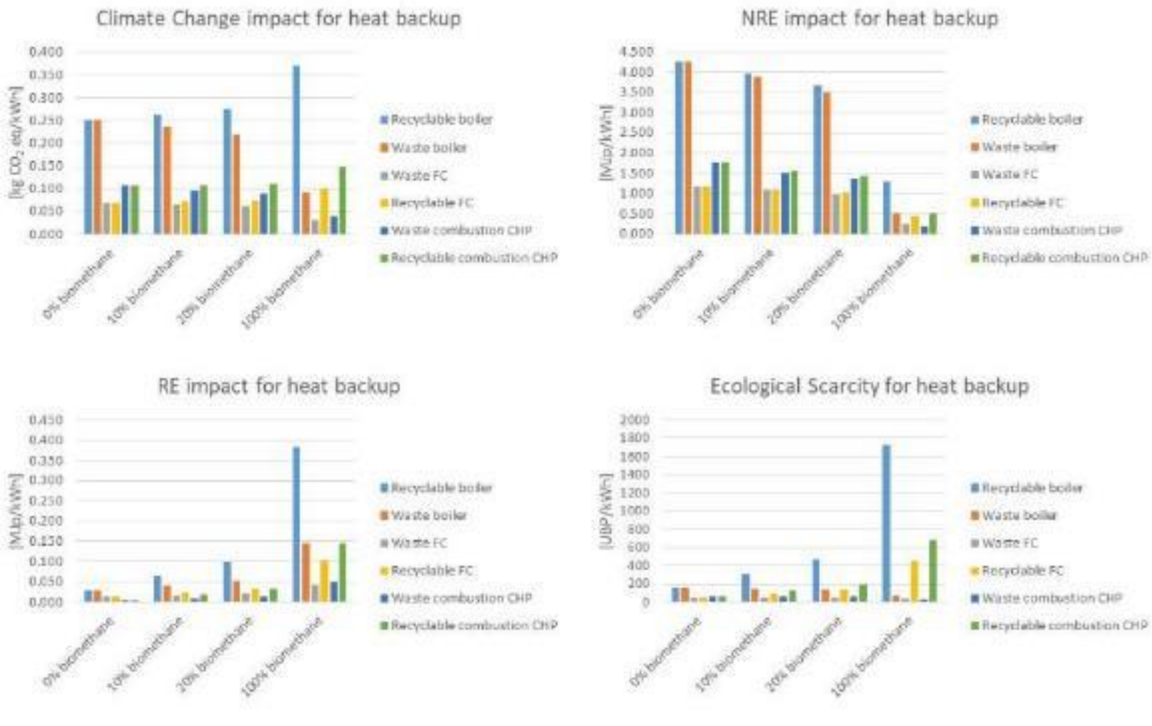


Figure 116 Comparison of the heat produced by the micro-CHP to the heat produced by a traditional condensing gas boiler (FC = Fuel Cell)

The environmental impacts of the heat produced by the micro-CHP units are significantly lower than those produced by a gas boiler, using the same share of bio-methane. In addition, the allocation assumption, regarding the biogas production, influences less the heat environmental impacts than it was the case for the electricity impacts, since the exergy allocation factor for the heat is lower, i.e. 0.139 compared to 1 for electricity). However, as it was the case for the electricity impacts, the biogas impact assumption will reverse the results. In other words, with the assumption “biogas as a waste treatment”, the higher the bio-methane share is, the lower the impacts are. On the contrary, for the assumption “biogas as a recyclable product”, the higher the bio-methane share is, the higher the impacts are. Furthermore, if biogas is produced from a waste treatment, the heat and electricity produced with micro-CHP are competitive to the grid electricity or the heat coming from a gas boiler, while high bio-methane shares have positive effect on the environmental impacts. On the contrary, if biogas is considered as a recyclable product, the heat impacts of the micro-CHP are lower than a traditional gas boiler, while this is not the case for the electricity impacts, which are higher than the impacts of the Swiss electricity mix. In this situation, the building heat and electricity profiles could be a key element, i.e. the high impacts of the electricity coming from the micro-CHP, have to be compensated by the environmental gain of the heat impacts of the micro-CHP.

Description of case studies

Four case studies have been considered for the micro-CHP environmental impact assessment. For each of them two scenarios have been considered, i.e. of a combustion-based micro-CHP or a fuel cell. The main building characteristics are given in Table 81.

Table 81 Characteristics for the Micro-CHP case studies

		Construction period	Surface [m^2]	Electricity Demand [kWh]	Heat Demand [kWh]	Heat covered by the CHP	Electricity covered by the CHP
CHP 1	a- Combustion-CHP	2013	2 663	37 332	136 534	77.1%	69.9%
	b- Fuel Cell					16.1%	100.0%
CHP 2	a- Combustion-CHP	1919-1945	1 204	11 416	41 548	78.0%	67.1%
	b- Fuel Cell					16.2%	99.3%
CHP 3	a- Combustion-CHP	1919-1945	890	17 771	77 059	69.0%	74.6%
	b- Fuel Cell					12.2%	99.9%
CHP 4	a- Combustion-CHP	Before 1919	375	4 650	29 229	50.7%	74.7%
	b- Fuel Cell					8.3%	99.0%

The CHP1 case corresponds to the case study CS5 presented in chapter 4-a. The CHP2 to CHP4 cases correspond to MFH buildings, located in the canton of Neuchâtel. The energy data have been provided by Viteos for the year 2018. The attributes (construction period and surface) have been extracted from the RegBL. The overall yearly heat demand profiles are displayed in Figure 117 and the yearly electricity demand profiles are given in Figure 118.

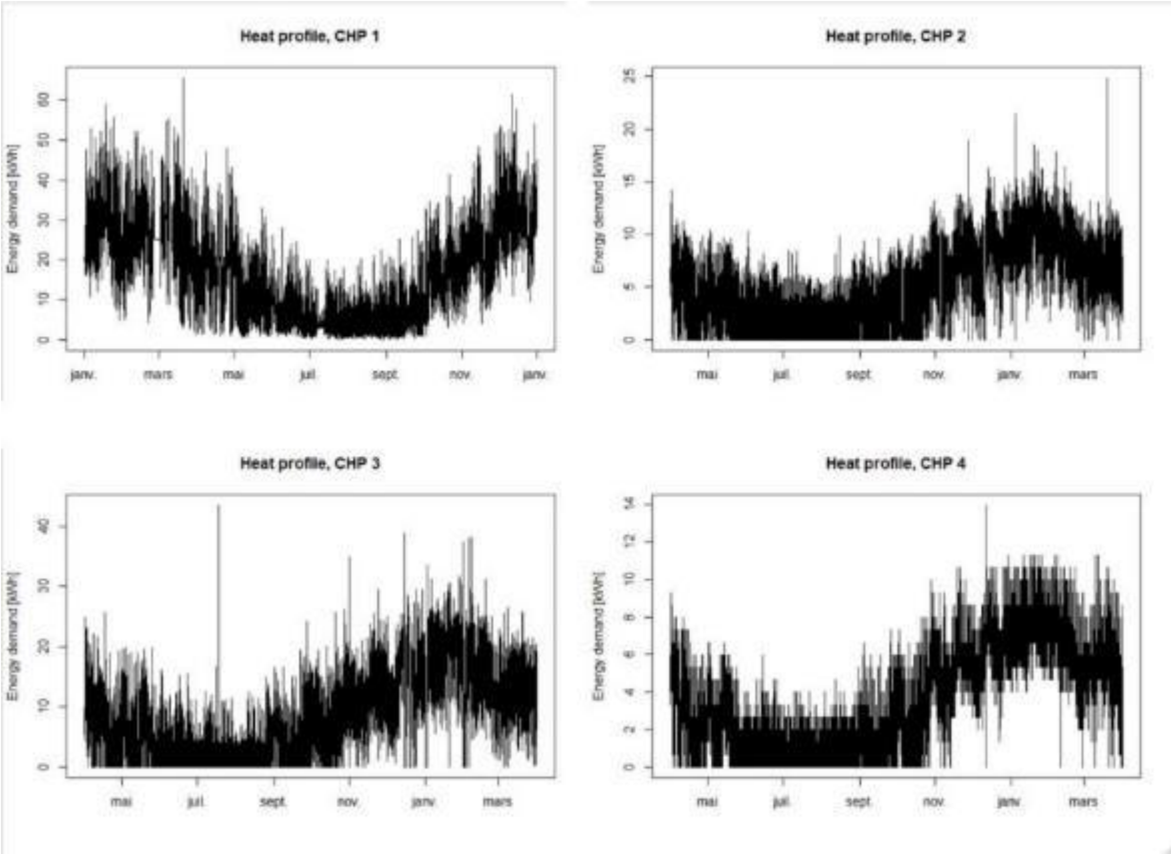


Figure 117 Annual heat demand profiles of the four case studies

The CHP1 corresponds to a low energy consumption building and its heating demand profile presents a high seasonality. For CHP1, the period (mid-april to mid-september) for which the heat demand corresponds to domestic hot water preparation is longer than for CHP 2 to 4.

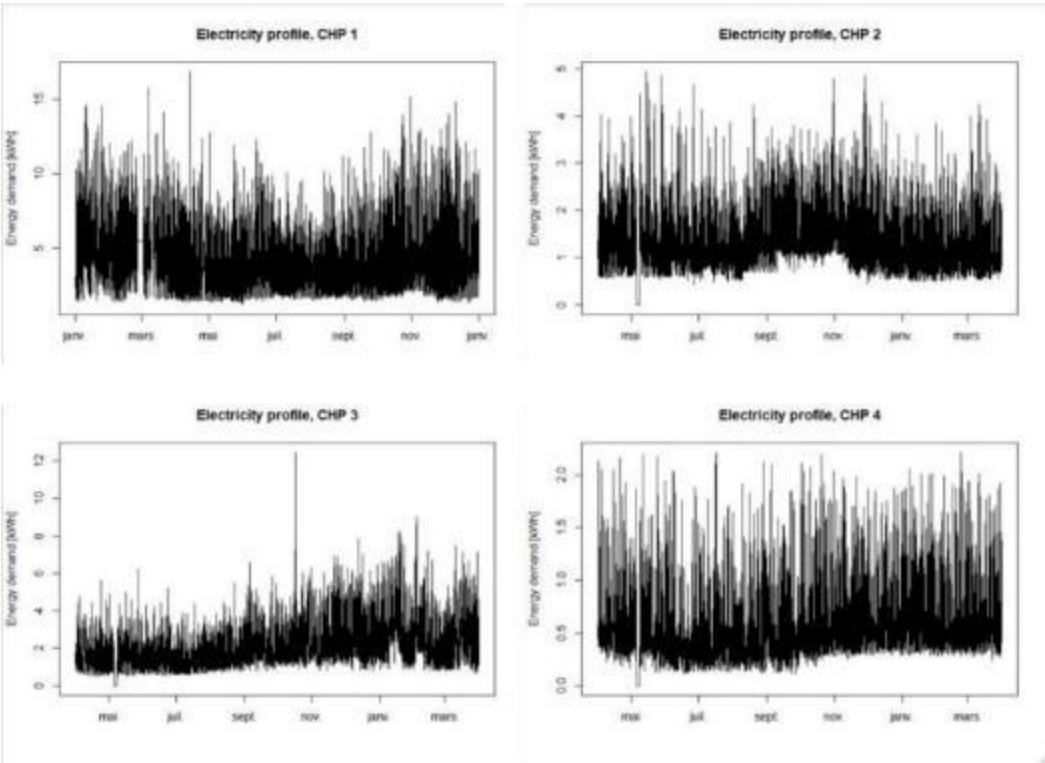


Figure 118 Annual electricity demand profiles of the four case studies

The overall electricity demand profiles are quite similar among the four case studies. The annual trend does not exhibit seasonality. However, there are some small variations for the CHP 2 and CHP 4. For the CHP 2, there is a small increase of the electricity demand in autumn, while for the CHP 4, there is a slight decrease in summer. The latter could be explained because of the holiday period in summer, while the former could be probably linked to the occupants' behavior.

There are important intraday fluctuations, even though the electricity demand does not show seasonality. These fluctuations are presented for a typical day in Figure 119, for both heat and electricity. The electricity daily demand profiles are similar for all case studies and show the typical daily trends, i.e. one peak at noon and one in the evening. The heat profiles show a peak in the early morning (heating system restart after the night) and a smaller one, in the evening.

The percentage of heat and electricity covered by the micro-CHP units have been calculated, using the model developed in chapter 2. The combustion-based scenarios offer the largest share of covered energy for both heat and electricity (approx. 70% on average). Conversely, the fuel-cell scenarios covers almost all the electricity needs. Moreover, in the used model, the use of a thermal stock enables to produce electricity when necessary and to store the associated heat production. It has to be noted, that this difference of coverage is influencial on the overall building energy demand overall impact. Indeed, for the fuel cell scenario, there will be almost no electricity taken from the grid while for the combustion-based units, still 30% will be consumed. Moreover, the heat backup will be more used in the fuel-cell scenario than for the other case.

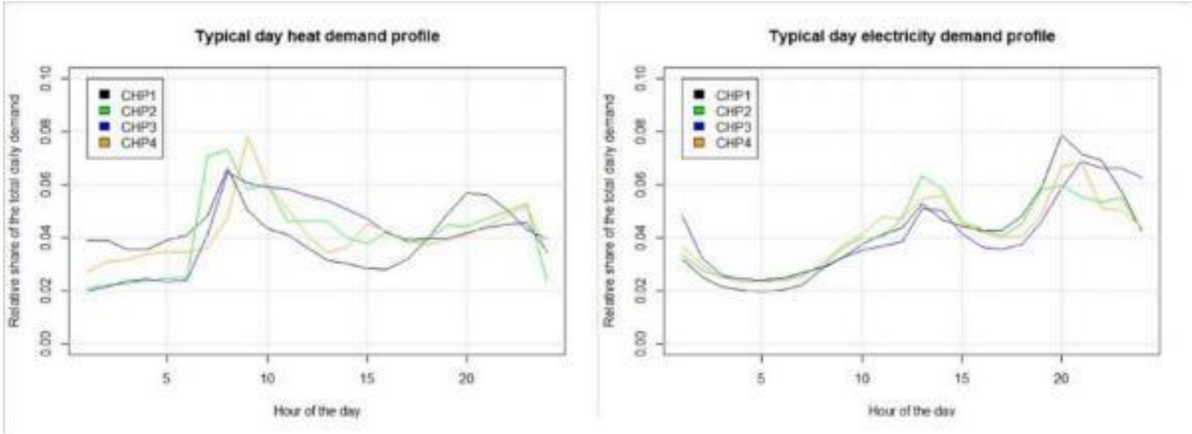


Figure 119 Typical daily heat and electricity demand profiles of the CHP 1 to 4

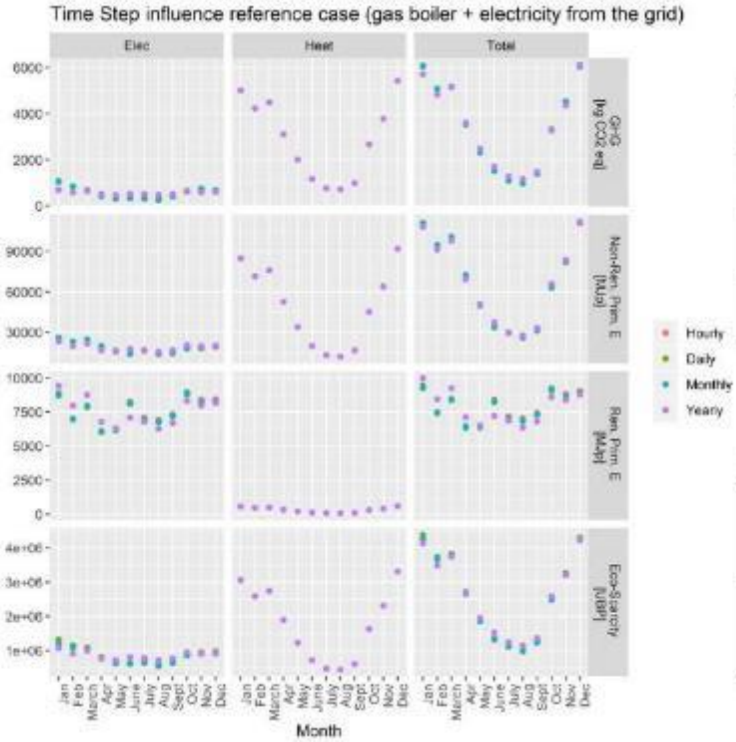
Environmental impact results

In this section, for all the case studies, the time step influence on the environmental impacts is presented for the reference scenario (gas boiler for heat and electricity from the grid), as well as for the combustion-based and fuel cell micro-CHP alternatives.

Case study: CHP1

Reference scenario

The results of the reference situation (i.e. gas boiler for space heat and domestic hot water and electricity from the grid) are presented in Figure 120:



		Electricity impact	Heat impact	Total impact
Climate Change [kg CO_2 eq/kWh]	Hourly	6 650	34 407	41 057
	Daily	6 825	34 407	41 235
	Monthly	6 785	34 407	41 192
	Yearly	6 725	34 407	41 151
NRE [MJp/kWh]	Hourly	223 638	581 634	805 272
	Daily	227 370	581 634	809 004
	Monthly	227 736	581 634	809 370
	Yearly	224 832	581 634	806 466
RE [MJp/kWh]	Hourly	91 572	3 823	95 395
	Daily	90 159	3 823	93 982
	Monthly	90 449	3 823	94 272
	Yearly	90 562	3 823	94 385
ES [UBP/kWh]	Hourly	10 251 261	21 033 442	31 284 703
	Daily	10 388 918	21 033 442	31 422 360
	Monthly	9 894 204	21 033 442	30 927 647
	Yearly	10 351 052	21 033 442	31 384 494

		Time Step influence in % compared to Yearly calculation			
		Hourly	Daily	Monthly	Yearly
Electricity	Climate Change [kg CO_2 eq/kWh]	-1.4%	1.5%	0.9%	0.0%
	NRE [MJp/kWh]	-0.5%	1.1%	1.3%	0.0%
	RE [MJp/kWh]	1.1%	-0.4%	-0.1%	0.0%
	ES [UBP/kWh]	-1.2%	0.4%	-4.4%	0.0%
Total	Climate Change [kg CO_2 eq/kWh]	-0.2%	0.8%	0.1%	0.0%
	NRE [MJp/kWh]	-0.1%	0.3%	0.4%	0.0%
	RE [MJp/kWh]	1.1%	-0.4%	-0.1%	0.0%
	ES [UBP/kWh]	-0.4%	0.1%	-1.5%	0.0%

Figure 120 Monthly environmental impact profile, CHP1 - Reference case

The total environmental impacts of the building energy demand are strongly influenced by the heat demand. In this reference case, the heat is covered by a gas boiler, operating with natural gas. The impacts of the gas are significantly high, as compared to that of the electricity, which has a small contribution to the overall environmental impacts. Therefore, the time step influence is very small, i.e., comparing the impacts of the yearly time step to the other time steps, implies approximately a difference of 1%.

Combustion-based CHP

The results of the combustion-based micro-CHP are displayed in Table 82 and Figure 121.

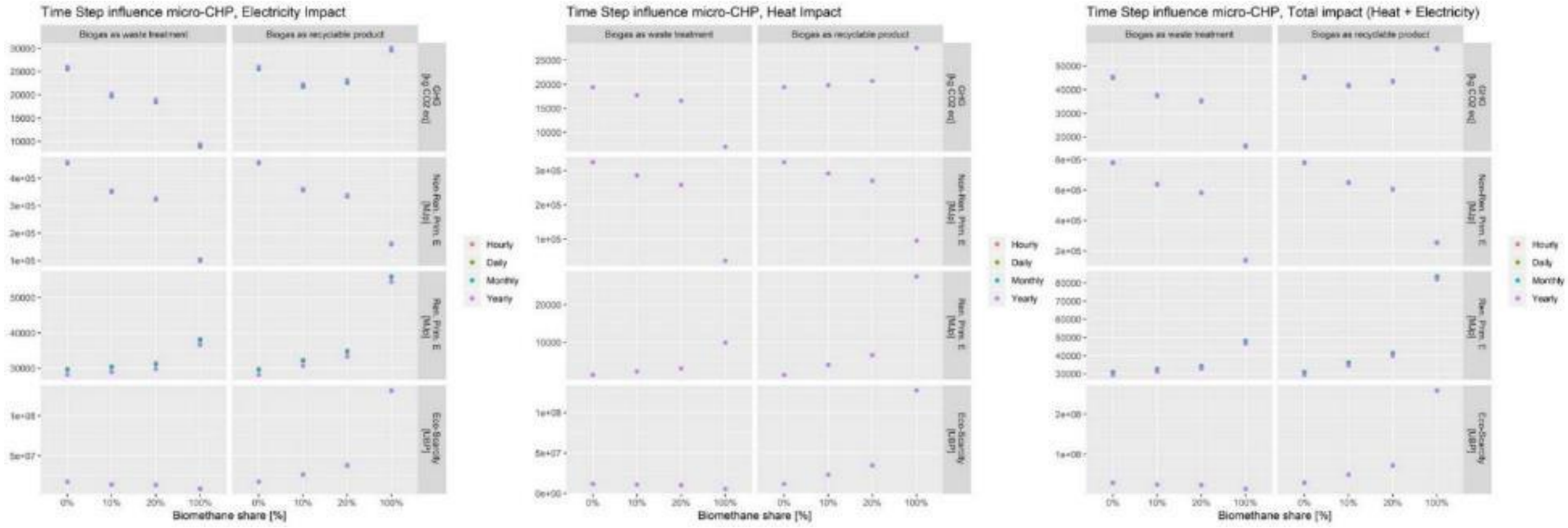


Figure 121 Time step influence on the environmental impacts of CHP1, for the combustion based unit

Table 82 Environmental impact results of CHP1, for the combustion based CHP

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO_2 eq/kWh]	Hourly	25 550	19 680	18 428	8 879	19 422	17 744	16 592	7 061	44 972	37 424	35 020	15 940
		Daily	25 578	19 708	18 455	8 906	19 422	17 744	16 592	7 061	45 000	37 451	35 047	15 967
		Monthly	25 591	19 720	18 468	8 919	19 422	17 744	16 592	7 061	45 013	37 464	35 060	15 980
		Yearly	26 080	20 210	18 957	9 408	19 422	17 744	16 592	7 061	45 502	37 954	35 549	16 469
	NRE [MJp /kWh]	Hourly	454 487	350 571	322 706	99 767	324 581	285 899	258 268	37 008	779 068	636 469	580 974	136 774
		Daily	455 354	351 438	323 574	100 634	324 581	285 899	258 268	37 008	779 935	637 337	581 841	137 642
		Monthly	455 756	351 839	323 975	101 035	324 581	285 899	258 268	37 008	780 337	637 738	582 243	138 043
		Yearly	459 237	355 320	327 456	104 516	324 581	285 899	258 268	37 008	783 818	641 219	585 723	141 524
	RE [MJp /kWh]	Hourly	29 746	30 528	31 389	38 251	1 341	2 242	3 038	9 930	31 087	32 770	34 427	48 181
		Daily	29 542	30 325	31 186	38 047	1 341	2 242	3 038	9 930	30 883	32 567	34 224	47 978
		Monthly	29 510	30 293	31 154	38 016	1 341	2 242	3 038	9 930	30 852	32 535	34 192	47 946
		Yearly	28 132	28 914	29 775	36 637	1 341	2 242	3 038	9 930	29 473	31 157	32 813	46 568
	ES [UBP/kWh]	Hourly	17 351 692	13 987 406	13 359 653	8 525 297	11 908 674	11 023 258	10 421 903	5 610 965	29 260 365	25 010 663	23 781 556	14 136 262
		Daily	17 374 640	14 010 354	13 382 601	8 548 245	11 908 674	11 023 258	10 421 903	5 610 965	29 283 314	25 033 611	23 804 505	14 159 210
		Monthly	17 335 202	13 970 916	13 343 163	8 508 807	11 908 674	11 023 258	10 421 903	5 610 965	29 243 876	24 994 174	23 765 067	14 119 773
		Yearly	17 791 002	14 426 716	13 798 964	8 964 607	11 908 674	11 023 258	10 421 903	5 610 965	29 699 676	25 449 974	24 220 867	14 575 573
Biogas as a recyclable product	Climate Change [kg CO_2 eq/kWh]	Hourly	25 550	21 741	22 628	29 568	19 422	19 804	20 712	27 556	44 972	41 545	43 340	57 124
		Daily	25 578	21 769	22 656	29 596	19 422	19 804	20 712	27 556	45 000	41 573	43 368	57 152
		Monthly	25 591	21 782	22 669	29 609	19 422	19 804	20 712	27 556	45 013	41 585	43 381	57 165
		Yearly	26 080	22 271	23 158	30 098	19 422	19 804	20 712	27 556	45 502	42 075	43 870	57 654
	NRE [MJp /kWh]	Hourly	454 487	356 467	334 473	158 652	324 581	291 731	269 932	95 437	779 068	648 198	604 405	254 089
		Daily	455 354	357 334	335 340	159 519	324 581	291 731	269 932	95 437	779 935	649 065	605 273	254 957
		Monthly	455 756	357 735	335 742	159 921	324 581	291 731	269 932	95 437	780 337	649 467	605 674	255 358
		Yearly	459 237	361 216	339 222	163 402	324 581	291 731	269 932	95 437	783 818	652 948	609 155	258 839
	RE [MJp /kWh]	Hourly	29 746	32 302	34 937	56 070	1 341	3 967	6 593	27 601	31 087	36 270	41 531	83 672
		Daily	29 542	32 099	34 734	55 867	1 341	3 967	6 593	27 601	30 883	36 066	41 327	83 468
		Monthly	29 510	32 067	34 702	55 835	1 341	3 967	6 593	27 601	30 852	36 034	41 296	83 437
		Yearly	28 132	30 689	33 324	54 457	1 341	3 967	6 593	27 601	29 473	34 656	39 917	82 058
	ES [UBP/kWh]	Hourly	17 351 692	26 276 368	37 958 450	131 415 104	11 908 674	23 220 635	34 816 658	127 584 635	29 260 365	49 497 003	72 775 108	258 999 739
		Daily	17 374 640	26 299 316	37 981 398	131 438 052	11 908 674	23 220 635	34 816 658	127 584 635	29 283 314	49 519 951	72 798 056	259 022 687
		Monthly	17 335 202	26 259 879	37 941 960	131 398 615	11 908 674	23 220 635	34 816 658	127 584 635	29 243 876	49 480 514	72 758 619	258 983 249
		Yearly	17 791 002	26 715 679	38 397 761	131 854 415	11 908 674	23 220 635	34 816 658	127 584 635	29 699 676	49 936 314	73 214 419	259 439 050

The relative time step influence has been calculated, based on the results of Table 82 and the results are summarized in Table 83. For each time step, the relative influence has been calculated compared to the annual time step.

Table 83 CHP1: Combustion based unit - Time step influence compared to the annual time step

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	Hourly	-2.0%	-2.6%	-2.8%	-5.6%	0.0%	0.0%	0.0%	0.0%	-1.2%	-1.4%	-1.5%	-3.2%
		Daily	-1.9%	-2.5%	-2.6%	-5.3%	0.0%	0.0%	0.0%	0.0%	-1.1%	-1.3%	-1.4%	-3.0%
		Monthly	-1.9%	-2.4%	-2.6%	-5.2%	0.0%	0.0%	0.0%	0.0%	-1.1%	-1.3%	-1.4%	-3.0%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE	Hourly	-1.0%	-1.3%	-1.5%	-4.5%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.7%	-0.8%	-3.4%
		Daily	-0.8%	-1.1%	-1.2%	-3.7%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.6%	-0.7%	-2.7%
		Monthly	-0.8%	-1.0%	-1.1%	-3.3%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.6%	-2.5%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE	Hourly	5.7%	5.6%	5.4%	4.4%	0.0%	0.0%	0.0%	0.0%	5.5%	5.2%	4.9%	3.5%
		Daily	5.0%	4.9%	4.7%	3.8%	0.0%	0.0%	0.0%	0.0%	4.8%	4.5%	4.3%	3.0%
		Monthly	4.9%	4.8%	4.6%	3.8%	0.0%	0.0%	0.0%	0.0%	4.7%	4.4%	4.2%	3.0%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES	Hourly	-2.5%	-3.0%	-3.2%	-4.9%	0.0%	0.0%	0.0%	0.0%	-1.5%	-1.7%	-1.8%	-3.0%
		Daily	-2.3%	-2.9%	-3.0%	-4.6%	0.0%	0.0%	0.0%	0.0%	-1.4%	-1.6%	-1.7%	-2.9%
		Monthly	-2.6%	-3.2%	-3.3%	-5.1%	0.0%	0.0%	0.0%	0.0%	-1.5%	-1.8%	-1.9%	-3.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biogas as a recyclable product	Climate Change	Hourly	-2.0%	-2.4%	-2.3%	-1.8%	0.0%	0.0%	0.0%	0.0%	-1.2%	-1.3%	-1.2%	-0.9%
		Daily	-1.9%	-2.3%	-2.2%	-1.7%	0.0%	0.0%	0.0%	0.0%	-1.1%	-1.2%	-1.1%	-0.9%
		Monthly	-1.9%	-2.2%	-2.1%	-1.6%	0.0%	0.0%	0.0%	0.0%	-1.1%	-1.2%	-1.1%	-0.8%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE	Hourly	-1.0%	-1.3%	-1.4%	-2.9%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.7%	-0.8%	-1.8%
		Daily	-0.8%	-1.1%	-1.1%	-2.4%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.6%	-0.6%	-1.5%
		Monthly	-0.8%	-1.0%	-1.0%	-2.1%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.6%	-1.3%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE	Hourly	5.7%	5.3%	4.8%	3.0%	0.0%	0.0%	0.0%	0.0%	5.5%	4.7%	4.0%	2.0%
		Daily	5.0%	4.6%	4.2%	2.6%	0.0%	0.0%	0.0%	0.0%	4.8%	4.1%	3.5%	1.7%
		Monthly	4.9%	4.5%	4.1%	2.5%	0.0%	0.0%	0.0%	0.0%	4.7%	4.0%	3.5%	1.7%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES	Hourly	-2.5%	-1.6%	-1.1%	-0.3%	0.0%	0.0%	0.0%	0.0%	-1.5%	-0.9%	-0.6%	-0.2%
		Daily	-2.3%	-1.6%	-1.1%	-0.3%	0.0%	0.0%	0.0%	0.0%	-1.4%	-0.8%	-0.6%	-0.2%
		Monthly	-2.6%	-1.7%	-1.2%	-0.3%	0.0%	0.0%	0.0%	0.0%	-1.5%	-0.9%	-0.6%	-0.2%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The relative time step influence of the heat is zero, since the environmental impacts of the gas boiler or the micro-CHP are stable.

The relative time step difference of the electricity is still insignificant. Indeed, for the case of a micro-CHP unit, the electricity impact has a constant impact and covers 69.9% of the demand, in the "CHP1 combustion based unit". The time step influence is higher, when the biogas is considered as a waste treatment than with the other modelling assumption. In addition, the time step influences more the scenarios that have a higher share of bio-methane (100%). Nevertheless, in both cases, for the total energy demand level, the influence appears to be negligible, 2.4% on average. The Renewable Energy indicator is found to be the most sensitive on the time step, although the maximum relative time step difference from the annual time step is 5.2%, for the case of 10% bio-methane.

Thereby, the time step influence is negligible for this scenario. As already showed in chapter 4-a, the time step influences mostly seasonal energy profiles. However, this is not the case for the CHP 1, since the electricity profile was relatively constant and the seasonal heat demand was covered, by the micro – CHP or by the backup gas boiler.

The monthly environmental impact profiles for all the bio-methane shares are compared with the reference scenario in Figure 122. The relative difference from the reference case is given in Table 84.

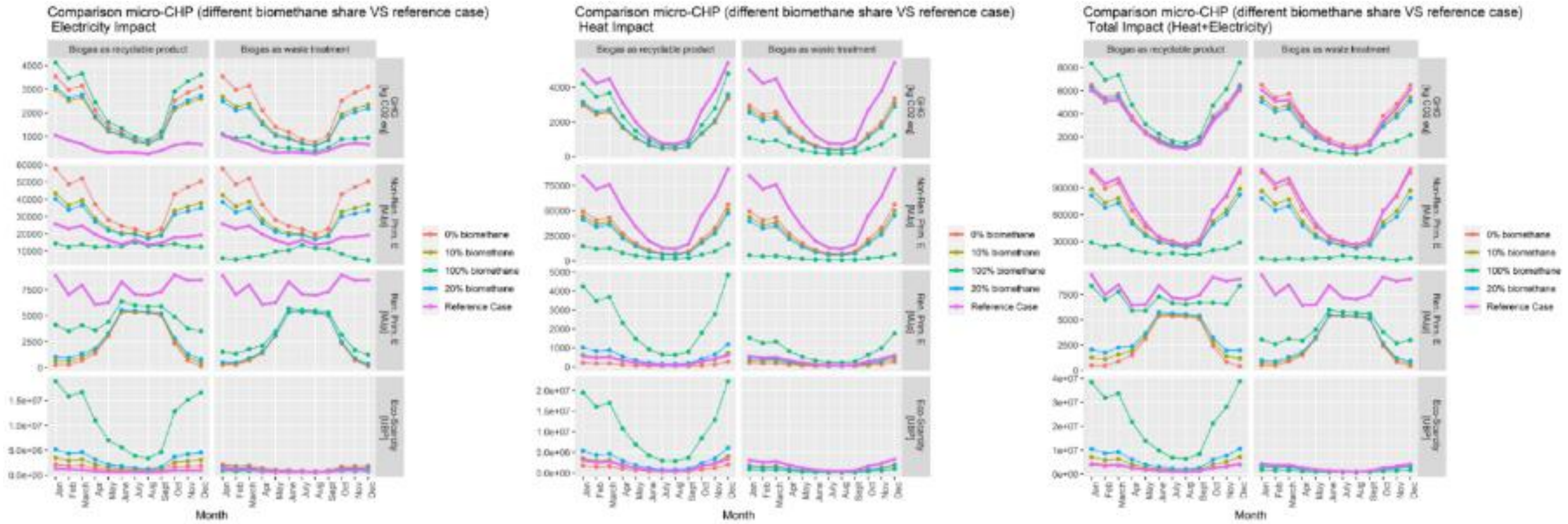


Figure 122 CHP1: Comparison of the reference case to the combustion based CHP for various bio-methane shares

Table 84 Comparison of the reference case to the combustion based CHP for various bio-methane shares (CHP1)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	285%	197%	178%	34%	-44%	-48%	-52%	-79%	9%	-9%	-15%	-61%
	NRE	103%	57%	44%	-55%	-44%	-51%	-56%	-94%	-3%	-21%	-28%	-83%
	RE	-68%	-67%	-66%	-58%	-65%	-41%	-21%	160%	-67%	-66%	-64%	-49%
	ES	31%	6%	1%	-36%	-44%	-47%	-37%	-74%	-6%	-20%	-24%	-55%
Biogas as a recyclable product	Climate Change	285%	228%	241%	346%	-44%	-42%	-40%	-20%	9%	1%	5%	38%
	NRE	103%	59%	50%	-29%	-44%	-50%	-54%	-84%	-3%	-20%	-25%	-68%
	RE	-68%	-65%	-62%	-39%	-65%	4%	72%	622%	-67%	-62%	-56%	-12%
	ES	31%	99%	187%	893%	-44%	9%	63%	498%	-6%	58%	133%	728%

The comparison between the combustion-based scenario and the reference scenario shows that the allocation regarding the biogas impact influences the results. Table 85 summarizes the results, regarding the electricity demand, while Table 86 summarizes the results of the heat impacts. Concerning the overall energy demand impact of the building, the observations are summarized in the Table 87.

Table 85 CHP-1: Key findings regarding the combustion-based scenario compared to the reference case for the electricity demand

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case for any bio-methane share. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share - Increase of bio-methane share implies reduction of the impact - 100% of bio-methane implies impact reduction compared to reference case (Threshold at about 56% of bio-methane share)
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies an increase of the impact
	ES	- Impact higher than reference case until almost 100% of bio-methane share (Threshold at about 22% of bio-methane share) - Increase of bio-methane share implies reduction of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend as the other allocation choice (Threshold at about 70% of bio-methane share)
	RE	- Same trend as the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 86 CHP-1: Key findings regarding the combustion-based scenario compared to the reference case for the heat demand

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Increase of bio-methane share implies increase of the impact - With 100% bio-methane the impact is higher than the reference case. This breakdown occurs at about 29% of bio-methane share in the supply mix
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact always lower than the reference case - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact already higher than reference case when 10% of bio-methane in the mix - Increase of bio-methane share implies increase of the impact - Largely above the reference case for large bio-methane share
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 87 Key findings regarding the combustion-based scenario compared to the reference case for the total energy demand (CHP1)

		Impact of total energy demand
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case except for no bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case - For 10 and 20% of bio-methane, the difference is small (1 to 5%) - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Impact lower only when 100% natural gas is used to supply the micro-CHP - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

The impact of the combustion-based alternative is thus highly influenced by the assumption regarding the impacts of the biogas production. If the biogas has no impact, promoting the micro-CHP alternative is of interest, because the environmental impacts are lower than the reference scenario. In this case, increasing the bio-methane share increases the environmental benefits of the micro-CHP.

On the contrary, for the other biogas impact assumption, the impact of the micro-CHP are higher than the reference case, for climate change and ecological scarcity. With this biogas assumption, the impacts increase when the bio-methane share increases. Nevertheless, for 10 and 20% bio-methane in the supply mix, the climate change impact is very similar to the standard configuration. The ecological-scarcity is however much higher than the reference even with low bio-methane share. For the primary energy indicators, the impacts are found to be lowered by micro-CHP uses and the improvement increase with the high bio-methane share.

Thus, the combustion-based micro-CHP has lower environmental impact than the reference when the biogas is considered to have no impacts. In the other case, low bio-methane share could be considered (10%) since the primary energy indicators show improvement and the climate change impact is equivalent. However, in such case, the ecological scarcity impact will be higher.

Fuel cell CHP

The results for the fuel cell micro-CHP are displayed in Table 88 and Figure 123. As it was the case for the combustion-based micro-CHP, the environmental impacts are strongly influenced by the assumption related to the biogas production. Indeed, the climate change and eco-scarcity indicators show the same trend as the combustion based micro-CHP, i.e, when the biogas is considered as issued from waste treatment, the higher the bio-methane share, the lower the impact is for both heat and electricity (and therefore the total building energy demand). The results are opposite when the biogas is considered as a recyclable product.

The allocation choice of the biogas influences less the primary energy indicators. In addition, it is found that the fuel cell reduce the non-renewable primary energy consumption while increasing the renewable primary energy indicator, because of the use of a renewable resource (bio-methane). In both cases, increasing the share of bio-methane reduced the environmental impacts.

The time step influence is found to be null for the fuel cell case study. Indeed, as showed, in Table 10the fuel cell covers 100% of the building electricity needs. Since the heat is covered by a non-electricity based solution, the overall time step influence is therefore zero. The comparison between the scenario with fuel cell and the reference case is displayed in Table 89 and in Figure 124.

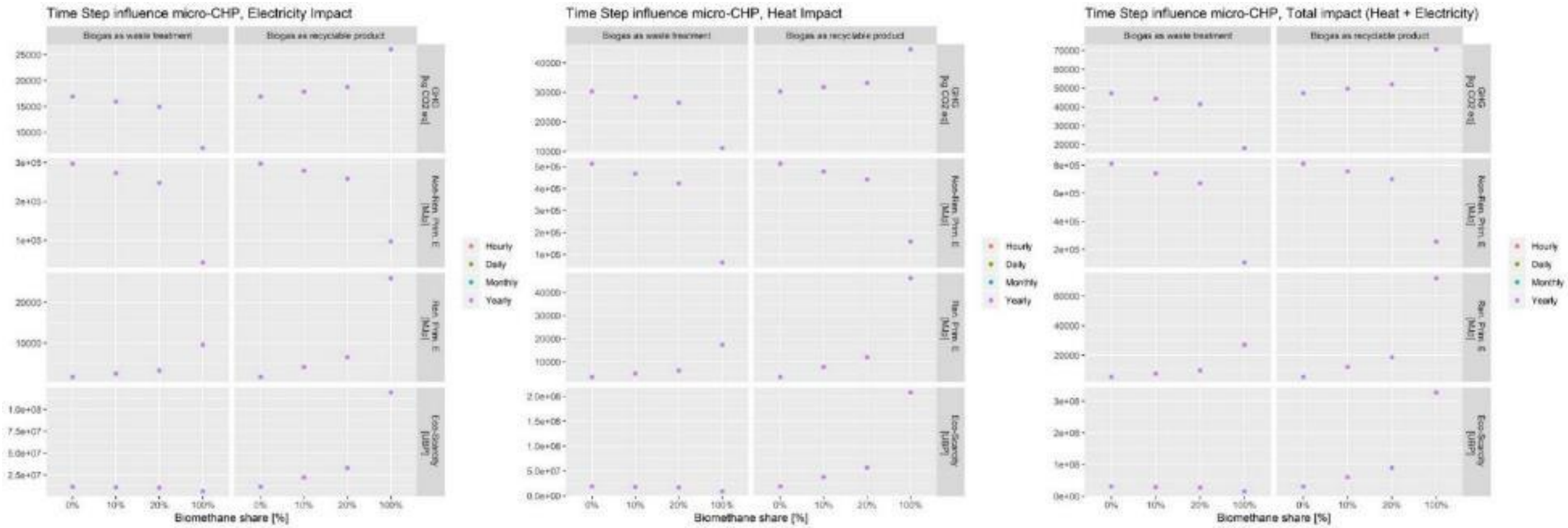


Figure 123 Yearly environmental impact for CHP1 with a fuel cell unit

Table 88 Environmental impact results of CHP1 with a fuel cell unit

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO_2 eq/kWh]	Hourly	16945	15975	14967	7018	30339	28434	26506	11130	47284	44409	41473	18148
		Daily	16945	15975	14967	7019	30339	28434	26506	11130	47285	44409	41474	18148
		Monthly	16945	15975	14967	7019	30339	28434	26506	11130	47285	44409	41474	18148
		Yearly	16945	15974	14967	7018	30339	28434	26506	11130	47284	44408	41473	18148
	NRE [MJp /kWh]	Hourly	297212	273515	247877	42999	514013	468966	423919	63520	811225	742480	671795	106519
		Daily	297220	273522	247885	43007	514013	468966	423919	63520	811232	742488	671803	106527
		Monthly	297219	273522	247884	43006	514013	468966	423919	63520	811232	742488	671803	106526
		Yearly	297205	273508	247870	42992	514013	468966	423919	63520	811218	742474	671789	106512
	RE [MJp /kWh]	Hourly	1710	2494	3278	9585	3560	4951	6342	17445	5271	7445	9620	27030
		Daily	1708	2491	3275	9582	3560	4951	6342	17445	5268	7442	9617	27027
		Monthly	1708	2492	3276	9583	3560	4951	6342	17445	5269	7443	9617	27028
		Yearly	1712	2496	3279	9586	3560	4951	6342	17445	5272	7447	9621	27031
	ES [UBP/kWh]	Hourly	11448288	10962739	10452596	6371532	18839105	17865071	16891038	9098722	30287393	28827810	27343634	15470254
		Daily	11448508	10962959	10452816	6371751	18839105	17865071	16891038	9098722	30287613	28828030	27343854	15470474
		Monthly	11448396	10962846	10452704	6371639	18839105	17865071	16891038	9098722	30287501	28827918	27343742	15470361
		Yearly	11447911	10962362	10452219	6371154	18839105	17865071	16891038	9098722	30287016	28827433	27343257	15469877
Biogas as a recyclable product	Climate Change [kg CO_2 eq/kWh]	Hourly	16945	17878	18774	26013	30339	31777	33193	44564	47284	49655	51967	70577
		Daily	16945	17878	18774	26014	30339	31777	33193	44564	47285	49655	51967	70577
		Monthly	16945	17878	18774	26014	30339	31777	33193	44564	47285	49655	51967	70577
		Yearly	16945	17878	18773	26013	30339	31777	33193	44564	47284	49655	51966	70577
	NRE [MJp /kWh]	Hourly	297212	278926	258737	97148	514013	478488	442942	158727	811225	757414	701679	255875
		Daily	297220	278934	258744	97156	514013	478488	442942	158727	811232	757422	701687	255883
		Monthly	297219	278933	258744	97155	514013	478488	442942	158727	811232	757422	701686	255882
		Yearly	297205	278919	258730	97141	514013	478488	442942	158727	811218	757408	701672	255868
	RE [MJp /kWh]	Hourly	1710	4136	6562	25967	3560	7832	12104	46256	5271	11968	18666	72223
		Daily	1708	4133	6559	25965	3560	7832	12104	46256	5268	11966	18663	72220
		Monthly	1708	4134	6560	25965	3560	7832	12104	46256	5269	11966	18664	72221
		Yearly	1712	4138	6563	25969	3560	7832	12104	46256	5272	11970	18667	72225
	ES [UBP/kWh]	Hourly	11448288	22257412	33041905	119318073	18839105	37731696	56624287	207764973	30287393	59989108	89666192	327083046
		Daily	11448508	22257631	33042124	119318292	18839105	37731696	56624287	207764973	30287613	59989327	89666411	327083266
		Monthly	11448396	22257519	33042012	119318180	18839105	37731696	56624287	207764973	30287501	59989215	89666299	327083154
		Yearly	11447911	22257034	33041527	119317696	18839105	37731696	56624287	207764973	30287016	59988731	89665815	327082669

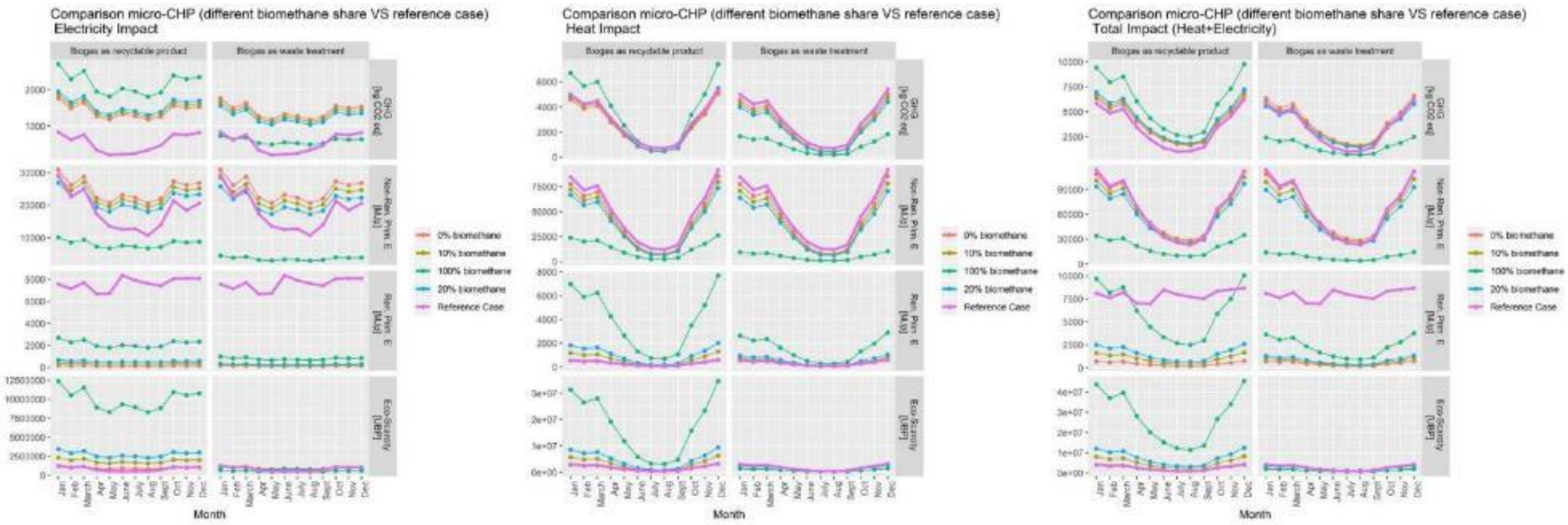


Figure 124 CHP1: Comparison of the reference case to a fuel cell unit, for various bio-methane shares

Table 89 Comparison ot the reference case to a fuel cell unit, for various bio-methane shares

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	167%	152%	136%	11%	-12%	-17%	-23%	-68%	16%	9%	2%	-55%
	NRE	36%	25%	14%	-80%	-12%	-19%	-27%	-89%	1%	-7%	-16%	-87%
	RE	-98%	-97%	-96%	-90%	-7%	30%	66%	356%	-94%	-92%	-90%	-72%
	ES	14%	9%	4%	-36%	-10%	-15%	-20%	-57%	-2%	-7%	-12%	-50%
Biogas as a recyclable product	Climate Change	167%	182%	196%	310%	-12%	-8%	-4%	30%	16%	22%	28%	73%
	NRE	36%	28%	19%	-55%	-12%	-18%	-24%	-73%	1%	-5%	-12%	-68%
	RE	-98%	-95%	-93%	-72%	-7%	105%	217%	1110%	-94%	-87%	-80%	-24%
	ES	14%	122%	230%	1090%	-10%	79%	169%	888%	-2%	93%	189%	953%

The comparison between the fuel-cell scenario and the reference is highly dependent of the allocation of the biogas impact, as it was the case for the combustion-based micro-CHP. Table 90 summarizes the observations regarding the electricity demand, while the heat impacts are presented in Table 91.

Table 90 Key findings regarding the fuel-cell scenario compared to the reference case for the electricity demand

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share - Increase of bio-methane share implies reduction of the impact - With 31% of bio-methane, the micro-CHP configuration implies an impact reduction compared to reference case
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies a small increase of the impact
	ES	- Impact higher than reference case until 20% of bio-methane but difference small - Increase of bio-methane share implies reduction of the impact - 28% of bio-methane implies an impact reduction compared to reference case
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend has the other allocation choice (but threshold at 39% of bio-methane share in the supply mix)
	RE	- Same trend has the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 91 Key findings regarding the fuel-cell scenario compared to the reference case for the heat demand

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact - Difference between all alternatives in summer is lower because is related to a small amount of energy demand for DHW
	NRE	- Same as climate change indicator
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Only the configuration with no bio-methane as a lower impact than the reference case
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower for fuel-cell than reference case until a bio-methane share of 28% then higher - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower for fuel-cell than reference case - Increase of bio-methane share implies a reduction of the impact
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Impact largely above the reference case
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

By summing the impact of the heat and electricity contributions, the overall impact of the building energy demand is obtained. It is found that the building energy demand overall impact is decreased by the fuel-cell operated with bio-methane for the NRE, RE and ecological scarcity indicators, when the biogas is considered as obtained from a waste treatment. In this case, increasing the bio-methane share will increase the gain related to the fuel-cell use. The climate change indicator will show a gain by using fuel-cell with a bio-methane share of 22%. Thereby, under this assumption of biogas being obtained from a waste treatment, the fuel-cell appears to be a promising solution to lower the building energy demand environmental impact when the bio-methane share in the supply mix is higher than 22%. In fact, the impact of the electricity demand with fuel-cell is higher, but since the overall electricity demand (in kWh) is by far lower the heat demand (in kWh), the gain related to the fuel-cell heat compensates for the increase of the electricity impact, and the overall impact of the energy demand is thereby lower with the fuel cell alternatives.

Conversely, when the biogas is considered as a recyclable product, the trend is not the same. For the climate change indicator, since the impacts of both heat and electricity increase with the share of bio-methane, the overall impact of the building energy demand is also increased when using a fuel-cell. For the NRE indicator, the overall energy demand impact is lower with the fuel-cell compared to the reference case and increasing the bio-methane share lower the impact. The RE indicator is also improved with fuel-cells, but increasing the bio-methane share reduce the gain. Finally, the ecological scarcity impact is exploding for the fuel cell scenarios, especially when the bio-methane share is 100%.

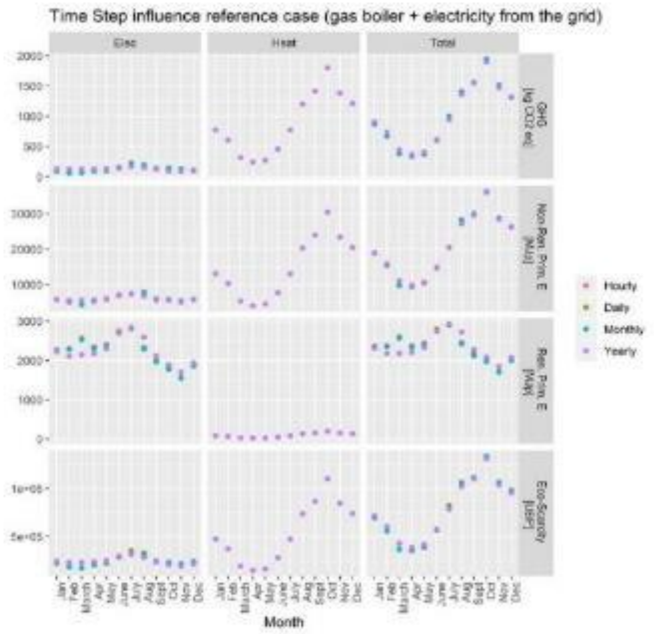
Thereby, for the fuel cell scenario, the allocation choice regarding the biogas production is, again, a key factor, especially for ecological scarcity and climate change indicators. For NRE and RE, it seems that in any case the fuel-cell is lowering the impact when operated with bio-methane. The question regarding the biogas allocation has thereby to be solved. It is difficult for non-LCA practitioners, to understand why, for some bio-methane production chains, the impact will be null and thereby the electricity and heat obtained via a micro-CHP valorization will be low and conversely, for another production process, the impact would be drastically high and would lead to discard micro-CHP as a technical solution to provide heat and electricity at the building level.

Case study: CHP2

The case CHP2 corresponds to a multi-family house building, located in Neuchatel and built between 1919 and 1945, according to the Federal Register of buildings.

Reference situation

The results of the reference situation (i.e gas boiler for space heat and domestic hot water and electricity from the grid) for the case CHP2 are presented in Figure 125.



		Electricity impact	Heat impact	Total impact
Climate Change [kg CO_2 eq/kWh]	Hourly	1 460	10 470	11 930
	Daily	1 499	10 470	11 969
	Monthly	1 524	10 470	11 994
	Yearly	1 545	10 470	12 015
NRE [MJp /kWh]	Hourly	71 029	176 993	248 022
	Daily	72 372	176 993	249 365
	Monthly	72 806	176 993	249 799
	Yearly	72 364	176 993	249 357
RE [MJp /kWh]	Hourly	27 199	1 163	28 362
	Daily	26 840	1 163	28 003
	Monthly	26 731	1 163	27 894
	Yearly	26 757	1 163	27 921
ES [UBP/kWh]	Hourly	2 869 464	6 400 554	9 270 017
	Daily	2 902 831	6 400 554	9 303 385
	Monthly	2 884 328	6 400 554	9 284 881
	Yearly	2 939 337	6 400 554	9 339 891

		Hourly	Daily	Monthly	Yearly
Electricity	Climate Change [kg CO2 eq/kWh]	-5.5%	-3.0%	-1.3%	0.0%
	NRE [MJp /kWh]	-1.8%	0.0%	0.6%	0.0%
	RE [MJp /kWh]	1.7%	0.3%	-0.1%	0.0%
	ES [UBP/kWh]	-2.4%	-1.2%	-1.9%	0.0%
Total	Climate Change [kg CO2 eq/kWh]	-0.7%	-0.4%	-0.2%	0.0%
	NRE [MJp /kWh]	-0.5%	0.0%	0.2%	0.0%
	RE [MJp /kWh]	1.6%	0.3%	-0.1%	0.0%
	ES [UBP/kWh]	-0.7%	-0.4%	-0.6%	0.0%

Figure 125 Monthly environmental impact profile, CHP2 - Reference case

The time step influence is found to be small for the reference case since it concerns only the domestic uses. Indeed, the heat is provided by a gas boiler. At the most, the time step has an influence of -5.5% between the annual and hourly time step for the climate change impact and the domestic uses. No impact of the time step is observed for the heat demand, since the heat is covered by the gas boiler.

Combustion-based CHP

The results of the combustion-based micro-CHP are displayed in Table 92 and Figure 126.

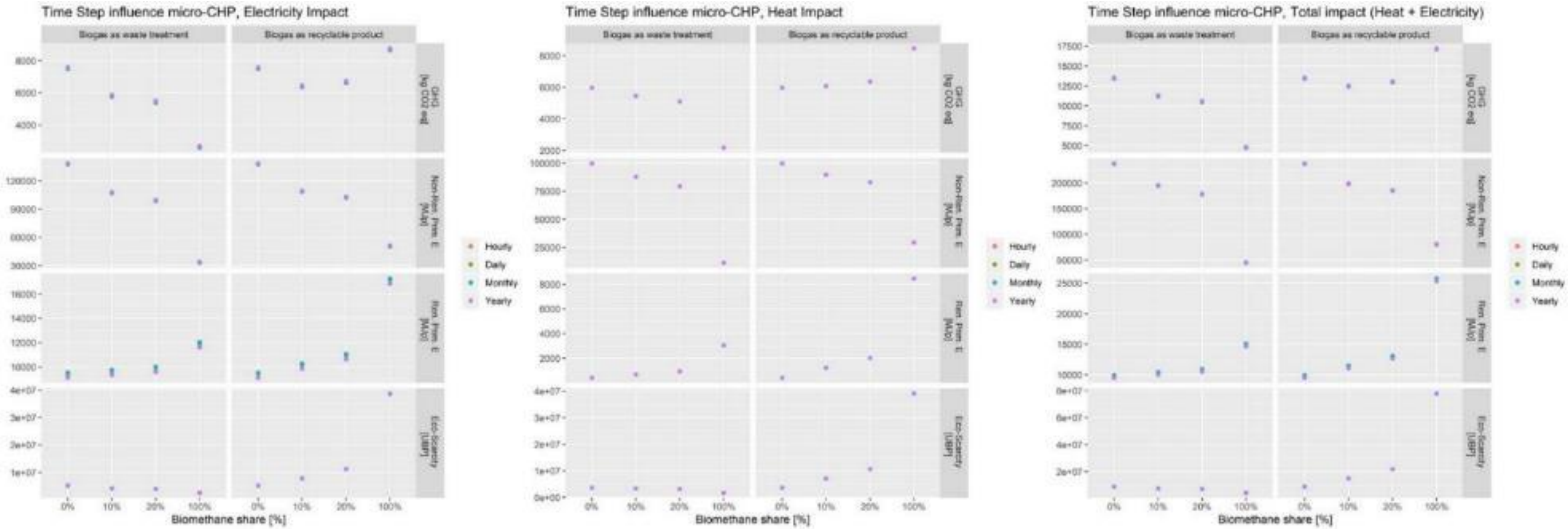


Figure 126 Time step influence of the environmental impact of the CHP2 with combustion based unit

Table 92 Environmental impact results of CHP2 with combustion based CHP

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	7 486	5 763	5 395	2 591	5 968	5 452	5 098	2 170	13 455	11 215	10 493	4 761
		Daily	7 480	5 756	5 388	2 584	5 968	5 452	5 098	2 170	13 448	11 208	10 487	4 754
		Monthly	7 491	5 768	5 400	2 596	5 968	5 452	5 098	2 170	13 460	11 220	10 498	4 766
		Yearly	7 588	5 864	5 496	2 692	5 968	5 452	5 098	2 170	13 556	11 316	10 595	4 862
	NRE [MJp /kWh]	Hourly	137 771	107 257	99 075	33 610	99 740	87 846	79 356	11 371	237 512	195 103	178 430	44 980
		Daily	137 378	106 863	98 681	33 216	99 740	87 846	79 356	11 371	237 118	194 709	178 037	44 587
		Monthly	137 485	106 970	98 788	33 323	99 740	87 846	79 356	11 371	237 225	194 816	178 144	44 694
		Yearly	138 431	107 916	99 734	34 269	99 740	87 846	79 356	11 371	238 171	195 762	179 090	45 640
	RE [MJp /kWh]	Hourly	9 384	9 614	9 867	11 882	411	688	933	3 051	9 796	10 303	10 800	14 933
		Daily	9 545	9 775	10 028	12 043	411	688	933	3 051	9 957	10 463	10 961	15 093
		Monthly	9 522	9 752	10 004	12 019	411	688	933	3 051	9 933	10 440	10 937	15 070
		Yearly	9 120	9 350	9 603	11 618	411	688	933	3 051	9 532	10 038	10 536	14 668
	ES [UBP/kWh]	Hourly	5 204 022	4 216 119	4 031 783	2 612 202	3 659 546	3 387 259	3 202 484	1 724 251	8 863 568	7 603 378	7 234 266	4 336 452
		Daily	5 193 874	4 205 970	4 021 634	2 602 054	3 659 546	3 387 259	3 202 484	1 724 251	8 853 420	7 593 229	7 224 118	4 326 304
		Monthly	5 191 089	4 203 186	4 018 850	2 599 269	3 659 546	3 387 259	3 202 484	1 724 251	8 850 635	7 590 445	7 221 334	4 323 520
		Yearly	5 280 533	4 292 630	4 108 294	2 688 713	3 659 546	3 387 259	3 202 484	1 724 251	8 940 079	7 679 889	7 310 778	4 412 964
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	7 486	6 368	6 628	8 666	5 968	6 085	6 364	8 467	13 455	12 453	12 993	17 133
		Daily	7 480	6 361	6 622	8 660	5 968	6 085	6 364	8 467	13 448	12 447	12 986	17 127
		Monthly	7 491	6 373	6 633	8 671	5 968	6 085	6 364	8 467	13 460	12 458	12 998	17 138
		Yearly	7 588	6 469	6 730	8 768	5 968	6 085	6 364	8 467	13 556	12 554	13 094	17 235
	NRE [MJp /kWh]	Hourly	137 771	108 988	102 530	50 901	99 740	89 638	82 940	29 324	237 512	198 626	185 470	80 225
		Daily	137 378	108 595	102 136	50 507	99 740	89 638	82 940	29 324	237 118	198 232	185 076	79 831
		Monthly	137 485	108 701	102 243	50 614	99 740	89 638	82 940	29 324	237 225	198 339	185 183	79 938
		Yearly	138 431	109 648	103 189	51 560	99 740	89 638	82 940	29 324	238 171	199 286	186 129	80 884
	RE [MJp /kWh]	Hourly	9 384	10 135	10 909	17 115	411	1 218	2 025	8 480	9 796	11 354	12 934	25 595
		Daily	9 545	10 296	11 070	17 275	411	1 218	2 025	8 480	9 957	11 514	13 095	25 756
		Monthly	9 522	10 273	11 046	17 252	411	1 218	2 025	8 480	9 933	11 491	13 072	25 732
		Yearly	9 120	9 871	10 645	16 850	411	1 218	2 025	8 480	9 532	11 089	12 670	25 331
	ES [UBP/kWh]	Hourly	5 204 022	7 824 702	11 255 078	38 698 085	3 659 546	7 135 066	10 698 098	39 202 289	8 863 568	14 959 768	21 953 175	77 900 374
		Daily	5 193 874	7 814 553	11 244 929	38 687 937	3 659 546	7 135 066	10 698 098	39 202 289	8 853 420	14 949 619	21 943 027	77 890 225
		Monthly	5 191 089	7 811 769	11 242 145	38 685 152	3 659 546	7 135 066	10 698 098	39 202 289	8 850 635	14 946 835	21 940 243	77 887 441
		Yearly	5 280 533	7 901 213	11 331 589	38 774 596	3 659 546	7 135 066	10 698 098	39 202 289	8 940 079	15 036 279	22 029 687	77 976 885

The relative time step influence has been calculated based on the results of Table 92 and it is summarized in Table 93. For each time step, the relative influence has been calculated compared to the annual time step.

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	-1.3%	-1.7%	-1.8%	-3.8%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.9%	-1.0%	-2.1%
		Daily	-1.4%	-1.8%	-2.0%	-4.0%	0.0%	0.0%	0.0%	0.0%	-0.8%	-1.0%	-1.0%	-2.2%
		Monthly	-1.3%	-1.6%	-1.8%	-3.6%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.9%	-0.9%	-2.0%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE [MJp /kWh]	Hourly	-0.5%	-0.6%	-0.7%	-1.9%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.4%	-1.4%
		Daily	-0.8%	-1.0%	-1.1%	-3.1%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.6%	-2.3%
		Monthly	-0.7%	-0.9%	-0.9%	-2.8%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.5%	-2.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE [MJp /kWh]	Hourly	2.9%	2.8%	2.8%	2.3%	0.0%	0.0%	0.0%	0.0%	2.8%	2.6%	2.5%	1.8%
		Daily	4.7%	4.5%	4.4%	3.7%	0.0%	0.0%	0.0%	0.0%	4.5%	4.2%	4.0%	2.9%
		Monthly	4.4%	4.3%	4.2%	3.5%	0.0%	0.0%	0.0%	0.0%	4.2%	4.0%	3.8%	2.7%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES [UBP/kWh]	Hourly	-1.4%	-1.8%	-1.9%	-2.8%	0.0%	0.0%	0.0%	0.0%	-0.9%	-1.0%	-1.0%	-1.7%
		Daily	-1.6%	-2.0%	-2.1%	-3.2%	0.0%	0.0%	0.0%	0.0%	-1.0%	-1.1%	-1.2%	-2.0%
		Monthly	-1.7%	-2.1%	-2.2%	-3.3%	0.0%	0.0%	0.0%	0.0%	-1.0%	-1.2%	-1.2%	-2.0%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	-1.3%	-1.6%	-1.5%	-1.2%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.8%	-0.8%	-0.6%
		Daily	-1.4%	-1.7%	-1.6%	-1.2%	0.0%	0.0%	0.0%	0.0%	-0.8%	-0.9%	-0.8%	-0.6%
		Monthly	-1.3%	-1.5%	-1.4%	-1.1%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.8%	-0.7%	-0.6%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE [MJp /kWh]	Hourly	-0.5%	-0.6%	-0.6%	-1.3%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.4%	-0.8%
		Daily	-0.8%	-1.0%	-1.0%	-2.0%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.6%	-1.3%
		Monthly	-0.7%	-0.9%	-0.9%	-1.8%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.5%	-1.2%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE [MJp /kWh]	Hourly	2.9%	2.7%	2.5%	1.6%	0.0%	0.0%	0.0%	0.0%	2.8%	2.4%	2.1%	1.0%
		Daily	4.7%	4.3%	4.0%	2.5%	0.0%	0.0%	0.0%	0.0%	4.5%	3.8%	3.4%	1.7%
		Monthly	4.4%	4.1%	3.8%	2.4%	0.0%	0.0%	0.0%	0.0%	4.2%	3.6%	3.2%	1.6%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES [UBP/kWh]	Hourly	-1.4%	-1.0%	-0.7%	-0.2%	0.0%	0.0%	0.0%	0.0%	-0.9%	-0.5%	-0.3%	-0.1%
		Daily	-1.6%	-1.1%	-0.8%	-0.2%	0.0%	0.0%	0.0%	0.0%	-1.0%	-0.6%	-0.4%	-0.1%
		Monthly	-1.7%	-1.1%	-0.8%	-0.2%	0.0%	0.0%	0.0%	0.0%	-1.0%	-0.6%	-0.4%	-0.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 93 CHP2: combustion based unit - Time step influence compared to yearly time step

The combustion-based CHP applied to the case CHP 2 shows that the time step has a small influence on the environmental impact. The heat impact is not influenced, since it is covered by gas. The Climate Change as well as Renewable Energy are the indicators that vary the most, with a maximum of 4 and 4.7% difference, respectively for the electricity impact. For the overall building energy level, this difference is around 2.2 and 2.9% respectively, which is still negligible. The results show the same trend for the two model choices of the biogas, regarding the environmental impact.

The environmental impacts of the “CHP2 combustion based unit” scenario is compared to the environmental impacts of the reference scenario, i.e gas boiler + electricity from the grid. The results are displayed in Figure 127 and Table 94 on a monthly basis.

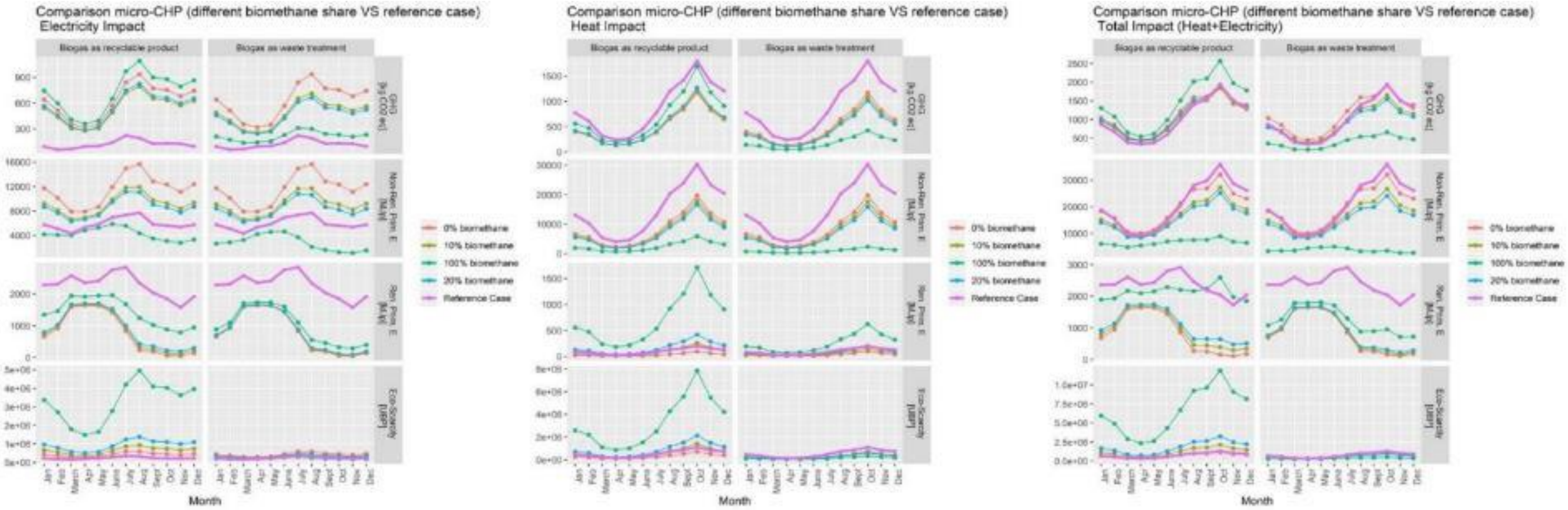


Figure 127 CHP2: Comparison of the reference case to the combustion based CHP for various bio-methane shares

Table 94 Comparison of the reference case to the combustion based CHP for various bio-methane shares (CHP2)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	413%	295%	270%	77%	-43%	-48%	-51%	-79%	13%	-6%	-12%	-60%
	NRE	94%	51%	39%	-53%	-44%	-50%	-55%	-94%	-4%	-21%	-28%	-82%
	RE	-65%	-65%	-64%	-56%	-65%	-41%	-20%	162%	-65%	-64%	-62%	-47%
	ES	81%	47%	41%	-9%	-43%	-47%	-50%	-73%	-4%	-18%	-22%	-53%
Biogas as a recyclable product	Climate Change	413%	336%	354%	494%	-43%	-42%	-39%	-19%	13%	4%	9%	44%
	NRE	94%	53%	44%	-28%	-44%	-49%	-53%	-83%	-4%	-20%	-25%	-68%
	RE	-65%	-63%	-60%	-37%	-65%	5%	74%	629%	-65%	-60%	-54%	-10%
	ES	81%	173%	292%	1249%	-43%	11%	67%	512%	-4%	61%	137%	740%

For this case study too, the impacts are driven, by the assumption choice, regarding the biogas production. The summary of the observations are provided in Table 95 for the electricity impact, while results of heat impacts are summarized Table 96. Concerning the overall energy demand impact of the building, the observations are summarized in Table 97.

Table 95 Key findings regarding the combustion-based CHP scenario compared to the reference case for the electricity demand

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share - Increase of bio-methane share implies reduction of the impact - Above 54% of bio-methane ➔ implies impact reduction compared to reference case
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies an increase of the impact
	ES	- Impact higher than reference case until almost 85% of bio-methane share then lower - Increase of bio-methane share implies reduction of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend as the other allocation choice but threshold at 69%
	RE	- Same trend as the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 96 Key findings regarding the combustion-based CHP scenario compared to the reference case for the heat demand

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Increase of bio-methane share implies increase of the impact - Above 29% of bio-methane in the supply mix, the impact is higher than the reference case
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower than reference case - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than reference case - Increase of bio-methane share implies a reduction of the impact
	RE	- Impact higher than reference case already with 10% of bio-methane in the mix - Increase of bio-methane share implies increase of the impact - Impact largely above the reference case for 100% bio-methane as supply mix
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 97 Key findings regarding the combustion-based CHP scenario compared to the reference case for the total energy demand (CHP2)

		Impact of total energy demand
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case except for no bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case - Increase of bio-methane share implies increase of the impact - Solution with no bio-methane in the supply mix as lower impacts than the solution with 100% of bio-methane
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Based on the observation described above, it appears that the conclusions regarding the combustion-based micro-CHP scenario compared to the reference case are driven by the assumption regarding the biogas production such as for the case study CHP 1. As a second important observation, it is worth to mention that the overall building impact is driven by the heat demand, which is more important than the electricity demand. Thereby, a reduction of impact related to the heat demand has a higher influence on the overall impact of the building energy demand.

For the CHP2 case study, the combustion-based micro-CHP could be a solution that allows impact reduction even with low bio-methane shares, when the biogas is issued from a waste treatment. For the other case (recyclable product), the climate change and ecological scarcity scores are higher and therefore, it should probably be avoided.

Fuel cell CHP

The results regarding the time step influence of the fuel cell micro-CHP alternative are displayed in Table 98 and Figure 128. It is found that the time step influence is null. Indeed, in this scenario, 99.3% of the electricity is covered by the fuel cell unit and thereby, there are no fluctuations related to any of the time step considerations. The comparison between the scenario with fuel cell and the reference case, is displayed in Table 99 and Figure 129.

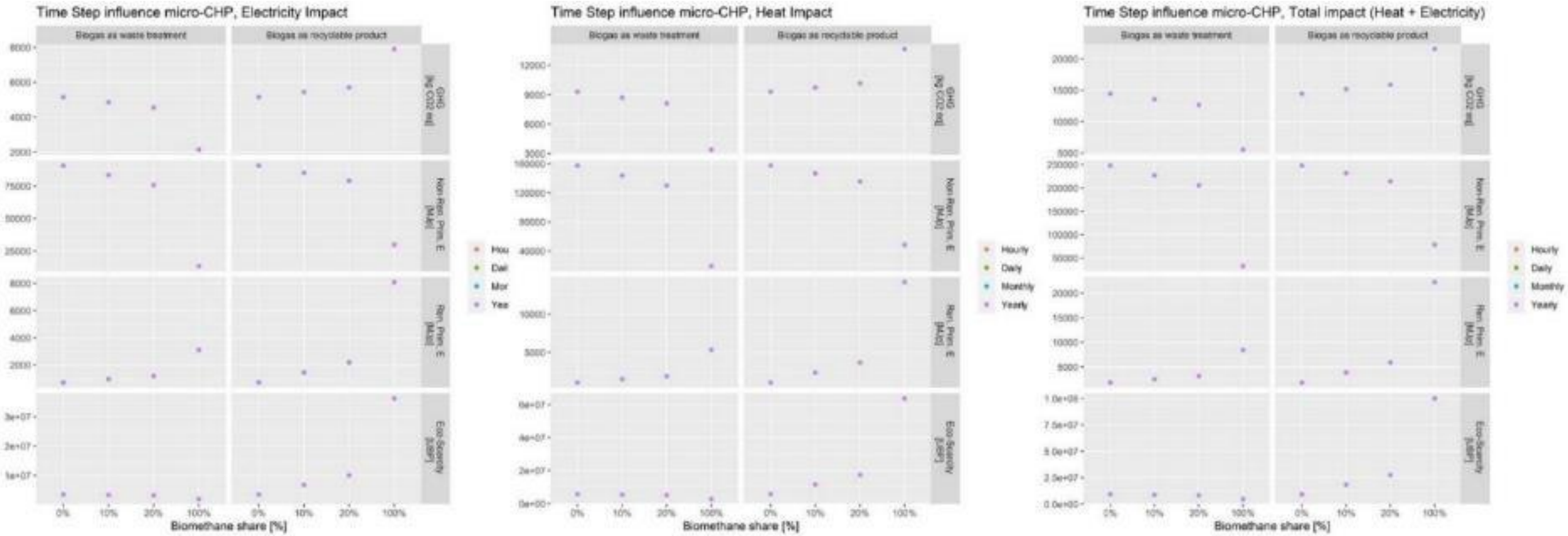


Figure 128 Time step influence of the environmental impact of the CHP2, with a fuel cell unit

Table 98 Environmental impact results of CHP2, with a fuel cell unit

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	5 153	4 858	4 552	2 139	9 298	8 714	8 124	3 411	14 451	13 573	12 676	5 550
		Daily	5 154	4 859	4 554	2 140	9 298	8 714	8 124	3 411	14 452	13 574	12 677	5 551
		Monthly	5 154	4 860	4 554	2 141	9 298	8 714	8 124	3 411	14 453	13 574	12 678	5 552
		Yearly	5 156	4 861	4 555	2 142	9 298	8 714	8 124	3 411	14 454	13 576	12 679	5 553
	NRE [MJp /kWh]	Hourly	90 681	83 486	75 702	13 499	157 536	143 730	129 924	19 468	248 217	227 216	205 626	32 967
		Daily	90 737	83 542	75 758	13 554	157 536	143 730	129 924	19 468	248 273	227 272	205 682	33 023
		Monthly	90 744	83 549	75 765	13 561	157 536	143 730	129 924	19 468	248 279	227 279	205 688	33 029
		Yearly	90 750	83 556	75 772	13 568	157 536	143 730	129 924	19 468	248 286	227 285	205 695	33 036
	RE [MJp /kWh]	Hourly	733	971	1 209	3 124	1 091	1 517	1 944	5 347	1 825	2 489	3 153	8 471
		Daily	719	957	1 195	3 109	1 091	1 517	1 944	5 347	1 810	2 474	3 138	8 456
		Monthly	715	953	1 191	3 106	1 091	1 517	1 944	5 347	1 806	2 470	3 134	8 452
		Yearly	711	949	1 187	3 102	1 091	1 517	1 944	5 347	1 802	2 467	3 131	8 449
	ES [UBP/kWh]	Hourly	3 494 378	3 346 959	3 192 072	1 953 005	5 773 906	5 475 384	5 176 862	2 788 671	9 268 284	8 822 343	8 368 934	4 741 676
		Daily	3 495 510	3 348 091	3 193 204	1 954 137	5 773 906	5 475 384	5 176 862	2 788 671	9 269 416	8 823 475	8 370 066	4 742 808
		Monthly	3 495 457	3 348 037	3 193 151	1 954 083	5 773 906	5 475 384	5 176 862	2 788 671	9 269 363	8 823 421	8 370 013	4 742 754
		Yearly	3 496 760	3 349 340	3 194 454	1 955 386	5 773 906	5 475 384	5 176 862	2 788 671	9 270 666	8 824 724	8 371 316	4 744 057
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	5 153	5 436	5 708	7 906	9 298	9 739	10 173	13 658	14 451	15 175	15 881	21 564
		Daily	5 154	5 437	5 709	7 907	9 298	9 739	10 173	13 658	14 452	15 176	15 882	21 565
		Monthly	5 154	5 438	5 710	7 908	9 298	9 739	10 173	13 658	14 453	15 177	15 883	21 566
		Yearly	5 156	5 439	5 711	7 909	9 298	9 739	10 173	13 658	14 454	15 178	15 884	21 567
	NRE [MJp /kWh]	Hourly	90 681	85 129	79 000	29 939	157 536	146 648	135 754	48 647	248 217	231 778	214 754	78 586
		Daily	90 737	85 185	79 055	29 995	157 536	146 648	135 754	48 647	248 273	231 833	214 809	78 642
		Monthly	90 744	85 192	79 062	30 002	157 536	146 648	135 754	48 647	248 279	231 840	214 816	78 649
		Yearly	90 750	85 198	79 069	30 008	157 536	146 648	135 754	48 647	248 286	231 847	214 823	78 656
	RE [MJp /kWh]	Hourly	733	1 470	2 206	8 098	1 091	2 400	3 710	14 177	1 825	3 870	5 916	22 275
		Daily	719	1 455	2 192	8 084	1 091	2 400	3 710	14 177	1 810	3 856	5 901	22 260
		Monthly	715	1 451	2 188	8 080	1 091	2 400	3 710	14 177	1 806	3 852	5 898	22 256
		Yearly	711	1 448	2 184	8 076	1 091	2 400	3 710	14 177	1 802	3 848	5 894	22 253
	ES [UBP/kWh]	Hourly	3 494 378	6 776 178	10 050 499	36 245 139	5 773 906	11 564 127	17 354 348	63 676 103	9 268 284	18 340 305	27 404 847	99 921 242
		Daily	3 495 510	6 777 310	10 051 631	36 246 271	5 773 906	11 564 127	17 354 348	63 676 103	9 269 416	18 341 437	27 405 979	99 922 374
		Monthly	3 495 457	6 777 256	10 051 578	36 246 218	5 773 906	11 564 127	17 354 348	63 676 103	9 269 363	18 341 383	27 405 926	99 922 321
		Yearly	3 496 760	6 778 559	10 052 881	36 247 521	5 773 906	11 564 127	17 354 348	63 676 103	9 270 666	18 342 686	27 407 229	99 923 624

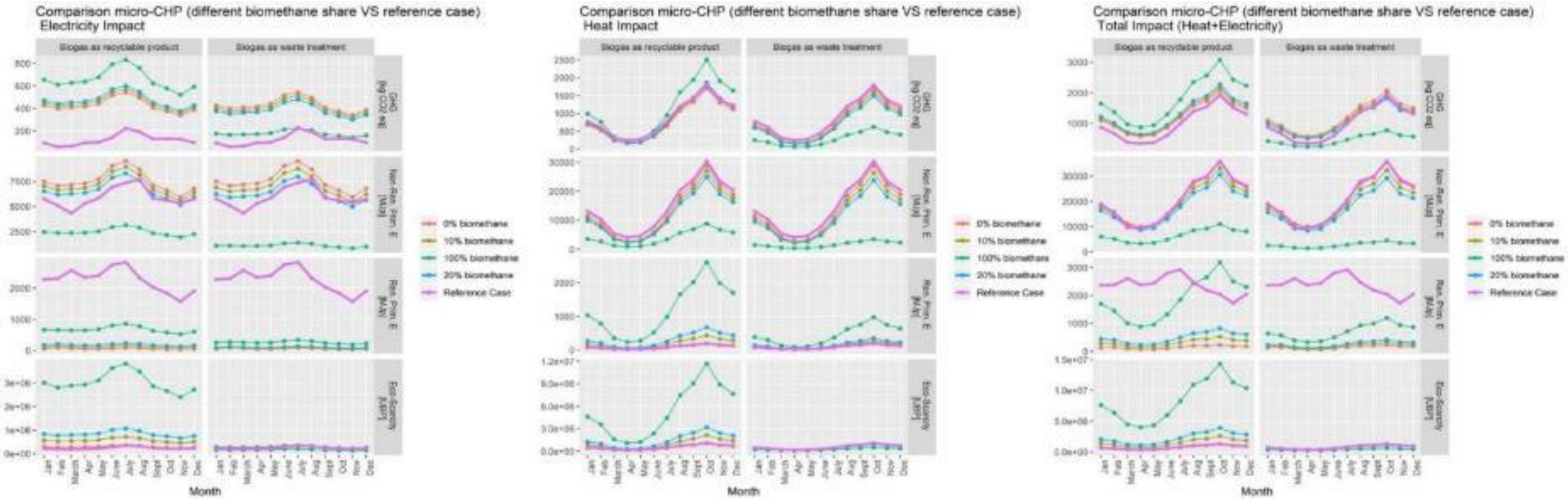


Figure 129 CHP2: Comparison of the reference case to the fuel cell unit of the CHP2, for various bio-methane shares

Table 99 Comparison of the reference case to the fuel cell unit, for various bio-methane shares (CHP2)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	253%	233%	212%	47%	-11%	-17%	-22%	-67%	21%	14%	6%	-53%
	NRE	28%	18%	7%	-81%	-11%	-19%	-27%	-89%	0%	-8%	-17%	-87%
	RE	-97%	-96%	-96%	-89%	-6%	30%	67%	360%	-94%	-91%	-89%	-70%
	ES	22%	17%	11%	-32%	-10%	-14%	-19%	-56%	0%	-5%	-10%	-49%
Biogas as a recyclable product	Climate Change	253%	272%	291%	442%	-11%	-7%	-3%	30%	21%	27%	33%	81%
	NRE	28%	20%	11%	-58%	-11%	-17%	-23%	-73%	0%	-7%	-13%	-68%
	RE	-97%	-95%	-92%	-70%	-6%	106%	219%	1119%	-94%	-86%	-79%	-21%
	ES	22%	136%	250%	1163%	-10%	81%	171%	895%	0%	98%	196%	978%

Table 100 summarizes the observations regarding the electricity demand, while the heat impacts are summarized in Table 101. Concerning the overall energy demand impact of the building, the observations are summarized in Table 102.

Table 100 Key findings regarding the fuel-cell scenario compared to the reference case for the electricity demand (CHP2)

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share - Increase of bio-methane share implies reduction of the impact - Above 26% of bio-methane in the supply mix → impact reduction compared to reference case
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies an increase of the impact
	ES	- Impact higher than reference case until 41 % of bio-methane but difference small - Increase of bio-methane share implies reduction of the impact - 100% of bio-methane implies impact reduction compared to reference case
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend has the other allocation choice but threshold at 33% of bio-methane
	RE	- Same trend has the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 101 Key findings regarding the fuel-cell scenario compared to the reference case for the heat demand (CHP2)

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Impact higher for fuel-cell than reference case when using bio-methane (no bio-methane = impact slightly lower) - Increase of bio-methane share implies increase of the impact
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower for fuel-cell than reference case until 26% of bio-methane, then higher - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than reference case for any bio-methane share - Bio-methane share increase implies a reduction of the impact
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Largely above the reference case
	ES	- Impact higher than reference case for any bio-methane share - Impact lower only when no bio-methane to supply the CHP - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 102 Key findings regarding the fuel cell scenario compared to the reference case for the total energy demand (CHP2)

		Impact of total energy demand
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case until 28% of bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case - Increase of bio-methane share implies increase of the impact - Solution with no bio-methane in the supply mix as lower impacts than the solution with 100% of bio-methane
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

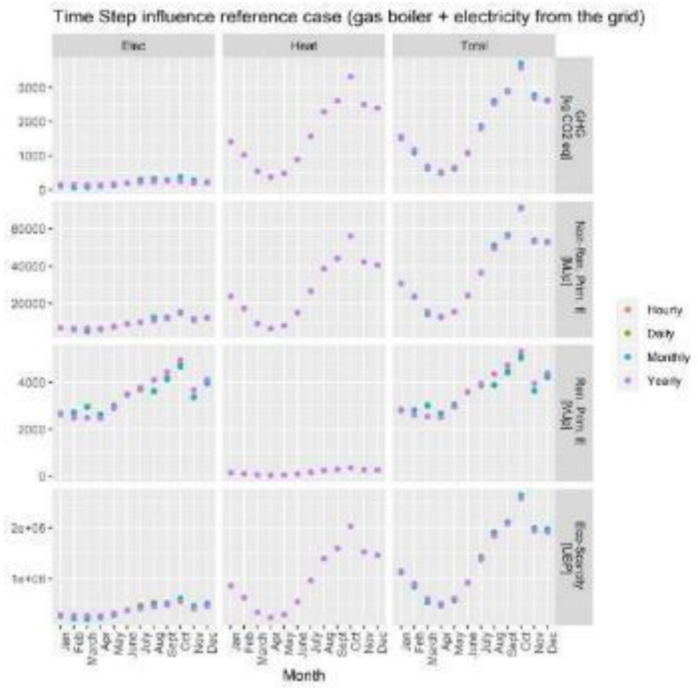
The impact is again driven by the assumption regarding the impact of the biogas production. If considered as issued from a waste treatment, the fuel-cell are of interest, despite that fact that it slightly increases the climate change impact for low bio-methane share (10 and 20%), compared to the reference case. For 28% of bio-methane in the supply mix, all impacts are positively affected by the use of a fuel-cell.

If considered as issued from a recyclable product, such as for the combustion-based CHP, the fuel-cell alternative should be probably avoided, because it increases the climate change and ecological scarcity impact significantly, while implying a reduction of the primary energy indicators.

Case study: CHP3

Reference situation

The results of the reference situation (i.e gas boiler for space heat and domestic hot water and electricity from the grid) are presented in Figure 130.



		Electricity Impact	Heat Impact	Total Impact
Climate Change [kg CO_2 eq/kWh]	Hourly	2 425	19 419	21 844
	Daily	2 452	19 419	21 871
	Monthly	2 495	19 419	21 914
	Yearly	2 365	19 419	21 784
NRE [MJp /kWh]	Hourly	113 189	328 270	441 459
	Daily	115 018	328 270	443 288
	Monthly	115 817	328 270	444 087
	Yearly	113 514	328 270	441 785
RE [MJp /kWh]	Hourly	41 232	2 158	43 389
	Daily	40 932	2 158	43 089
	Monthly	40 799	2 158	42 957
	Yearly	41 485	2 158	43 642
ES [UBP/kWh]	Hourly	4 590 884	11 871 139	16 462 023
	Daily	4 618 072	11 871 139	16 489 211
	Monthly	4 607 368	11 871 139	16 478 507
	Yearly	4 563 459	11 871 139	16 434 597

		Hourly	Daily	Monthly	Yearly
Electricity	Climate Change [kg CO2 eq/kWh]	2.5%	3.7%	5.5%	0.0%
	NRE [MJp /kWh]	-0.3%	1.3%	2.0%	0.0%
	RE [MJp /kWh]	-0.6%	-1.3%	-1.7%	0.0%
	ES [UBP/kWh]	0.6%	1.2%	1.0%	0.0%
Total	Climate Change [kg CO2 eq/kWh]	0.3%	0.4%	0.6%	0.0%
	NRE [MJp /kWh]	-0.1%	0.3%	0.5%	0.0%
	RE [MJp /kWh]	-0.6%	-1.3%	-1.6%	0.0%
	ES [UBP/kWh]	0.2%	0.3%	0.3%	0.0%

Figure 130 Monthly environmental impact profile, CHP3 - Reference case

As it was the case for the CHP1 and CHP2, the time step influence is found to be small for the reference case since the time step influences only the domestic uses. Indeed, the heat is provided by a gas boiler. At the most, the time step has an influence of 5.5%, between the annual and the monthly time step for the climate change impact and the domestic uses. The time step influence of the total energy demand of the building is negligible, since the highest impacts come from the heat demand, which is covered by a gas boiler that has a constant environmental impact.

Combustion-based CHP

The results of the combustion-based micro-CHP are displayed in Table 103 and Figure 131.

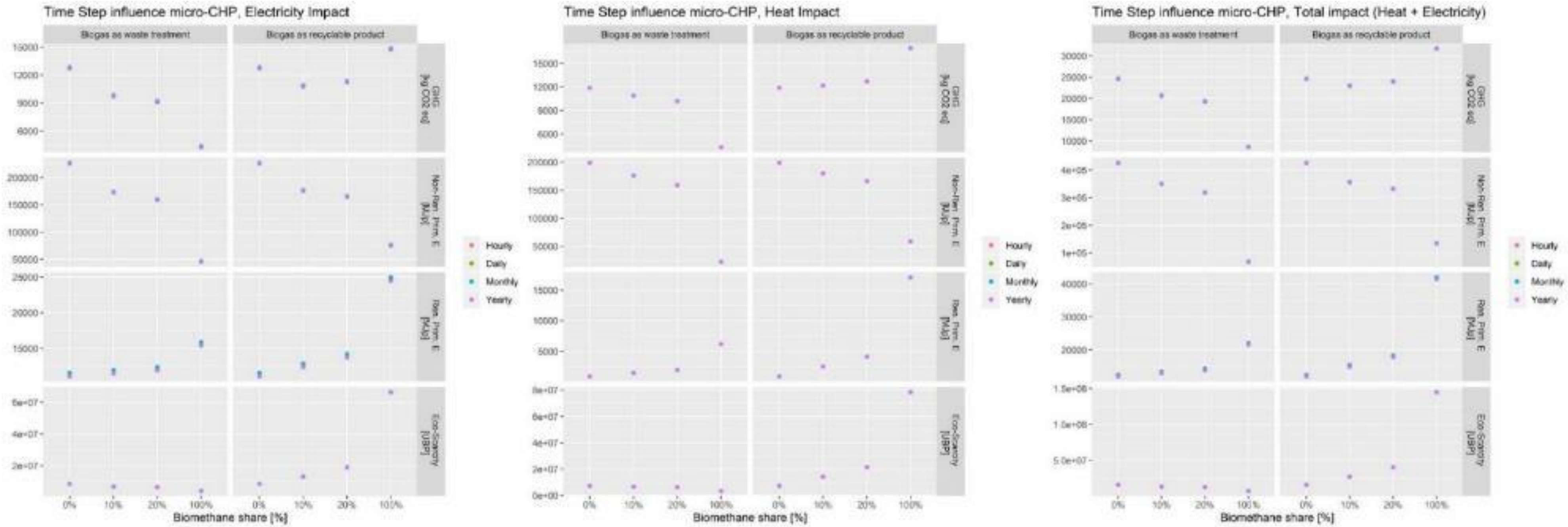


Figure 131 Yearly environmental impact for CHP3 with combustion based unit

Table 103 Environmental impact results of CHP3 with combustion based CHP

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	12 735	9 752	9 115	4 263	11 871	10 892	10 178	4 313	24 605	20 643	19 294	8 576
		Daily	12 726	9 743	9 107	4 255	11 871	10 892	10 178	4 313	24 597	20 635	19 285	8 568
		Monthly	12 739	9 756	9 119	4 267	11 871	10 892	10 178	4 313	24 609	20 647	19 298	8 580
		Yearly	12 851	9 868	9 232	4 380	11 871	10 892	10 178	4 313	24 722	20 760	19 410	8 692
	NRE [MJp /kWh]	Hourly	226 514	173 711	159 552	46 270	198 813	176 204	159 177	22 855	425 328	349 915	318 729	69 125
		Daily	226 060	173 257	159 098	45 816	198 813	176 204	159 177	22 855	424 874	349 461	318 276	68 671
		Monthly	226 099	173 295	159 137	45 854	198 813	176 204	159 177	22 855	424 912	349 499	318 314	68 709
		Yearly	227 204	174 401	160 242	46 960	198 813	176 204	159 177	22 855	426 018	350 605	319 420	69 815
	RE [MJp /kWh]	Hourly	11 354	11 751	12 189	15 675	910	1 460	1 956	6 195	12 263	13 211	14 145	21 870
		Daily	11 556	11 953	12 391	15 877	910	1 460	1 956	6 195	12 465	13 413	14 347	22 072
		Monthly	11 559	11 957	12 395	15 881	910	1 460	1 956	6 195	12 469	13 417	14 351	22 076
		Yearly	11 088	11 486	11 924	15 410	910	1 460	1 956	6 195	11 998	12 946	13 880	21 605
	ES [UBP/kWh]	Hourly	8 533 003	6 823 505	6 504 524	4 048 036	7 275 889	6 762 036	6 391 674	3 428 722	15 808 893	13 585 541	12 896 198	7 476 758
		Daily	8 520 079	6 810 581	6 491 600	4 035 112	7 275 889	6 762 036	6 391 674	3 428 722	15 795 969	13 572 617	12 883 274	7 463 834
		Monthly	8 518 884	6 809 385	6 490 404	4 033 917	7 275 889	6 762 036	6 391 674	3 428 722	15 794 773	13 571 421	12 882 078	7 462 638
		Yearly	8 623 722	6 914 223	6 595 242	4 138 755	7 275 889	6 762 036	6 391 674	3 428 722	15 899 611	13 676 259	12 986 916	7 567 477
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	12 735	10 799	11 250	14 776	11 871	12 160	12 715	16 944	24 605	22 959	23 965	31 720
		Daily	12 726	10 791	11 241	14 768	11 871	12 160	12 715	16 944	24 597	22 951	23 957	31 711
		Monthly	12 739	10 803	11 254	14 780	11 871	12 160	12 715	16 944	24 609	22 963	23 969	31 724
		Yearly	12 851	10 915	11 366	14 892	11 871	12 160	12 715	16 944	24 722	23 075	24 081	31 836
	NRE [MJp /kWh]	Hourly	226 514	176 707	165 531	76 191	198 813	179 799	166 367	58 857	425 328	356 506	331 898	135 048
		Daily	226 060	176 253	165 077	75 737	198 813	179 799	166 367	58 857	424 874	356 052	331 444	134 594
		Monthly	226 099	176 291	165 116	75 776	198 813	179 799	166 367	58 857	424 912	356 090	331 482	134 632
		Yearly	227 204	177 397	166 221	76 881	198 813	179 799	166 367	58 857	426 018	357 196	332 588	135 738
	RE [MJp /kWh]	Hourly	11 354	12 653	13 992	24 730	910	2 527	4 145	17 084	12 263	15 180	18 136	41 814
		Daily	11 556	12 855	14 194	24 932	910	2 527	4 145	17 084	12 465	15 382	18 338	42 016
		Monthly	11 559	12 859	14 198	24 936	910	2 527	4 145	17 084	12 469	15 386	18 342	42 020
		Yearly	11 088	12 388	13 727	24 465	910	2 527	4 145	17 084	11 998	14 915	17 871	41 549
	ES [UBP/kWh]	Hourly	8 533 003	13 067 910	19 003 941	66 492 187	7 275 889	14 277 013	21 421 627	78 578 432	15 808 893	27 344 923	40 425 568	145 070 619
		Daily	8 520 079	13 054 986	18 991 017	66 479 263	7 275 889	14 277 013	21 421 627	78 578 432	15 795 969	27 331 999	40 412 644	145 057 695
		Monthly	8 518 884	13 053 791	18 989 821	66 478 068	7 275 889	14 277 013	21 421 627	78 578 432	15 794 773	27 330 803	40 411 448	145 056 499
		Yearly	8 623 722	13 158 629	19 094 659	66 582 906	7 275 889	14 277 013	21 421 627	78 578 432	15 899 611	27 435 641	40 516 286	145 161 338

The relative time step influence has been calculated based on the results of Table 103 and it is summarized in Table 104. For each time step, the relative influence has been calculated compared to the annual time step.

Table 104 CHP3: combustion based unit - Time step influence compared to yearly time step

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	-0.9%	-1.2%	-1.3%	-2.7%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.6%	-0.6%	-1.3%
		Daily	-1.0%	-1.3%	-1.4%	-2.8%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.6%	-0.6%	-1.4%
		Monthly	-0.9%	-1.1%	-1.2%	-2.6%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.6%	-1.3%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE [MJp /kWh]	Hourly	-0.3%	-0.4%	-0.4%	-1.5%	0.0%	0.0%	0.0%	0.0%	-0.2%	-0.2%	-0.2%	-1.0%
		Daily	-0.5%	-0.7%	-0.7%	-2.4%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.4%	-1.6%
		Monthly	-0.5%	-0.6%	-0.7%	-2.4%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-1.6%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE [MJp /kWh]	Hourly	2.4%	2.3%	2.2%	1.7%	0.0%	0.0%	0.0%	0.0%	2.2%	2.0%	1.9%	1.2%
		Daily	4.2%	4.1%	3.9%	3.0%	0.0%	0.0%	0.0%	0.0%	3.9%	3.6%	3.4%	2.2%
		Monthly	4.2%	4.1%	3.9%	3.1%	0.0%	0.0%	0.0%	0.0%	3.9%	3.6%	3.4%	2.2%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES [UBP/kWh]	Hourly	-1.1%	-1.3%	-1.4%	-2.2%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.7%	-0.7%	-1.2%
		Daily	-1.2%	-1.5%	-1.6%	-2.5%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.8%	-0.8%	-1.4%
		Monthly	-1.2%	-1.5%	-1.6%	-2.5%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.8%	-0.8%	-1.4%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	-0.9%	-1.1%	-1.0%	-0.8%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.5%	-0.4%
		Daily	-1.0%	-1.1%	-1.1%	-0.8%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.5%	-0.4%
		Monthly	-0.9%	-1.0%	-1.0%	-0.8%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.5%	-0.4%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE [MJp /kWh]	Hourly	-0.3%	-0.4%	-0.4%	-0.9%	0.0%	0.0%	0.0%	0.0%	-0.2%	-0.2%	-0.2%	-0.5%
		Daily	-0.5%	-0.6%	-0.7%	-1.5%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-0.8%
		Monthly	-0.5%	-0.6%	-0.7%	-1.4%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-0.8%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE [MJp /kWh]	Hourly	2.4%	2.1%	1.9%	1.1%	0.0%	0.0%	0.0%	0.0%	2.2%	1.8%	1.5%	0.6%
		Daily	4.2%	3.8%	3.4%	1.9%	0.0%	0.0%	0.0%	0.0%	3.9%	3.1%	2.6%	1.1%
		Monthly	4.2%	3.8%	3.4%	1.9%	0.0%	0.0%	0.0%	0.0%	3.9%	3.2%	2.6%	1.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES [UBP/kWh]	Hourly	-1.1%	-0.7%	-0.5%	-0.1%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.3%	-0.2%	-0.1%
		Daily	-1.2%	-0.8%	-0.5%	-0.2%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.4%	-0.3%	-0.1%
		Monthly	-1.2%	-0.8%	-0.5%	-0.2%	0.0%	0.0%	0.0%	0.0%	-0.7%	-0.4%	-0.3%	-0.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The combustion-based micro-CHP applied to the case CHP3 shows that the time step has a low influence on the environmental impacts. The heat impact is not influenced, since the heat demand is covered by gas. The median of the time step influence on the impact of the building electricity demand is -0.4% and its standard deviation 1.6% for all possible configurations (from CHP without bio-methane to 100% bio-methane) and all indicators.

The Renewable Energy is the indicator that varies the most, with a maximum of 4.2% for the electricity impact (hourly impact compared to annual impact). At the overall building energy level, it represents a time step influence of maximum 3.9%, which is found to be negligible. The results show the same trend for the two assumptions, regarding the environmental impact of the biogas production. Thereby, a dynamic calculation when considering combustion-based CHP is not necessary.

Based on this observation, the environmental impacts of the “CHP3 combustion based unit” scenario is then compared to the environmental impacts of the reference scenario, i.e gas boiler + electricity from the grid. The results are displayed in Figure 132 and Table 105, on a monthly basis.

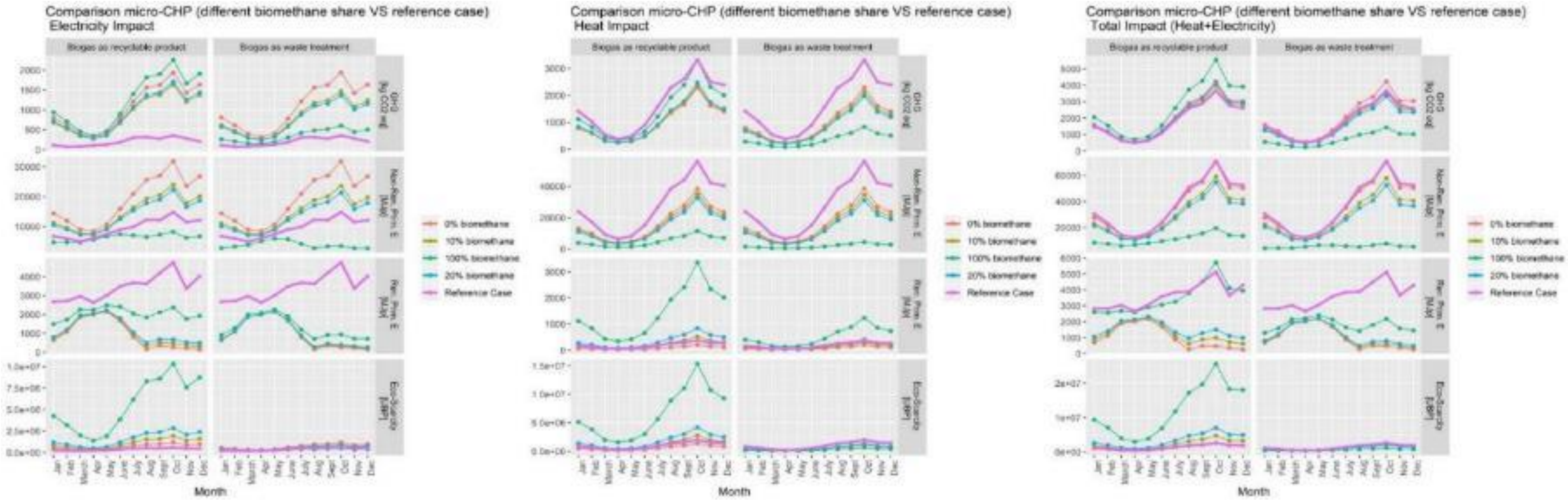


Figure 132 CHP3: Comparison of the reference case to a combustion based CHP, for various bio-methane shares

Table 105 Comparison of the reference case to a combustion based CHP, for various bio-methane shares (CHP3)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	425%	302%	276%	76%	-39%	-44%	-48%	-78%	13%	-5%	-12%	-61%
	NRE	100%	53%	41%	-59%	-39%	-46%	-52%	-93%	-4%	-21%	-28%	-84%
	RE	-72%	-71%	-70%	-62%	-58%	-32%	-9%	187%	-72%	-70%	-67%	-50%
	ES	86%	49%	42%	-12%	-39%	-43%	-46%	-71%	-4%	-17%	-22%	-55%
Biogas as a recyclable product	Climate Change	425%	345%	364%	509%	-39%	-37%	-35%	-13%	13%	5%	10%	45%
	NRE	100%	56%	46%	-33%	-39%	-45%	-49%	-82%	-4%	-19%	-25%	-69%
	RE	-72%	-69%	-66%	-40%	-58%	17%	92%	692%	-72%	-65%	-58%	-4%
	ES	86%	185%	314%	1348%	-39%	20%	80%	562%	-4%	66%	146%	781%

Such as for CHP1 and CHP2, the impacts are driven by the assumption choice regarding the biogas production. The summary of the observations are presented in Table 106 for the electricity impact, while the results of heat impacts are summarized in Table 107. Concerning the overall energy demand impact of the building, the observations are summarized in Table 108.

Table 106 Key findings regarding the combustion-based CHP scenario compared to the reference case for the electricity demand (CHP3)

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share - Increase of bio-methane share implies reduction of the impact - Above 53% of bio-methane in the supply mix ➔ impact reduced compared to reference case
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies an increase of the impact
	ES	- Impact higher than reference case until almost 82% of bio-methane share then lower - Increase of bio-methane share implies reduction of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend as the other allocation choice but threshold at 67% of bio-methane
	RE	- Same trend as the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 107 Key findings regarding the combustion-based CHP scenario compared to the reference case for the heat demand (CHP3)

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Increase of bio-methane share implies increase of the impact - Above 24% of bio-methane in the supply mix the impact is higher than the reference case
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower than reference case - Increase of bio-methane share implies an increase of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact already higher than reference case when 10% of bio-methane in the mix - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 108 Key findings regarding the combustion-based CHP scenario compared to the reference case for the total energy demand (CHP3)

		Impact of the overall energy demand
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case except for no bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case - Increase of bio-methane share implies increase of the impact - Solution with no bio-methane in the supply mix as lower impacts than the solution with 100% of bio-methane
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Fuel cell CHP

The results with the fuel cell micro-CHP are displayed in Table 109 and in Figure 133. The comparison between the scenario with fuel cell and the reference case is displayed in Table 110 and in Figure 134.

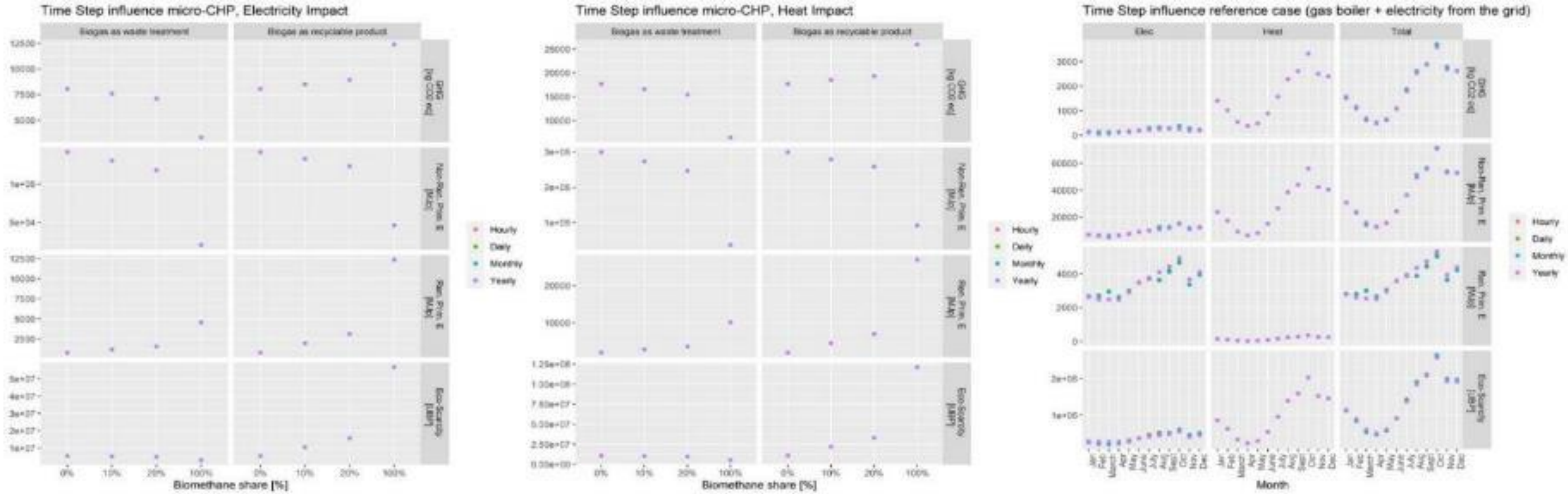


Figure 133 Time step influence of the environmental impacts for CHP3 with a fuel cell unit

Table 109 Environmental impact results of CHP3 with a fuel cell unit

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	8 066	7 604	7 125	3 342	17 682	16 566	15 442	6 465	25 747	24 171	22 566	9 806
		Daily	8 065	7 604	7 124	3 341	17 682	16 566	15 442	6 465	25 747	24 170	22 566	9 806
		Monthly	8 065	7 603	7 124	3 341	17 682	16 566	15 442	6 465	25 746	24 170	22 566	9 805
		Yearly	8 064	7 603	7 123	3 340	17 682	16 566	15 442	6 465	25 746	24 169	22 565	9 805
	NRE [MJp /kWh]	Hourly	141 489	130 211	118 011	20 511	299 463	273 185	246 907	36 672	440 952	403 396	364 918	57 184
		Daily	141 486	130 209	118 008	20 509	299 463	273 185	246 907	36 672	440 949	403 394	364 915	57 181
		Monthly	141 480	130 202	118 002	20 502	299 463	273 185	246 907	36 672	440 943	403 388	364 909	57 175
		Yearly	141 477	130 200	117 999	20 500	299 463	273 185	246 907	36 672	440 941	403 385	364 906	57 172
	RE [MJp /kWh]	Hourly	823	1 195	1 568	4 570	2 053	2 864	3 675	10 153	2 876	4 060	5 244	14 723
		Daily	824	1 197	1 570	4 571	2 053	2 864	3 675	10 153	2 877	4 061	5 245	14 724
		Monthly	826	1 199	1 572	4 573	2 053	2 864	3 675	10 153	2 879	4 063	5 247	14 726
		Yearly	827	1 200	1 573	4 574	2 053	2 864	3 675	10 153	2 880	4 064	5 248	14 727
	ES [UBP/kWh]	Hourly	5 450 144	5 219 076	4 976 305	3 034 169	10 936 506	10 367 785	9 799 064	5 249 277	16 386 650	15 586 861	14 775 369	8 283 446
		Daily	5 449 906	5 218 838	4 976 067	3 033 932	10 936 506	10 367 785	9 799 064	5 249 277	16 386 412	15 586 623	14 775 131	8 283 208
		Monthly	5 449 514	5 218 446	4 975 675	3 033 539	10 936 506	10 367 785	9 799 064	5 249 277	16 386 020	15 586 231	14 774 739	8 282 816
		Yearly	5 449 300	5 218 232	4 975 460	3 033 325	10 936 506	10 367 785	9 799 064	5 249 277	16 385 805	15 586 017	14 774 524	8 282 602
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	8 066	8 510	8 936	12 381	17 682	18 517	19 342	25 967	25 747	27 027	28 279	38 349
		Daily	8 065	8 509	8 936	12 381	17 682	18 517	19 342	25 967	25 747	27 026	28 278	38 348
		Monthly	8 065	8 509	8 935	12 380	17 682	18 517	19 342	25 967	25 746	27 026	28 278	38 348
		Yearly	8 064	8 508	8 935	12 380	17 682	18 517	19 342	25 967	25 746	27 025	28 277	38 347
	NRE [MJp /kWh]	Hourly	141 489	132 786	123 179	46 280	299 463	278 740	258 007	92 210	440 952	411 526	381 186	138 490
		Daily	141 486	132 784	123 176	46 277	299 463	278 740	258 007	92 210	440 949	411 523	381 183	138 487
		Monthly	141 480	132 778	123 170	46 271	299 463	278 740	258 007	92 210	440 943	411 517	381 177	138 481
		Yearly	141 477	132 775	123 167	46 269	299 463	278 740	258 007	92 210	440 941	411 515	381 174	138 479
	RE [MJp /kWh]	Hourly	823	1 977	3 131	12 366	2 053	4 545	7 037	26 960	2 876	6 522	10 168	39 326
		Daily	824	1 978	3 133	12 368	2 053	4 545	7 037	26 960	2 877	6 523	10 169	39 328
		Monthly	826	1 980	3 135	12 369	2 053	4 545	7 037	26 960	2 879	6 525	10 171	39 329
		Yearly	827	1 981	3 136	12 371	2 053	4 545	7 037	26 960	2 880	6 526	10 172	39 330
	ES [UBP/kWh]	Hourly	5 450 144	10 594 091	15 726 317	56 784 229	10 936 506	21 956 846	32 977 186	121 139 889	16 386 650	32 550 937	48 703 503	177 924 118
		Daily	5 449 906	10 593 853	15 726 079	56 783 992	10 936 506	21 956 846	32 977 186	121 139 889	16 386 412	32 550 699	48 703 265	177 923 881
		Monthly	5 449 514	10 593 461	15 725 687	56 783 599	10 936 506	21 956 846	32 977 186	121 139 889	16 386 020	32 550 307	48 702 873	177 923 488
		Yearly	5 449 300	10 593 247	15 725 472	56 783 385	10 936 506	21 956 846	32 977 186	121 139 889	16 385 805	32 550 093	48 702 658	177 923 274

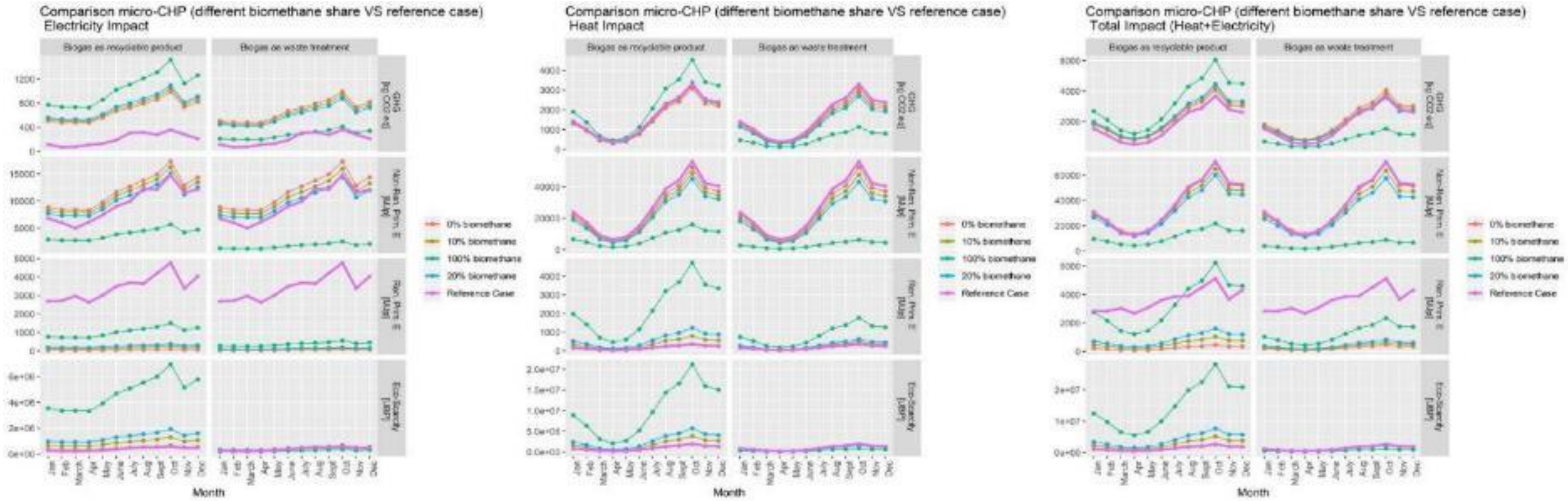


Figure 134 CHP3: Comparison of the reference case to a fuel cell unit, for various bio-methane shares

Table 110 Comparison of the reference case to a fuel cell unit for various bio-methane shares (CHP3)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	233%	214%	194%	38%	-9%	-15%	-20%	-67%	18%	11%	3%	-55%
	NRE	25%	15%	4%	-82%	-9%	-17%	-25%	-89%	0%	-9%	-17%	-87%
	RE	-98%	-97%	-96%	-89%	-5%	33%	70%	371%	-93%	-91%	-88%	-66%
	ES	19%	14%	8%	-34%	-8%	-13%	-17%	-56%	0%	-5%	-10%	-50%
Biogas as a recyclable product	Climate Change	233%	251%	268%	411%	-9%	-5%	0%	34%	18%	24%	29%	76%
	NRE	25%	17%	9%	-59%	-9%	-15%	-21%	-72%	0%	-7%	-14%	-69%
	RE	-98%	-95%	-92%	-70%	-5%	111%	226%	1150%	-93%	-85%	-77%	-9%
	ES	19%	131%	243%	1137%	-8%	85%	178%	920%	0%	98%	196%	981%

Table 111 presents a summary of the observations regarding the electricity demand, while the results of the heat impacts are summarized in Table 112. Concerning the overall energy demand impact of the building, the observation are summarized in Table 113

Table 111 Key findings regarding the fuel-cell scenario compared to the reference case for the electricity demand (CHP3)

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for low bio-methane share, i.e until 24% of bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies a light increase of the impact
	ES	- Impact higher than reference case until 36% of bio-methane but difference small - Increase of bio-methane share implies reduction of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend has the other allocation choice but threshold at 31% of bio-methane in the supply mix
	RE	- Same trend has the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 112 Key findings regarding the fuel-cell scenario compared to the reference case for the heat demand (CHP3)

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Impact higher for fuel-cell than reference case when using bio-methane (no bio-methane = impact slightly lower) - Increase of bio-methane share implies increase of the impact
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower for fuel-cell than reference case until 20% of bio-methane, then higher - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than reference case for any bio-methane share - Bio-methane share increase implied a reduction of the impact
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Largely above the reference case
	ES	- Impact higher than reference case for any bio-methane share - Impact lower only when no bio-methane to supply the CHP - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 113 Key findings regarding the fuel-cell scenario compared to the reference case for the total energy demand (CHP3)

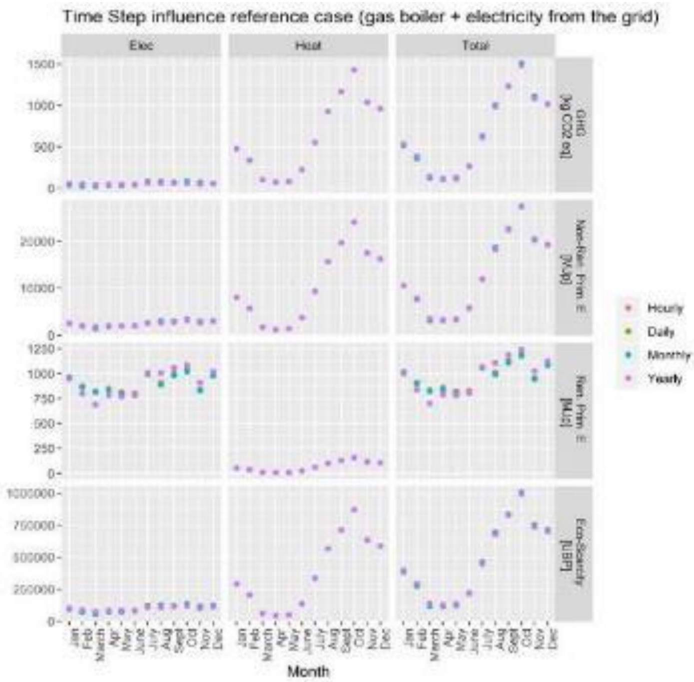
		Impact of total energy demand
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case except until 25% of bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case - Increase of bio-methane share implies increase of the impact - Solution with no bio-methane in the supply mix as lower impacts than the solution with 100% of bio-methane
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

The CHP3 fuel cell scenario is affected by the allocation choice regarding the biogas production. There is no significant change compared to the other case studies. The energy consumption profile slightly modifies the threshold points for which the fuel-cell micro-CHP alternative is either better or worst in term of environmental impact than the reference scenario. It means that the consumption profile has only a small influence on the environmental performance of the fuel-cell alternative. The fuel cells sizing has been defined under the same assumptions (see chapter 2) for each case study, it appears, therefore, that the environmental performances are the same.

Case study: CHP4

Reference situation

The results of the reference situation (i.e gas boiler for space heat and domestic hot water and electricity from the grid) are presented in Figure 135.



		Electricity Impact	Heat Impact	Total Impact
Climate Change [kg CO_2 eq/kWh]	Hourly	608	7 366	7 973
	Daily	626	7 366	7 992
	Monthly	636	7 366	8 002
	Yearly	622	7 366	7 988
NRE [MJp /kWh]	Hourly	29 279	124 517	153 795
	Daily	29 957	124 517	154 474
	Monthly	30 072	124 517	154 589
	Yearly	29 636	124 517	154 152
RE [MJp /kWh]	Hourly	10 959	818	11 777
	Daily	10 783	818	11 602
	Monthly	10 754	818	11 572
	Yearly	10 867	818	11 686
ES [UBP/kWh]	Hourly	1 181 885	4 502 855	5 684 741
	Daily	1 197 982	4 502 855	5 700 837
	Monthly	1 192 577	4 502 855	5 695 433
	Yearly	1 194 982	4 502 855	5 697 837

		Hourly	Daily	Monthly	Yearly
Electricity	Climate Change [kg CO2 eq/kWh]	-2.3%	0.7%	2.3%	0.0%
	NRE [MJp /kWh]	-1.2%	1.1%	1.5%	0.0%
	RE [MJp /kWh]	0.8%	-0.8%	-1.0%	0.0%
	ES [UBP/kWh]	-1.1%	0.3%	-0.2%	0.0%
Total	Climate Change [kg CO2 eq/kWh]	-0.2%	0.1%	0.2%	0.0%
	NRE [MJp /kWh]	-0.2%	0.2%	0.3%	0.0%
	RE [MJp /kWh]	0.8%	-0.7%	-1.0%	0.0%
	ES [UBP/kWh]	-0.2%	0.1%	0.0%	0.0%

Figure 135 Monthly environmental impact profile, CHP4 - Reference case

The impacts of the heat significantly overcome the impacts of the electricity and thereby, the overall impact of the building energy demand is driven by the heat impacts. This is the reason why the time step influence is negligible, since the heat demand, is covered by the gas boiler. However, for the RE indicator, the opposite trend is observed. The time step influence is found to be small for the electricity part, i.e, maximum 2.3% of difference, between the annual and the hourly time step.

Combustion-based CHP

The results for the combustion-based micro-CHP are displayed in Table 114 and in Figure 136.

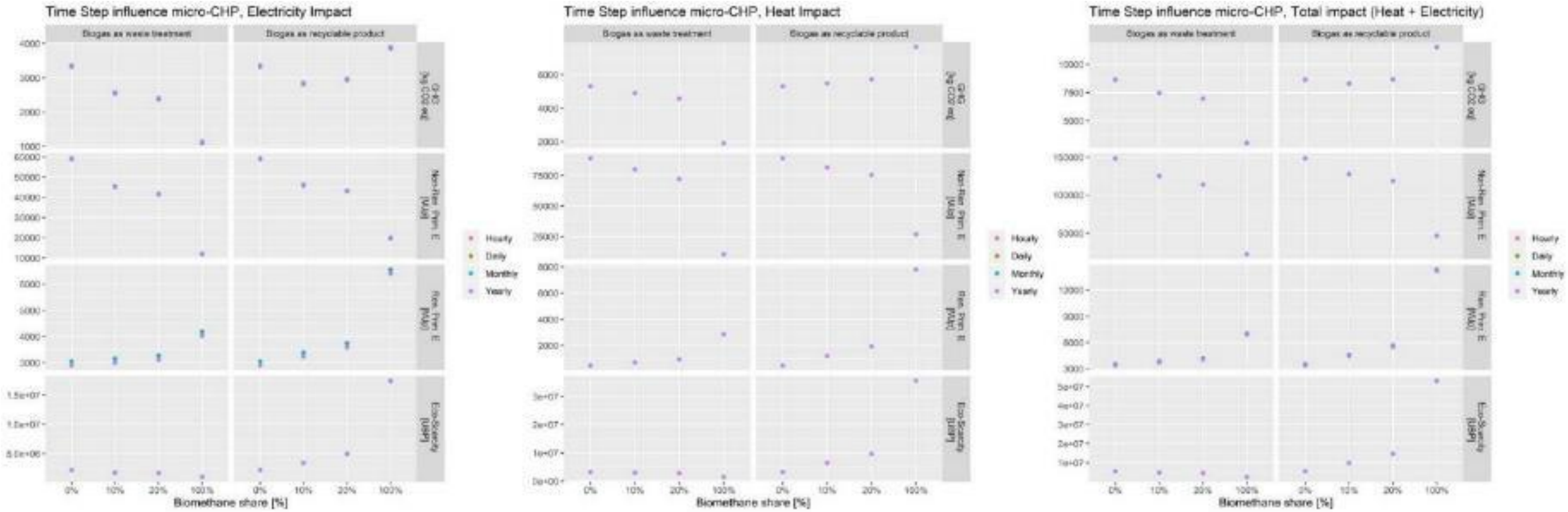


Figure 136 time step influence of environmental impact for CHP4 with combustion based unit

Table 114 Environmental impact results of CHP4 with combustion based CHP

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	3 326	2 544	2 377	1 106	5 307	4 907	4 580	1 926	8 633	7 451	6 958	3 032
		Daily	3 326	2 544	2 377	1 106	5 307	4 907	4 580	1 926	8 633	7 451	6 958	3 032
		Monthly	3 329	2 548	2 381	1 110	5 307	4 907	4 580	1 926	8 636	7 454	6 961	3 035
		Yearly	3 367	2 585	2 419	1 147	5 307	4 907	4 580	1 926	8 674	7 492	6 999	3 073
	NRE [MJp /kWh]	Hourly	59 097	45 262	41 553	11 872	89 226	79 947	72 223	10 407	148 323	125 209	113 776	22 279
		Daily	59 066	45 231	41 522	11 841	89 226	79 947	72 223	10 407	148 292	125 178	113 745	22 248
		Monthly	59 084	45 249	41 540	11 859	89 226	79 947	72 223	10 407	148 310	125 196	113 763	22 266
		Yearly	59 470	45 635	41 926	12 245	89 226	79 947	72 223	10 407	148 696	125 582	114 149	22 652
	RE [MJp /kWh]	Hourly	3 043	3 147	3 262	4 175	479	724	954	2 870	3 522	3 871	4 216	7 045
		Daily	3 059	3 163	3 278	4 191	479	724	954	2 870	3 538	3 887	4 232	7 061
		Monthly	3 054	3 159	3 273	4 187	479	724	954	2 870	3 533	3 883	4 227	7 056
		Yearly	2 894	2 999	3 113	4 027	479	724	954	2 870	3 373	3 723	4 067	6 896
	ES [UBP/kWh]	Hourly	2 224 539	1 776 644	1 693 070	1 049 461	3 250 617	3 042 787	2 874 956	1 532 291	5 475 156	4 819 432	4 568 026	2 581 752
		Daily	2 224 070	1 776 175	1 692 601	1 048 992	3 250 617	3 042 787	2 874 956	1 532 291	5 474 687	4 818 962	4 567 557	2 581 283
		Monthly	2 224 263	1 776 368	1 692 794	1 049 185	3 250 617	3 042 787	2 874 956	1 532 291	5 474 880	4 819 155	4 567 750	2 581 476
		Yearly	2 258 120	1 810 225	1 726 651	1 083 042	3 250 617	3 042 787	2 874 956	1 532 291	5 508 737	4 853 012	4 601 607	2 615 333
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	3 326	2 819	2 937	3 861	5 307	5 481	5 729	7 656	8 633	8 300	8 666	11 517
		Daily	3 326	2 819	2 937	3 861	5 307	5 481	5 729	7 656	8 633	8 300	8 666	11 517
		Monthly	3 329	2 822	2 940	3 864	5 307	5 481	5 729	7 656	8 636	8 303	8 669	11 520
		Yearly	3 367	2 860	2 978	3 902	5 307	5 481	5 729	7 656	8 674	8 341	8 707	11 558
	NRE [MJp /kWh]	Hourly	59 097	46 047	43 119	19 712	89 226	81 578	75 486	26 734	148 323	127 625	118 605	46 446
		Daily	59 066	46 016	43 088	19 681	89 226	81 578	75 486	26 734	148 292	127 594	118 574	46 414
		Monthly	59 084	46 034	43 106	19 699	89 226	81 578	75 486	26 734	148 310	127 612	118 592	46 433
		Yearly	59 470	46 420	43 492	20 085	89 226	81 578	75 486	26 734	148 696	127 998	118 978	46 819
	RE [MJp /kWh]	Hourly	3 043	3 383	3 734	6 548	479	1 212	1 945	7 809	3 522	4 595	5 679	14 357
		Daily	3 059	3 400	3 750	6 564	479	1 212	1 945	7 809	3 538	4 611	5 695	14 373
		Monthly	3 054	3 395	3 746	6 559	479	1 212	1 945	7 809	3 533	4 607	5 691	14 368
		Yearly	2 894	3 235	3 586	6 399	479	1 212	1 945	7 809	3 373	4 447	5 531	14 208
	ES [UBP/kWh]	Hourly	2 224 539	3 412 701	4 967 963	17 410 055	3 250 617	6 450 496	9 690 374	35 609 365	5 475 156	9 863 197	14 658 336	53 019 420
		Daily	2 224 070	3 412 232	4 967 493	17 409 585	3 250 617	6 450 496	9 690 374	35 609 365	5 474 687	9 862 728	14 657 867	53 018 951
		Monthly	2 224 263	3 412 425	4 967 686	17 409 779	3 250 617	6 450 496	9 690 374	35 609 365	5 474 880	9 862 921	14 658 060	53 019 144
		Yearly	2 258 120	3 446 282	5 001 543	17 443 636	3 250 617	6 450 496	9 690 374	35 609 365	5 508 737	9 896 778	14 691 917	53 053 001

The relative time step influence has been calculated based on the results of Table 114 and it is summarized in Table 115. For each time step, the relative influence has been calculated compared to the annual time step.

Table 115 CHP4: combustion based unit - Time step influence compared to yearly calculation

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	-1.2%	-1.6%	-1.7%	-3.6%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.6%	-0.6%	-1.3%
		Daily	-1.2%	-1.6%	-1.7%	-3.6%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.6%	-0.6%	-1.3%
		Monthly	-1.1%	-1.5%	-1.6%	-3.3%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.5%	-1.2%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE [MJp /kWh]	Hourly	-0.6%	-0.8%	-0.9%	-3.0%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-1.6%
		Daily	-0.7%	-0.9%	-1.0%	-3.3%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.4%	-1.8%
		Monthly	-0.6%	-0.8%	-0.9%	-3.2%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-1.7%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE [MJp /kWh]	Hourly	5.1%	4.9%	4.8%	3.7%	0.0%	0.0%	0.0%	0.0%	4.4%	4.0%	3.6%	2.2%
		Daily	5.7%	5.5%	5.3%	4.1%	0.0%	0.0%	0.0%	0.0%	4.9%	4.4%	4.0%	2.4%
		Monthly	5.5%	5.3%	5.1%	4.0%	0.0%	0.0%	0.0%	0.0%	4.7%	4.3%	3.9%	2.3%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES [UBP/kWh]	Hourly	-1.5%	-1.9%	-1.9%	-3.1%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.7%	-0.7%	-1.3%
		Daily	-1.5%	-1.9%	-2.0%	-3.1%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.7%	-0.7%	-1.3%
		Monthly	-1.5%	-1.9%	-2.0%	-3.1%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.7%	-0.7%	-1.3%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	-1.2%	-1.4%	-1.4%	-1.1%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.5%	-0.4%
		Daily	-1.2%	-1.4%	-1.4%	-1.1%	0.0%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.5%	-0.4%
		Monthly	-1.1%	-1.3%	-1.3%	-1.0%	0.0%	0.0%	0.0%	0.0%	-0.4%	-0.5%	-0.4%	-0.3%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NRE [MJp /kWh]	Hourly	-0.6%	-0.8%	-0.9%	-1.9%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-0.8%
		Daily	-0.7%	-0.9%	-0.9%	-2.0%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-0.9%
		Monthly	-0.6%	-0.8%	-0.9%	-1.9%	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.3%	-0.3%	-0.8%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RE [MJp /kWh]	Hourly	5.1%	4.6%	4.1%	2.3%	0.0%	0.0%	0.0%	0.0%	4.4%	3.3%	2.7%	1.0%
		Daily	5.7%	5.1%	4.6%	2.6%	0.0%	0.0%	0.0%	0.0%	4.9%	3.7%	3.0%	1.2%
		Monthly	5.5%	4.9%	4.5%	2.5%	0.0%	0.0%	0.0%	0.0%	4.7%	3.6%	2.9%	1.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	ES [UBP/kWh]	Hourly	-1.5%	-1.0%	-0.7%	-0.2%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.3%	-0.2%	-0.1%
		Daily	-1.5%	-1.0%	-0.7%	-0.2%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.3%	-0.2%	-0.1%
		Monthly	-1.5%	-1.0%	-0.7%	-0.2%	0.0%	0.0%	0.0%	0.0%	-0.6%	-0.3%	-0.2%	-0.1%
		Yearly	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The time step influence is found to be small, as for the other case studies. The RE indicator is the most sensitive, with a 5.5% of variation, for a daily calculation compared to the annual calculation for the electricity. For the total building energy demand, the influence is moderate with a maximum of 4.4% difference for 10% of bio-methane in the supply mix for the RE indicator, between the daily and annual time step. The other environmental indicators are sensitive to the time step. The second most influenced indicator is the climate change with a maximum of 3.6% difference between the hourly and annual time step for the electricity demand and 100% of bio-methane.. For the total building energy demand, this influence is insignificant, i.e.1.3%. Thereby, the time step influence is negligible for the combustion based micro-CHP. Based on this observation, the environmental impacts of the “CHP4 combustion based unit” scenario is then compared to the environmental impacts of the reference scenario, i.e gas boiler + electricity from the grid. The results are displayed in Figure 137 and Table 116 on a monthly basis.

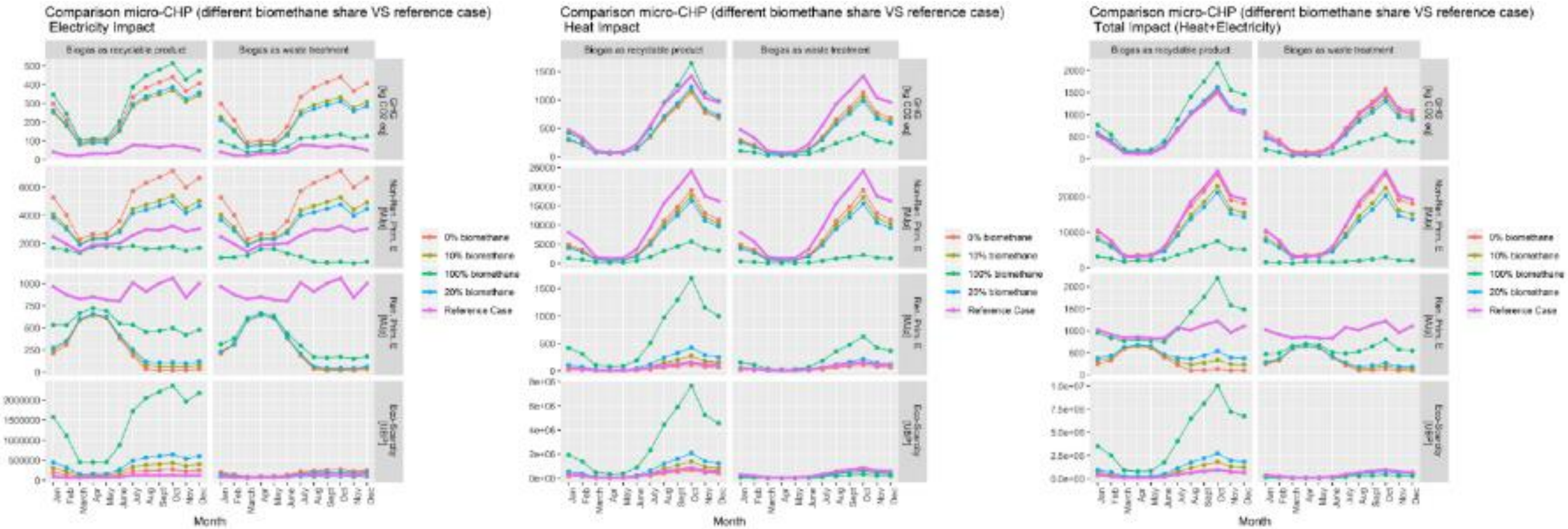


Figure 137 CHP4: Comparison of the reference case to combustion based CHP for various bio-methane shares

Table 116 Comparison of reference case to the combustion based CHP for various bio-methane shares (CHP4)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	447%	319%	291%	82%	-28%	-33%	-38%	-74%	8%	-7%	-13%	-62%
	NRE	102%	55%	42%	-59%	-28%	-36%	-42%	-92%	-4%	-19%	-26%	-86%
	RE	-72%	-71%	-70%	-62%	-41%	-12%	17%	251%	-70%	-67%	-64%	-40%
	ES	88%	50%	43%	-11%	-28%	-32%	-36%	-66%	-4%	-15%	-20%	-55%
Biogas as a recyclable product	Climate Change	447%	364%	383%	535%	-28%	-26%	-22%	4%	8%	4%	9%	44%
	NRE	102%	57%	47%	-33%	-28%	-34%	-39%	-79%	-4%	-17%	-23%	-70%
	RE	-72%	-69%	-66%	-40%	-41%	48%	138%	854%	-70%	-61%	-52%	22%
	ES	88%	189%	320%	1373%	-28%	43%	115%	691%	-4%	74%	158%	833%

As for the previous case studies, the impacts are driven by the assumption modelling choice, regarding the biogas production. The summary of the observation is provided in Table 117 for the electricity impact, while for the heat impacts in Table 118. Concerning the overall energy demand impact of the building, the observations are summarized in the Table 119.

Table 117 Key findings regarding the combustion-based CHP scenario compared to the reference case for the electricity demand (CHP4)

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case for any bio-methane share. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case for bio-methane share below 53% - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies an increase of the impact
	ES	- Impact higher than reference case - Increase of bio-methane share implies increase of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend as the other allocation choice but threshold at 67%
	RE	- Same trend as the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 118 Key findings regarding the combustion-based CHP scenario compared to the reference case for the heat demand (CHP4)

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Increase of bio-methane share implies increase of the impact - Below 14% of bio-methane in the supply mix, impact lower, then higher
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact lower than the reference case until 88% of bio-methane in the supply mix - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact already higher than reference case when 10% of bio-methane in the mix - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 119 Key findings regarding the combustion-based CHP scenario compared to the reference case for the total energy demand (CHP4)

		Impact of the overall energy demand
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case except for no bio-methane in the supply mix - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case but until 20% of bio-methane, difference small - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case until 76% then above - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Impact lower only when 100% natural gas is used to supply the micro-CHP - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

The same conclusions are drawn, as for the other case studies. Between the case studies, there are only slightly differences, according to the bio-methane shares but these differences do not change the overall observations and conclusions.

Fuel cell CHP

The results with of fuel cell micro-CHP are displayed in Figure 138 and Table 120. The comparison between the scenario with fuel cell and the reference case is displayed in Table 121 and in Figure 139.

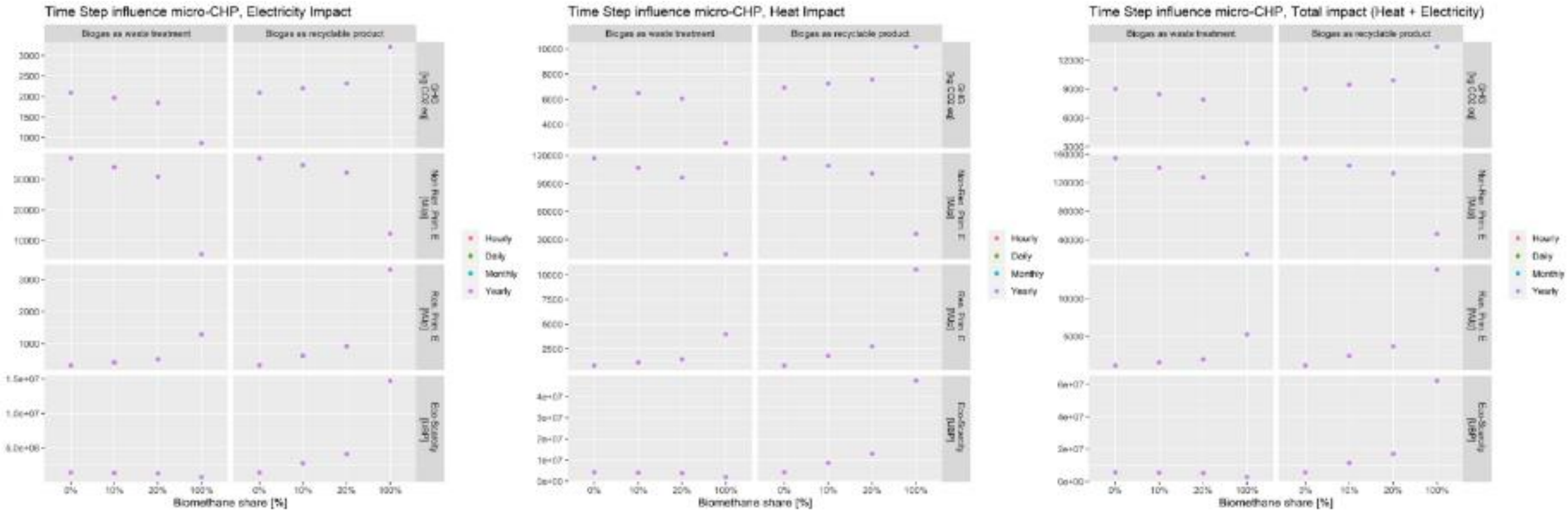


Figure 138 Time step influence on the environmental impact for CHP4 with a fuel cell unit

Table 120 Environmental impact results of CHP4 with a fuel cell unit

			Electricity Impact				Heat Impact				Total Impact			
			0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change [kg CO2 eq/kWh]	Hourly	2 095	1 976	1 851	871	6 932	6 493	6 051	2 526	9 027	8 468	7 903	3 397
		Daily	2 096	1 977	1 852	872	6 932	6 493	6 051	2 526	9 028	8 469	7 904	3 398
		Monthly	2 096	1 977	1 852	872	6 932	6 493	6 051	2 526	9 028	8 469	7 904	3 398
		Yearly	2 096	1 976	1 852	872	6 932	6 493	6 051	2 526	9 027	8 469	7 903	3 398
	NRE [MJp /kWh]	Hourly	36 919	33 996	30 834	5 564	117 359	107 048	96 737	14 248	154 278	141 044	127 571	19 812
		Daily	36 956	34 034	30 871	5 601	117 359	107 048	96 737	14 248	154 315	141 081	127 608	19 849
		Monthly	36 954	34 031	30 869	5 599	117 359	107 048	96 737	14 248	154 313	141 079	127 606	19 847
		Yearly	36 950	34 027	30 865	5 594	117 359	107 048	96 737	14 248	154 308	141 075	127 602	19 843
	RE [MJp /kWh]	Hourly	326	422	519	1 297	797	1 115	1 433	3 975	1 123	1 537	1 952	5 272
		Daily	315	412	509	1 286	797	1 115	1 433	3 975	1 112	1 527	1 942	5 261
		Monthly	315	412	509	1 286	797	1 115	1 433	3 975	1 112	1 527	1 942	5 261
		Yearly	317	413	510	1 288	797	1 115	1 433	3 975	1 114	1 528	1 943	5 263
	ES [UBP/kWh]	Hourly	1 423 058	1 363 169	1 300 246	796 874	4 271 550	4 048 210	3 824 869	2 038 141	5 694 609	5 411 379	5 125 116	2 835 015
		Daily	1 423 898	1 364 009	1 301 086	797 714	4 271 550	4 048 210	3 824 869	2 038 141	5 695 449	5 412 219	5 125 956	2 835 855
		Monthly	1 423 763	1 363 874	1 300 951	797 579	4 271 550	4 048 210	3 824 869	2 038 141	5 695 313	5 412 084	5 125 821	2 835 720
		Yearly	1 423 639	1 363 750	1 300 827	797 455	4 271 550	4 048 210	3 824 869	2 038 141	5 695 189	5 411 960	5 125 697	2 835 596
Biogas as a recyclable product	Climate Change [kg CO2 eq/kWh]	Hourly	2 095	2 210	2 321	3 214	6 932	7 258	7 582	10 178	9 027	9 468	9 903	13 392
		Daily	2 096	2 211	2 322	3 215	6 932	7 258	7 582	10 178	9 028	9 469	9 904	13 393
		Monthly	2 096	2 211	2 322	3 215	6 932	7 258	7 582	10 178	9 028	9 469	9 904	13 393
		Yearly	2 096	2 211	2 322	3 214	6 932	7 258	7 582	10 178	9 027	9 469	9 903	13 393
	NRE [MJp /kWh]	Hourly	36 919	34 664	32 174	12 243	117 359	109 227	101 093	36 039	154 278	143 891	133 267	48 282
		Daily	36 956	34 701	32 211	12 280	117 359	109 227	101 093	36 039	154 315	143 928	133 304	48 319
		Monthly	36 954	34 699	32 209	12 278	117 359	109 227	101 093	36 039	154 313	143 926	133 302	48 317
		Yearly	36 950	34 694	32 204	12 273	117 359	109 227	101 093	36 039	154 308	143 921	133 297	48 312
	RE [MJp /kWh]	Hourly	326	625	924	3 318	797	1 774	2 752	10 570	1 123	2 399	3 676	13 887
		Daily	315	614	914	3 307	797	1 774	2 752	10 570	1 112	2 389	3 666	13 877
		Monthly	315	614	914	3 307	797	1 774	2 752	10 570	1 112	2 389	3 666	13 877
		Yearly	317	616	915	3 309	797	1 774	2 752	10 570	1 114	2 390	3 667	13 878
	ES [UBP/kWh]	Hourly	1 423 058	2 756 292	4 086 489	14 728 085	4 271 550	8 595 371	12 919 191	47 509 750	5 694 609	11 351 663	17 005 680	62 237 835
		Daily	1 423 898	2 757 133	4 087 329	14 728 925	4 271 550	8 595 371	12 919 191	47 509 750	5 695 449	11 352 503	17 006 520	62 238 675
		Monthly	1 423 763	2 756 997	4 087 193	14 728 790	4 271 550	8 595 371	12 919 191	47 509 750	5 695 313	11 352 368	17 006 384	62 238 540
		Yearly	1 423 639	2 756 873	4 087 069	14 728 666	4 271 550	8 595 371	12 919 191	47 509 750	5 695 189	11 352 244	17 006 261	62 238 416

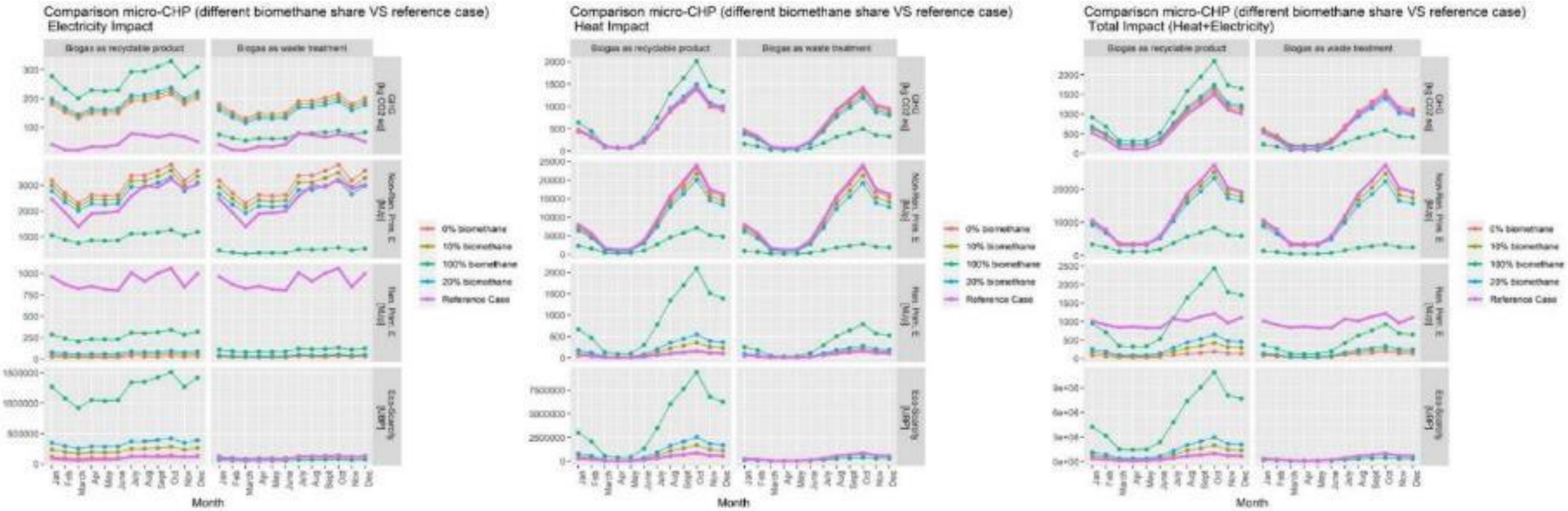


Figure 139 CHP4: Comparison of the reference case to the fuel cell unit for various bio-methane shares

Table 121 Comparison of the reference case to the fuel cell unit for various bio-methane shares (CHP4)

		Electricity Impact				Heat Impact				Total Impact			
		0%	10%	20%	100%	0%	10%	20%	100%	0%	10%	20%	100%
Biogas as a waste treatment	Climate Change	245%	225%	205%	43%	-6%	-12%	-18%	-66%	13%	6%	-1%	-57%
	NRE	26%	16%	5%	-81%	-6%	-14%	-22%	-89%	0%	-8%	-17%	-87%
	RE	-97%	-96%	-95%	-88%	-3%	36%	75%	386%	-90%	-87%	-83%	-55%
	ES	20%	15%	10%	-33%	-5%	-10%	-15%	-55%	0%	-5%	-10%	-50%
Biogas as a recyclable product	Climate Change	245%	264%	282%	429%	-6%	-1%	3%	38%	13%	19%	24%	68%
	NRE	26%	18%	10%	-58%	-6%	-12%	-19%	-71%	0%	-6%	-13%	-69%
	RE	-97%	-94%	-92%	-70%	-3%	117%	236%	1191%	-90%	-80%	-69%	18%
	ES	20%	133%	246%	1146%	-5%	91%	187%	955%	0%	100%	199%	995%

The comparison between the fuel-cell scenario and the reference is highly dependent of the allocation, regarding the biogas impact, as for the combustion-based micro-CHP. Table 122 summarizes the observations regarding the electricity demand, and the results of the heat impacts are summarized in Table 123. Concerning the overall energy demand impact of the building, the observation are summarized in Table 124.

Table 122 Key findings regarding the fuel-cell scenario compared to the reference case for the electricity demand

		Impact of electricity
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case. Largely higher for low bio-methane share. - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact higher than reference case until 25% of bio-methane in the supply ix - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than reference case in any cases - Increase of bio-methane share implies a light increase of the impact
	ES	- Impact higher than reference for low bio-methane share, threshold at 39%, impact lower when above - Increase of bio-methane share implies reduction of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than the reference case, largely higher for any bio-methane share - Increase of bio-methane share implies increase of the impact
	NRE	- Same trend has the other allocation choice (but threshold at 32% of bio-methane share in the supply mix)
	RE	- Same trend has the other allocation choice
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 123 Key findings regarding the fuel-cell scenario compared to the reference case for the heat demand

		Impact of heat
Biogas as a waste treatment	Climate Change	- Impact lower than the reference case. - Increase of bio-methane share implies reduction of the impact
	NRE	- Same as climate change indicator
	RE	- Impact higher for fuel-cell than reference case when using bio-methane (no bio-methane = impact slightly lower) - Increase of bio-methane share implies increase of the impact
	ES	- Same as climate change indicator
Biogas as a recyclable product	Climate Change	- Impact very slightly lower for fuel-cell than reference case until 13% of bio-methane, then higher - Increase of bio-methane share implies increase of the impact
	NRE	- Impact lower than reference case for any bio-methane share - Bio-methane share increase implied a reduction of the impact
	RE	- Impact higher for fuel-cell than reference case - Increase of bio-methane share implies increase of the impact - Largely above the reference case
	ES	- Impact higher than reference case for any bio-methane share - Impact lower only when no bio-methane to supply the CHP - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

Table 124 Key findings regarding the fuel-cell scenario compared to the reference case for the total energy demand (CHP4)

		Impact of total energy demand
Biogas as a waste treatment	Climate Change	- Impact higher than the reference case until 19%, then lower - Increase of bio-methane share implies reduction of the impact
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case - Increase of bio-methane share implies increase of the impact
	ES	- Impact lower than the reference case - Increase of bio-methane share implies decrease of the impact
Biogas as a recyclable product	Climate Change	- Impact higher than reference case - Increase of bio-methane share implies increase of the impact - Solution with no bio-methane in the supply mix as lower impacts than the solution with 100% of bio-methane
	NRE	- Impact lower than the reference case - Increase of bio-methane share implies reduction of the impact
	RE	- Impact lower than the reference case until 83% of bio-methane in the supply mix then higher - Increase of bio-methane share implies increase of the impact
	ES	- Impact higher than reference case for any bio-methane share - Increase of bio-methane share implies increase of the difference with the reference case - Impact largely above the reference case

The CHP4 fuel-cell results have no significant difference from the other case studies, which means that the consumption profile does not appear to influence the environmental performance of the fuel-cell alternative.