Combined Heat and Power (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

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1. Highlights

- Assessment of the hourly GHG emission factors for the consumed electricity in Switzerland
- Analysis of historical data hourly natural gas consumption for region-level aggregation
- Development of a model of hourly gas consumption for heating purposes
- Assessment of the impact of CHP expansion on the hourly emission factors for the consumed electricity in Switzerland

2. Key words

electricity production, electricity imports, hourly GHG emission factor, CHP, natural gas

3. Abstract

Having started the phasing-out of nuclear process, Switzerland will have to face the challenge of replacing nearly 30% of its domestic power generation in the medium run. Currently, imports from the European Union are used when indigenous production is unable to meet demand. However, growing import dependency in winter represents not only a potential threat to the security of supply but also electricity import with a heavy GHG content. The development of decentralized power generation through natural gas-fired combined heat and power (CHP) plants could be a short-medium run solution allowing to produce electricity on the Swiss territory during winter. In this work, we evaluate how the replacement of a part of the inflows from neighbouring countries by decentralized CHP plants fuelled by natural gas impacts the hourly carbon footprint of the electricity consumed in Switzerland. We developed a four-step methodology to answer this question. Firstly, we assess, for the years 2016 to 2019, the GHG content of the electricity consumed in Switzerland in accordance with the consumption principle and applying the attributional Life Cycle Analysis (LCA) approach. Secondly, based on natural gas delivery data, we modelled hourly gas consumption for heating purposes by means of the heating degree-hour method. Then, based on the previous part, we simulated hourly electricity production with natural gas CHP plants. Finally, we assessed the hourly GHG emission from electricity consumption with the new solution. The results show that, actually, imports impact strongly and negatively the GHG footprint of the electricity consumed in Switzerland. The results of the last part show that the development of decentralized power generation through natural gas-fired CHP plants can lower the GHG footprint of the electricity consumed in Switzerland. Indeed, in nearly all the scenarios, the natural-gas CHP solution is a less-GHG-emitting alternative to imports.

4. Abbreviations

CHP	combined heat and power
NG	natural gas
LCA	life cycle analysis
GHG	greenhouse gas
EF	emission factor

5. Nomenclature

Symbols

E	Electricity (MWh/h)
M	LCA GHG emissions (CO2-eq-Kg)
EF	Emission factor (g CO2-eq- /kWh)
Gen	Generation
Imp	Importation
Exp	Exportation
Cons	Consumption
CHP	CHP production (MWh/h)
$\hat{Y}$Heat	estimated hourly natural gas consumption for heating purposes (MWh/h)
Y	natural gas consumption (MWh/h)
$\beta_1,\ldots,\beta_5$	regression coefficients
HDH	heating degree hour
Hour	categorical variable accounting for the hour of the day
Weekday	categorical variable accounting for the day of the week
Bankholiday	dummy variable accounting the Swiss holidays
ε	random error term
θ	temperature

Subscripts

l	neighbouring country identifier (GE, FR, IT, AT)
i	production type identifier (biomass, lignite…)
t	hour identifier (1…8760)
CH	Switzerland
in	internal
ex	external
th	threshold

Superscripts

New	result of the CHP simulation

6. Introduction

Switzerland has committed to a transition to a low-carbon energy system through the Energy Strategy 2050. One of the pillars of the strategy is phasing-out of nuclear power (OFEN, 2013). It means that the country will have to face the challenge of replacing nearly 30% of its domestic power generation (31.7% in 2017) (OFEN, 2018). In the long run, it should be compensated by the development of renewable energies and reduction in consumption, the two other pillars of the strategy. Currently, imports from the European Union are used when indigenous production is unable to meet demand. Indeed, for the last years, the use of electricity inflows from neighbouring countries has been growing, particularly in winter. The Federal Electricity Commission (ElCom) has warned about this winter dependency. Indeed, it estimated that this winter dependency could potentially become a threat to the security of supply if it keeps growing due to the decommissioning of the nuclear power plants. This is the reason the ElCom recommends "that a substantial part of this missing winter production continues to be produced in Switzerland" (ElCom, 2018, p. 15). The commission also wanted to raise awareness concerning the fact that the majority imports during this period are of fossil origin (ElCom, 2018). These imports probably have an important impact on the carbon footprint of the electricity consumed in Switzerland as around 20% of the European Union's electricity production came from coal (21.5% in 2017) (IEA, 2019).

The use of small distributed combined heat and power (CHP) units fuelled with natural gas can potentially represent a temporary solution until the development of renewable energies and the reduction in consumption fully compensate the missing electricity production. Indeed, CHP, is a highly efficient energy conversion process which produces electricity near the site of use and capture the waste heat for space and water heating. From a thermodynamic point of view, this approach allows a more efficient use of natural gas compared to its direct combustion for heating purposes. Furthermore, this decentralized system is also more efficient than other conventional power plants where the waste heat is not recovered. Finally, this distributed energy-efficient option also allows to reduce reliance on grid electricity. This efficient technology has been considered as a serious cog in the wheel of the energy transition for a growing number of countries. Indeed, Japan, Germany, the UK, the Netherlands, and the U.S.A. are active in the introduction of CHP as a power generation solution in the energy transition process (J. E. Brown et al., 2007; Kobayashi et al., 2005). However, there are still obstacles for an appropriate market implementation (Bianca Howard et al., 2014; Kuhn et al., 2008; M. Liu et al., 2014). In Switzerland, there is only 496 MW of installed CHP capacity, accounting for around 2.5% of total national power generation (in 2018) (Kaufmann, 2019). There is plenty of room for the development of this technology in Switzerland.

As a result, the purpose of this work is to evaluate the environmental impact of a short-medium run solution allowing to produce electricity on the Swiss territory during winter : the development of decentralized power generation through natural gas-fired combined heat and power plants. More precisely, this work aims to answer the two following research questions :

1) What is the impact of the electricity inflows from neighbouring countries on the hourly carbon footprint of the electricity consumed in Switzerland ?
2) How the replacement of a part of the inflows from neighbouring by Combined Heat and Power (CHP) fuelled with natural gas impacts the hourly carbon footprint of the electricity consumed in Switzerland ?

We developed a four-step methodology to answer those two research questions. Firstly, we assess, for the years 2016 to 2019, the GHG content of the electricity consumed in Switzerland in accordance with the consumption principle and applying the attributional Life Cycle Analysis (LCA) approach. Secondly, based on natural gas delivery data, we modelled hourly gas consumption for heating purposes by means of the heating degree-hour method. Then, based on the previous part, we simulated hourly electricity production with natural gas CHP plants. Finally, we assessed the hourly GHG emission from electricity consumption with the new solution. One of the major contributions of our paper is the hourly granularity approach adopted in order to be closer to the real constraints of the electricity maker.

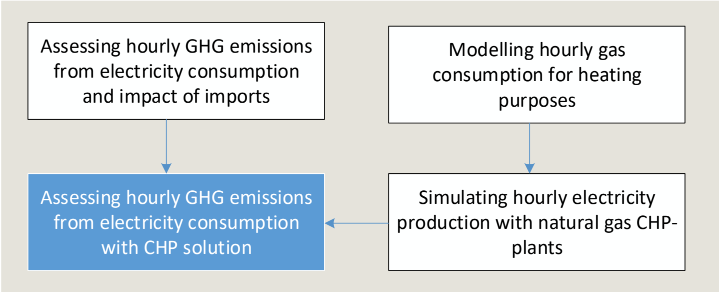

Figure 1 : The four parts of the research process

The remainder of this paper is structured as follows: Section 7 has the literature review. Section 8 presents the data and methodology used to address the research questions. The results are then presented and discussed in Section 9. Section 10 is dedicated to sensitivity analysis of the model. The paper concludes with section 11 with discussion and implication regarding the results.

7. Literature Review

Our paper addresses three different themes: CHP as a solution for the energy transition, the GHG content of the grid electricity consumed and natural gas heating demand modelling. This is the reason why we developed a literature review on the three of them. They are presented in the following sections.

7.1 Combined heat and power CHP as a solution for the energy transition

Combined heating and power systems, or sometimes called cogeneration, has been identified early as a highly efficient system which can lead to primary energy saving and emission reduction (IEA, 2008). Today, the body of literature analysing the potential role CHP can play in the energy transition toward a low-carbon energy system is extremely varied. This is due to the fact that different CHP systems (prime mover) exist such as turbines, engines and fuel cells, that they can work at different scales (from micro-scale to large-scale), that different operation strategies can be adopted (electric or thermal demand management) and that they can be deployed for different uses such as residential, industrial, commercial or for district heating. Liu et al. (2014) realized a survey of the state of the art around the world of this technology, highlighting all these different characteristics. The focus of this review has been on papers focusing on the analysis of CHP fuelled with natural gas deployed for residential or commercial use.

The most widely used measure to illustrate the environmental benefit of CHP implementation is primary energy saving (Bianchi et al., 2013) and GHG emissions saving. Sometimes, other measures are used such as exergy saving (Ehyaei et al., 2012; Wang et al., 2011) and other air pollutant savings. For instance, Ehyaei et al. (2012) considered, in addition to exergy saving and CO2 emissions saving, nitric oxide saving, a gas responsible of the formation of smog and acid rain. Another aspect often explored in the literature is how the deployment of CHP facilitate or hinder the deployment of intermittent renewable. For instance, several papers have shown that CHP technology has a symbiotic relationship with solar photovoltaic technology and contribute to the stability of the electricity grid (Mostofi et al., 2011; Nosrat et al., 2014; Pearce, 2009).

To assess the GHG emissions saving from implementing CHP systems, the avoided burden approach has been frequently used. It means that the GHG emissions produce with the CHP system is compared with a reference system for heat and electricity generation. The reference system is often a traditional boiler and grid electricity (Dorer & Weber, 2009; B. Howard & Modi, 2017; Bianca Howard et al., 2014; Hueffed & Mago, 2010; Mago et al., 2011; Mago & Smith, 2012; Rosato et al., 2013). As a result, the GHG content of the grid electricity has a heavy impact on the magnitude of the environmental benefit of a CHP system. Indeed, an element which regularly emerges from the literature is that the GHG benefit of CHP lessened with cleaner electricity system (B. Howard & Modi, 2017; H. Liu et al., 2017; Mago et al., 2011). Some authors highlighted the fact that, indeed, it has potential to reduce carbon emissions in the near future. However, in a highly renewable electric future, the benefits become less obvious (Kelly et al., 2014).

The vast majority of the literature carried out these analyses at the building level. Authors intended to explore which operation strategies (Wang et al., 2011), which scale (Wakui & Yokoyama, 2011), which technology (Rosato et al., 2013) offers the best performance in economic or environmental term (Bianchi et al., 2013; Dorer & Weber, 2009; Hueffed & Mago, 2010; Ren & Gao, 2010). Howard and Modi (2017) found out that, potential GHG reduction of the implementation of CHP systems fuelled with natural gas can range from less than 10% to 50% depending on the prime mover technology, the typology of the building, the operating strategy and the current GHG content of the grid electricity. Mago and Smith (2012) analysed different types of buildings in the same city in order to find out which type of building is more likely to save GHG emissions (Mago & Smith, 2012). Other authors analysed same hypothetical building in different cities to understand the impact of different climates on the results (Mago et al., 2011; Romero Rodríguez et al., 2016).

Starting from an analysis at the building level, some authors adopted a bottom-up approach to identify city or country CHP potential to reduce GHG emissions. This is the case for Howard et al. (2014) for New York City, H. Liu et al. (2017) for China and Kelly et al. (2014) for the UK. Another approach to identify CHP potential is a top-down approach, where global heating demand is used to derive potential CHP power and heating generation by applying average power to heat ration corresponding the current technology (IEA, 2008). This is the approach adopted by our paper.

In Switzerland, several authors have investigated the role CHP may play in the future Swiss energy system. Indeed, Rognon (2005) evaluated the efficiency potentials of heat pumps with CHP. A complete study has analysed how biogas-CHP swarms have the potential to balance intermittent renewable energy production (Buffat & Raubal, 2019; Panos & Kannan, 2016; Vögelin et al., 2016). The starting point of the analysis was that CHP units have to be fuelled only with biogenic resources. The result of the energy-economic modelling showed that CHP may have an important role in a very stringent climate policy environment.

To the best of our knowledge, there is no paper addressing the case of GHG emissions reduction potential of the deployment of CHP units fuelled with natural gas in Switzerland. One of the major contributions of our paper is addressing this question in an hourly approach. Indeed, the GHG content of the grid electricity is, in all the cases cited above, considered as constant over the year (B. Howard & Modi, 2017; Bianca Howard et al., 2014; Mago et al., 2011). Another contribution is that we adopted a top-down approach based on natural gas heating demand by using real hourly natural gas consumption.

Those two specific aspects are further discussed in the two following sections

7.2 GHG content of the electricity consumed

As pointed out in the previous paragraph, the GHG content of the grid electricity has a heavy impact on the magnitude of the environmental benefit of the deployment of CHP. However, determining GHG emission from electricity grid consumption is a challenging task (Soimakallio et al., 2011; Weber et al., 2010). Indeed, depending on the energy resource availability and the ever-changing demand, the generation mix varies continually and, as a result, it does not have the same GHG footprint over time. Moreover, because of the meshing of the network, it is not possible to trace back the electricity consumed to a specific power plant. This is the reason why there are plenty of different ways of associating GHG emission with electricity grid consumption. This is reflected in the great variety of studies attempting to achieve that result (Khan, 2019).

One of the most important features of carbon intensity of the electricity grid is its time-varying aspect. Indeed, the GHG content of electricity grid varies greatly over days and seasons. However, in his literature review on the GHG content of electricity generation, Khan (2019) identified that only 2% of studies considered this time-varying aspect. Fortunately, a growing body of literature is starting to focus on finer granularity (hourly, half-hourly) in order to be closer to the reality of the physical nature of electrons (Gordon & Fung, 2009; Khan, 2018; Khan et al., 2017; Kopsakangas-Savolainen et al., 2017; Messagie et al., 2014; Romano et al., 2019; Roux et al., 2016; Schram et al., 2019; Spork et al., 2015; St-Jacques et al., 2020; Vuarnoz & Jusselme, 2018).

Another aspect, as important as the temporal sensitivity of the GHG content of the electricity grid, is its spatial sensitivity such as the power exchanges with other countries. Two different approaches can be used: the production and the consumption principle (Munksgaard & Pedersen, 2001; Peters & Hertwich, 2008). The former is recommended by GHG quantification protocols such as the United Nations Framework Convention on Climate Change (UNFCCC) and is often used by national studies (Frischknecht et al., 2012). It takes into consideration production before exchange with other countries. It implies that countries are responsible for the GHG emissions of their electricity production. The latter, on the contrary, implies that countries are responsible for the GHG emissions of the electricity they consumed (local generation + import – export). Different degrees of details have been used to illustrate the GHG content of the power exchange between countries. For instance, Vuarnoz and Jusselme, (2018) considered the emission factor of the import of Switzerland as being the same as the European Network of Transmission System Operators for Electricity (ENTSO-E) mix supply emission factor. Some authors assessed the GHG emission factor of a country by taking into account imports and exports with its direct neighbours on top of the emissions generated in the local grids. They assumed that the imported electricity is entirely produced by the country of the origin of the import (Bai et al., 2014; Lindner et al., 2013; Romano et al., 2019). Other authors took into consideration exchanges between several interconnected grid (Ji et al., 2016).

Among the papers cited above, two different LCA approaches have been used: attributional and consequential. The former, also called average approach (Khan, 2019) can be described as "to describe the environmentally relevant physical flows of a past, current, or potential future product system" (Ekvall et al., 2005, p. 1). This approach calculates the average GHG content of the electricity mix. It has been used by authors willing to explore historical data or to compare different national mixes (Gordon & Fung, 2009; Ji et al., 2016; Khan, 2018; Khan et al., 2017; Lindner et al., 2013; Messagie et al., 2014; Roux et al., 2016; Schram et al., 2019; Spork et al., 2015; St-Jacques et al., 2020; Vuarnoz & Jusselme, 2018). Consequential, or sometimes called the marginal approach (Khan, 2019), can be described as a "Method for describing how environmentally relevant physical flows would have been, or will be, changed in response to possible decisions that would have been or will be made" (Soimakallio et al., 2011, p. 2). This approach takes into account the merit order of production (i.e. generators with low marginal cost are first brought on to meet demand) assuming that a change in electricity consumption will impact the generator with the higher marginal costs. This approach has been used by authors willing to assess the impact of a change in the electric system (Kopsakangas-Savolainen et al., 2017; Romano et al., 2019). The two different approaches have been discussed by Dotzaeuer (2010) and Soimakallio et al. (2011).

Concerning Switzerland, a few studies have analysed the GHG content of this country at the heart of Europe. Messmer and Frischknecht (2016) used three different approaches of carbon accounting. The generation mix, the supplier mix and the consumer mix. The first one is in accordance with the production principle presented earlier. The second one considers certified electricity through the system of Guarantee of origin. The last one, the consumer mix, is the carbon footprint for non-certified consumption. The paper considered neither exchanges with other countries nor time variability of the GHG content of electricity. On the contrary, Vuarnoz and Jusselme (2018) applied an hourly approach and considered exchanges with other countries. However, the emission factor of the import from neighbouring countries (Germany and Austria) have been considered as time-independent and as the same as the European Network of Transmission System Operators for Electricity (ENTSO-E) mix supply emission factor. Finally, Romano et al. (2019) also considered both spatial and temporal sensitivity. They applied the marginal technology approach and took into account exchanges with the country's direct neighbours.

There is a gap in the literature in the combination of both detailed consumption principle and finer time granularity. As a solution to the gap in literature, this paper used a method accounting for both aspects where the country of interest is Switzerland and adopts an attributional approach.

7.3 Natural Gas Heating Demand Modelling

As stated in the CHP literature review, our paper adopted a top-down approach, starting from a global heating demand, to identify CHP potential in Switzerland (IEA, 2008). To be precise, we derived natural gas consumption for heating purposes only starting from global natural gas consumption. The following section is dedicated to this specific aspect.

Natural gas consumption modelling has been the focus of many recent studies as pointed out by Tamba et al. (2018), Šebalj et al. (2017) and Soldo (2012) in their respective literature review on forecasting of natural gas consumption. They brought to light the great variety of methods being used such as time-series regression (J. H. Herbert, 1987; John H. Herbert et al., 1987; Huntington, 2007; L.-M. Liu & Lin, 1991; Sailor & Muñoz, 1997; Timmer & Lamb, 2007; Vitullo et al., 2009), econometric models (Yu et al., 2014), artificial neural networks (R. H. Brown et al., 1994; Gorucu, 2004; Khotanzad & Elragal, 1999; Suykens et al., 1996; Szoplik, 2015), fuzzy logic (Khotanzad et al., 2000; Musilek et al., 2006; Tonković et al., 2009), genetic algorithms (N. Aras, 2008), a combination of different models (P. Potočnik et al., 2007; Primož Potočnik et al., 2014; Soldo et al., 2014; Taşpınar et al., 2013). Šebalj et al (2017) identified that the most often used method was neural network or technique based on similar principles. According to Tamba et al. (2018), it is still not clear among researchers which models surpass the other. Indeed, clear criterion for the selection of relevant variables and features for the construction of forecasting models is clearly lacking.

However, the importance of outdoor temperature when modelling natural gas consumption has been recognized a long time ago. Indeed, many researchers concluded that the most acceptable models where the one taking temperature into account (Sabo et al., 2011). As a result, temperature is very often integrated as one of the most important variables in the model (Bianco et al., 2014; Gil & Deferrari, 2004; John H. Herbert et al., 1987; Khotanzad et al., 2000; Khotanzad & Elragal, 1999; L.-M. Liu & Lin, 1991; P. Potočnik et al., 2007; Primož Potočnik et al., 2007; Sabo et al., 2011; Soldo et al., 2014; Spoladore et al., 2016; Suykens et al., 1996; Szoplik, 2015; Timmer & Lamb, 2007) The heating degree-day approach is used to correct the temperature dependency when no heating is needed and the boilers are off. (N. Aras, 2008; Berger & Worlitschek, 2018; R. H. Brown et al., 1994; Durmayaz et al., 2000; F. Gümrah, 2001; Gorucu, 2004; J. H. Herbert, 1987, 1987; John H. Herbert et al., 1987; Huntington, 2007; Sailor & Muñoz, 1997; Sarak & Satman, 2003; Timmer & Lamb, 2007; Vitullo et al., 2009; Yu et al., 2014). Another approach has been developed by Aras and Aras (2004) where they used an autoregressive time series models for two distinct periods within a year: heating and non-heating periods. Another aspect has been the use of stepwise regression in order to illustrate this feature. (Soldo et al., 2014)[1]

[1] The focus of this review has been on papers deploying the top-down approach to model natural gas consumption at city or country level using temperature or heating degree day as additional variables.

As pointed out above, natural gas consumption has been mainly modelled for the purpose of forecasting. However, in our study we need to model the global natural gas consumption in order to derive, at an hourly time step, natural gas consumed for heating purposes. This aspect has not been the focus of many researchers. Brabec et al. (2015) and Brabec (2010) developed a statistical model for disaggregation and reaggregation of natural gas consumption data to different time intervals. Grandjean et al. (2012), realized an analysis of the different existing residential electric load curve models and pointed out different disaggregation aggregation methods. They highlighted two different approaches: the Top-down and the Bottom-up approaches (Fumo, 2014; Grandjean et al., 2012; Swan & Ugursal, 2009). The former uses macroscopic data (e.g. total residential sector energy consumption) to attribute energy consumption to a sector according to its characteristics while the second use microscopic data (e.g. individual energy consumption) and then extrapolate to a sector.

Among the studies cited above, only three have been working with hourly data (Primož Potočnik et al., 2014; Soldo et al., 2014; Spoladore et al., 2016).

Concerning Switzerland, Buffat & Raubal (2019) realized a bottom-up approach GIS-based building energy demand model for residential buildings. Using the register of buildings and dwellings to identify building using natural gas for space heating, they developed a model able to estimate the monthly energy demand for space heating. Berger & Worlitschek (2018), in a top-down approach, used heating degree days and map of population density to create a tempo-spatial map of heating demand suitable for energy system modelling.

As stated earlier, the disaggregation of global natural gas consumption in order to derive, at an hourly time step, natural gas consumed for heating purposes is something which has not been covered in the literature. As a solution to the gap in literature, this paper used various methods such as an econometric model based on the heating degree-hour methods using real hourly data where the country of interest is Switzerland.

8. Data and Methodology

8.1. Data collection and pre-processing

8.1.1 Countries electricity generation and cross-border electrical physical flows

Country-specific hourly data (in MWh/h) on electricity generation per production type and countries cross-border electrical physical flows data (in MWh/h) have been obtained from the ENTSO-E Transparency platform (Hirth et al., 2018). This platform, operated by the European Network of Transmission System Operators for Electricity (ENTSO-E), is a freely accessible online data platform. Even though this platform is an incredible data source of the European power system, some shortcomings regarding data quality have been pointed out (Hirth et al., 2018a) .

This is the reason we conducted different stages of data pre-processing (see figure 2). First, given the fact that countries operate in different power market, data are reported at different time unit. Germany and Austria data are reported every 15 minutes and the other countries every hour. As a result, we had to aggregate quarter-hourly data to produce an hourly dataset. After having analysed descriptively the dataset, we compared the yearly total of the hourly data with national publicly available statistics. For France, the match was nearly perfect (around 98%). For Austria, Germany and Italy, the data from the platform corresponded for more than 80% to national statistics. In contrast, for Switzerland, we were able to identify important differences, particularly concerning the hydropower base generation type. Even though these differences were fading out through time (from 55% in 2016 to 72% in 2019), we decided to scale up hourly data to match national statistics. Differences can partly be explained by the fact that only power plant with a generation capacity above 100 MW must be reported on the platform. Finally, outlier detection and missing value analysis were conducted to obtain final datasets.

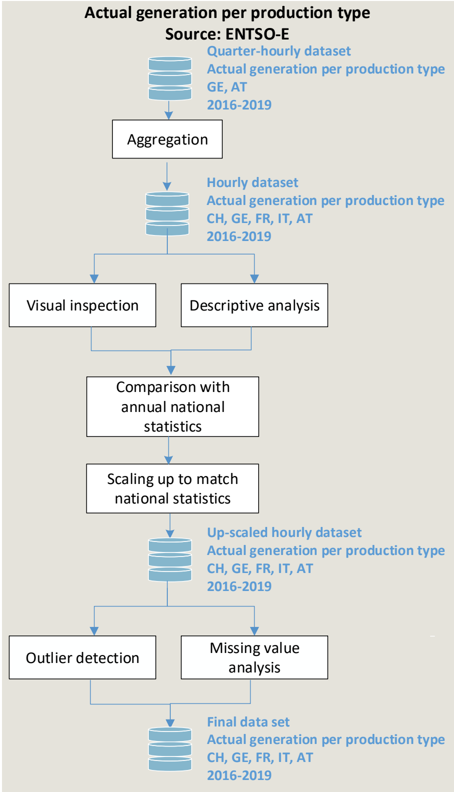

Figure 2 : Data processing process for country's electricity generation

8.1.2 GHG content of each generator type

Carbon intensity of each generator type (in kg of CO2-eq per kWh of the power produced) has been obtained from the 3.7.1 version of the Ecoinvent database on Life Cycle Inventory data (Wernet et al., 2016). After retrieving those data, we had to match them with the production type categories used in the ENTSO-E Transparency platform. The exact content of the categories used in the ENTSO-E platform is not clearly defined. Indeed, as reported by Hirth et al. (2018), this is due to the lack of accessible documentation and because there is room to interpretation of the few existing documentation. Even after mail exchanges with the platform, we had to make several assumptions regarding those categories.

8.1.3 Gas Consumption data

Hourly natural gas delivery data (in Nm3) and outside temperature (in °C) data have been made available thanks to the collaboration with the company which supplies and transports high-pressure natural gas to Western Switzerland. After discussion with experts and the company who provide us the data, we took the hypothesis that the hourly pattern of the Western part of Switzerland was similar to the whole country. This is the reason we decided to scale up Western Switzerland data to match national statistics. Then, we conducted the same stages of data processing than for the data from the ENTSO-E transparency platform.

8.2 Methodology

As stated earlier (see figure 1), we developed a four-step methodology to answer the research questions. Each step is presented in detail in the following sections.

8.2.1 Assessing hourly GHG emission from electricity consumption and the impact of imports

The hourly carbon footprint (i.e. emission factor) of the electricity consumed in Switzerland in hour t ($EFCons_{CH,t}$) has been assessed according to the following equation:

$$EFCons_{CH,t} = \frac{MCons_{CH,t}}{ECons_{CH,t}} \tag{1}$$

The hourly electricity consumption in Switzerland ($ECons_{CH,t}$) in hour t and the related hourly GHG emissions ($MCons_{CH,t}$) in hour t have been assessed in accordance with the consumption principle (Vuarnoz & Jusselme, 2018; Bai et al., 2014; West et al., 2016). It means that the Swiss electricity generation mix has been considered as well as the country's electricity cross-border physical flows (imports and exports) with its neighbours (Germany, France, Austria and Italy) as illustrated in equations (2) and (3). Swiss hourly electricity generation ($EGen_{CH,t}$), importation ($EImp_{CH,t}$) and exportation ($EExp_{CH,t}$) data were taken from the ENTSO-E platform.

$$ECons_{CH,t} = EGen_{CH,t} + EImp_{CH,t} - EExp_{CH,t} \tag{2}$$

$$MCons_{CH,t} = MGen_{CH,t} + MImp_{CH,t} - MExp_{CH,t} \tag{3}$$

To assess the GHG emissions related to the electricity generation in Switzerland ($MGen_{CH,t}$) in hour t, the amount of hourly electricity generation by production type i ($EGen_{CH,it}$) in hour t has been multiplied by the emission factor of each production type i ($EF_{CH,i}$) as illustrated by equation (4). As stated earlier, the EF of a production type i in a given country l was taken from the ecoivent database version 3.1.

$$MGen_{CH,t} = \sum_{i=1}^{I} \left(EGen_{CH,it} * \ EF_{CH,i} \right) \tag{4}$$

Equation (5) expressed how the GHG emissions related to electricity imports from neighbouring countries to Switzerland in hour t ($MImp_{CH,t}$) has been assessed: by adding the amount of hourly physical electricity imports from each neighbouring countries l ($EImp_{lt}$) multiplied by an hourly emission factor of the electricity generated in each country ($EFGen_{lt}$).

$$MImp_{CH,t} = \sum_{l=1}^{L} (EImp_{lt} * EFGen_{lt}) \tag{5}$$

The latter has been assessed by the following equation:

$$EFGen_{lt} = \sum_{i=1}^{I} \left(\frac{EGen_{lit}}{\sum_{i=1}^{I}(EGen_{lit})} * EF_{li} \right) \tag{6}$$

As expressed in equation (5) and (6), the hourly GHG content of the electricity imports to Switzerland from neighbouring countries ($MImp_{CH,t}$) has been considered as being the same as the generation mix of the country of origin of the imports.

Finally, the hourly GHG content of the electricity exported from Switzerland to neighbouring countries ($MExp_{CH,t}$) has been assessed by the two following equations:

$$MExp_{CH,t} = \sum_{l=1}^{L} \left(Eexp_{lt} * \ EFExp_{CH,t} \right) \tag{7}$$

$$EFExp_{CH,t} = \frac{MGen_{CH,t} + MImp_{CH,t}}{EGen_{CH,t} + EImp_{CH,t}} \tag{8}$$

As illustrated in equation (7) and (8), the hourly GHG content of the electricity exported from Switzerland to neighbouring countries ($MExp_{CH,t}$) has been considered as being the same as the GHG content of the electricity generated in Switzerland and of the electricity imported from neighbouring countries.

8.2.2 Modelling hourly gas consumption for heating purposes

The second step of the methodology consisted of, based on raw hourly natural gas delivery data, deriving natural gas consumed for heating purpose only. We adopted a top-down econometric approach. Indeed, we used the two following equations to derive $\hat{\mathrm{Y}}\mathrm{Heat}_\mathrm{t}$, the estimated hourly natural gas consumption for heating purposes.

$$\hat{\mathrm{Y}}\mathrm{Heat}_\mathrm{t} = \beta_1 \, \mathrm{HDH}_\mathrm{t} \tag{9}$$

$$\mathrm{Y}_\mathrm{t} = \beta_0 + \beta_1 \, \mathrm{HDH}_\mathrm{t} + \ \beta_2 \, \mathrm{Hour}_t \ + \beta_3 \, \mathrm{Weekday}_t \ + \beta_5 \, \mathrm{Bankholiday}_t + \ \varepsilon_\mathrm{t} \tag{10}$$

Where Y_t is natural gas consumption at the time t, $\beta_1,\ldots,\beta_5$ are regression coefficients which we want to estimate, HDH_t is the heating degree-hour value for hour t, Hour_t is a categorical variable accounting for the hour of the day i.e. $\mathrm{Hour}_t \in \{1, \ldots, 23\}$, $\mathrm{Weekday}_t$ is a categorical variable accounting for the day of the week i.e. $\mathrm{Weekday}_t \in \{2, \ldots, 7\}$, $\mathrm{Bankholiday}_t$ is a dummy variable accounting for the Swiss holidays i.e. $\mathrm{Bankholiday}_t \in \{0,1\}$ and ε_t is a random error . Assumptions for the errors are that they are independently identically distributed (i.i.d.) with distribution $\varepsilon \sim N(0, \sigma^2)$. Estimation of regression coefficients is done by ordinary least square (OLS).

Heating degree hour (HDH_t) has been assessed by adopting the definition of the heating degree day of the Swiss SIA standard 381/3 (SIA, 1982) to an hourly usage as represented in the following equation:

$$\boldsymbol{HDH}(\theta_\mathrm{in}, \theta_\mathrm{th}) = \mathrm{m_t} \sum_{t=1}^{T} \left(\theta_\mathrm{in} - \theta_\mathrm{ex,t} \right) \tag{11}$$
$$\mathrm{m_t} = 1 \, hour \ \ if \ \theta_\mathrm{ex,t} \ \leq \ \theta_\mathrm{th}$$
$$\mathrm{m_t} = 0 \, hour \ \ if \ \theta_\mathrm{ex,t} \ > \ \theta_\mathrm{th}$$

Where θ_{in} denotes the internal temperature, $\theta_\mathrm{e,t}$ the hourly mean external temperature, θ_th the threshold temperature for heating, t stands for the hour number in the year i.e. $t \in \{1,\ldots,8760\}$. According to the Swiss SIA standard 381/3, $\theta_\mathrm{in} = 20°C$ and $\theta_\mathrm{th} = 12°C$ were assumed in this study.

To define equation (10) we first identified in the literature potential model and variables. Then, we developed an equation which we tested and transformed (inclusion/exclusion of variables) until we reached the validity of the model and ruled out any hypotheses of endogeneity, serial-correlation, heteroskedasticity and non-normality of the error term. The process is illustrated in the following figure:

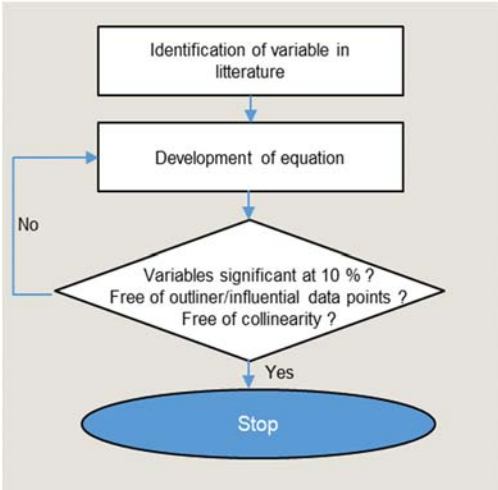

Figure 3 : Flow chart diagram illustrating the methodology to develop the equation (inspired by (Aydinalp-Koksal & Ugursal, 2008))

In order to ensure the robustness of the model, we compared it with two others: an engineering approach which is the heating signature and a two-point regression model. Those two models are illustrated in Appendix 2.

<u>8.2.3 Simulating hourly electricity production with natural gas CHP plants</u>

The approach adopted here was that the hourly heat needs identified earlier had to be covered by the thermal output of the CHP plant. We considered the CHP plant as a linear model which is an energy converter with fixed electrical and thermal efficiencies. We did not consider load modulation. As stated in the literature review, we adopted a top-down approach, where global heating demand is used to derive potential CHP power and heating generation by applying average power to heat ratio corresponding the current technology (IEA, 2008).

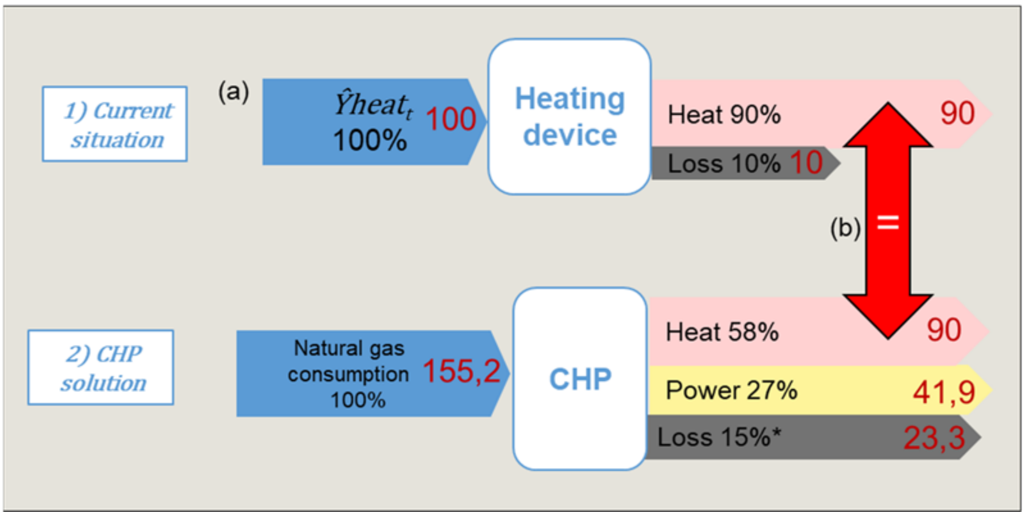

Figure 4 : CHP plant model scheme and its parameters

As Bianca Howard et al. (2014), only internal combustion engines and microturbines were considered for the current analysis because of their great range of sizes and because they can easily be fuelled with natural gas. We used CHP plant parametrization indicated in the EcoIvent 3.7.1 database for the electricity generated with CHP in Switzerland. In order to ensure the robustness of the model, we conducted multiple simulation with variation of those parameters.

8.2.4 Assessing hourly GHG emissions from electricity consumption with CHP solution

For the last part, we used a conditional attribution of the electricity produced with the simulated CHP solution. Indeed, the electricity produced replaced at first imports (without any generation type selected or country but the global mix). If the CHP electricity production was higher than the imports, the domestic generation was replaced.

The following equations illustrated how the new emission factor ($EFCons_{CH,t}^{New}$) is assessed when the electricity produced by the simulated CHP solution ($ECHP_{CH,t}$) is strictly smaller than the imports ($EImp_{CH,t}$) (see equation (12)). The other cases are presented in appendix 3.

$$ECHP_{CH,t} \leq EImp_{CH,t} \tag{12}$$

As in the first step of the methodology, the new hourly electricity consumption in Switzerland $ECons_{CH,t}^{New}$ in hour t and the related hourly GHG emissions $MCons_{CH,t}^{New}$ in hour t have been assessed in accordance with the consumption principle as illustrated in equations (14) and (15).

$$EFCons_{CH,t}^{New} = \frac{MCons_{CH,t}^{New}}{ECons_{CH,t}^{New}} \tag{13}$$

$$ECons_{CH,t}^{New} = ECHP_{CH,t} + EGen_{CH,t} + EImp_{CH,t}^{New} - EExp_{CH,t} \tag{14}$$

$$MCons_{CH,t}^{New} = MCHP_{CH,t} + MGen_{CH,t} + MImp_{CH,t}^{New} - MExp_{CH,t}^{New} \tag{15}$$

The difference is that, we have in addition electricity produced by the simulated CHP solution ($ECHP_{CH,t}$and the GHG related emissions ($MCHP_{CH,t}$). As stated earlier, the electricity production from the CHP solution is used to diminish the importation as illustrated in equation (16).

$$EImp_{CH,t}^{New} = EImp_{CH,t} - ECHP_{CH,t} \tag{16}$$

The GHG emissions related to the electricity produced by the simulated CHP solution ($MCHP_{CH,t}$) has been assessed by multiplying the hourly electricity production by an emission factor (EF_{CHP}) taken from the Ecoivent database version 3.1.

$$MCHP_{CH,t} = ECHP_{CH,t} * EF_{CHP} \tag{17}$$

As stated earlier, the approach adopted was that the electricity produced replaced imports without any generation type selected or country, but the global mix. This is illustrated in the two following equations:

$$MImp_{CH,t}^{New} = EImp_{CH,t}^{New} * EFImp_{CH,t} \tag{18}$$

$$EFImp_{CH,t} = \frac{MImp_{CH,t}}{EImp_{CH,t}} \tag{19}$$

As illustrated in question (20) et (21), the GHG content of the export has been assessed similarly as in the first part, with the exception of the fact that we have taken into consideration the electricity produced and the GHG emissions related of CHP solution.

$$MExp_{CH,t}^{New} = Eexp_{CH,t} * \ EFExp_{CH,t} \quad (20)$$

$$EFExp_{CH,t} = \frac{New_{MImp}{}_{CH,t} + MGen_{CH} + MCHP_{CH}}{New_{EImp}{}_{CH,t} + EGen_{CH} + \ ECHP_{CH}} \quad (21)$$

9. Results

9.1 GHG content of the electricity consumed in Switzerland and impact of imports

This section presents the results answering our first research question. The results for the year 2016 to 2019 show that, imports impact strongly and negatively the GHG footprint of the electricity consumed in Switzerland. More precisely, it is heavily impacted by imports from Germany and its coal-based power production. As illustrated in figure 5, for the year 2016, imports from Germany account for 19% of the electricity consumed in Switzerland while they account for 74% of its GHG content. On the contrary, domestic electricity generation accounts for 67% of the electricity consumed while it accounts only for 19% of its GHG content. Indeed, in Switzerland, electricity is mainly generated by hydropower and nuclear power (respectively 64% and 35% in 2016), two low-carbon technologies.

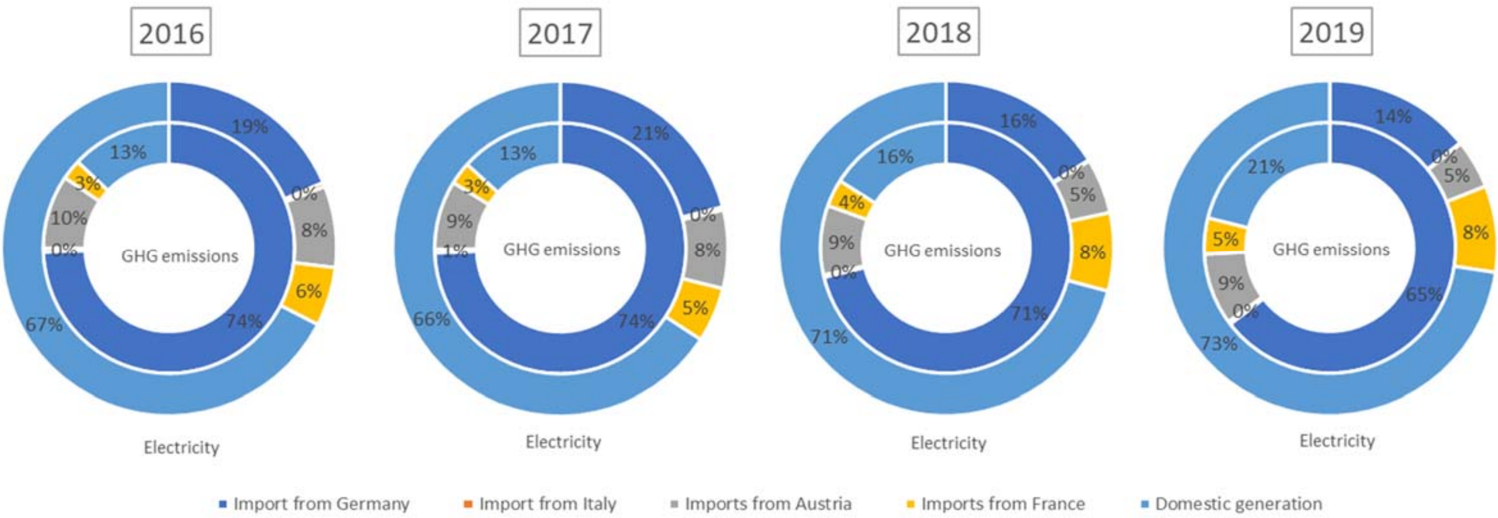

Figure 5: Source of the electricity consumed in Switzerland and its related GHG content

The impact of the imports from Germany on the carbon footprint of the electricity consumed in Switzerland is fading through time. Indeed, it accounts for 74% in 2017, 71% in 2018 and finally drops to reach 65% in 2019. This downward trend can be explained by the change in the generation mix in Germany. Indeed, as presented in figure 6, we can see that share of new renewable energies increased from 29% in 2016 to 42% in 2019 and the share of coal and lignite decrease from 40% in 2016 to 29% in 2019. Imports from Italy, Austria and France have a relatively low importance on the carbon footprint of the electricity consumed (15 % for the three of them in 2016) even if they account for 14% of the electricity consumed in 2016.

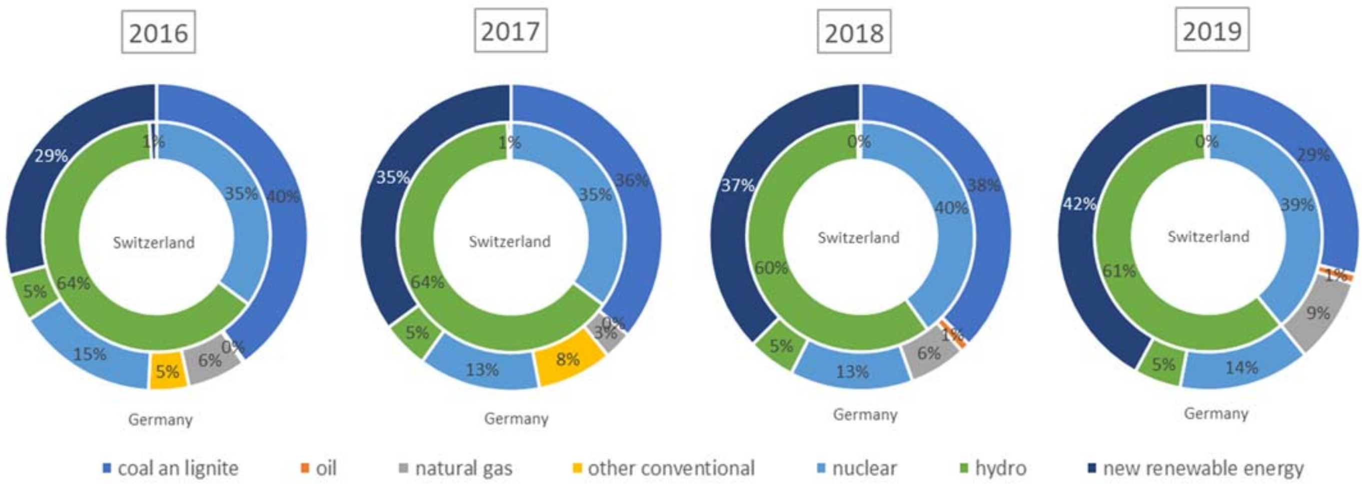

Figure 6: Switzerland and Germany Generation Mix

Figure 7 displays the huge range between which the hourly EF varies over time. Indeed, between 2016 and 2019 the maximum value in winter was up to 579.640 g CO2eq/kWh and the minimum value, in summer, was less than 5.126 g CO2eq/kWh. It means that the carbon footprint of electricity consumed in winter can be 113 times higher than in summer. The seasonal impact on the carbon footprint of the electricity consumed is very pronounced in Switzerland. It is interesting to note that the pattern is very similar to the seasonal pattern of the natural gas consumption (see figure 8) which confirms the validity of the idea of the deployment of CHP fuelled with natural gas.

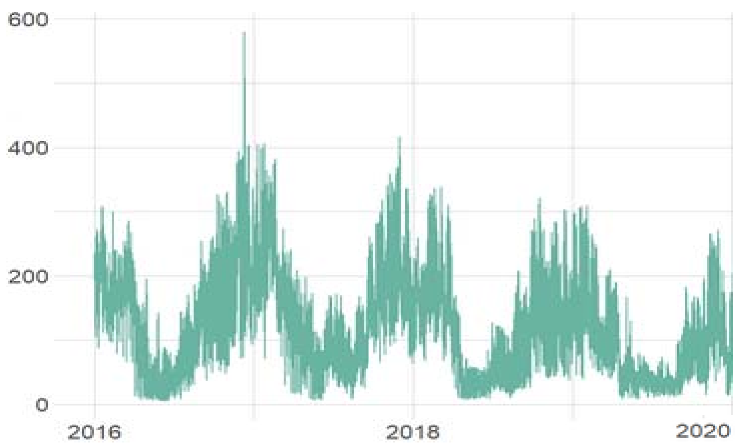

Figure 7: Hourly emission factor of the electricity consumed in Switzerland (in g CO2eq/kWh)

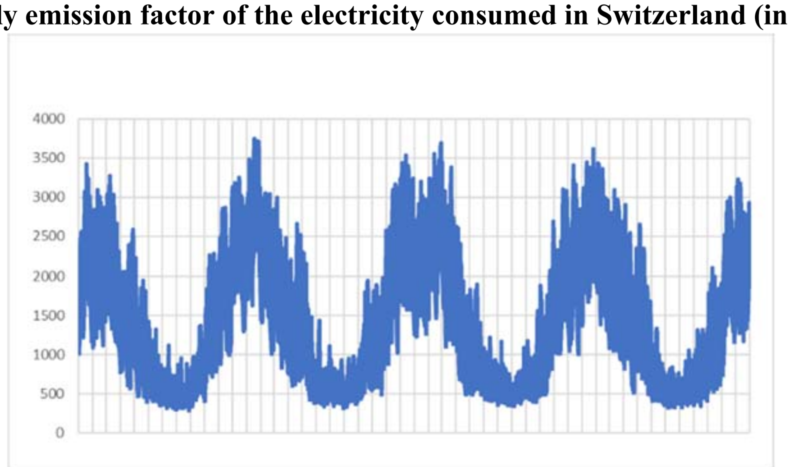

Figure 8: Hourly natural gas consumption in Western Switzerland (MWh/h)

9.2 GHG content of the electricity consumed in Switzerland with the CHP simulation

The results of the simulation part show that the development of decentralized power generation through natural gas-fired CHP plants can lower the GHG footprint of the electricity consumed in Switzerland (see table 2). Indeed, for the year 2016 the EF is 6.83% lower for the CHP simulation (133.76 g CO2eq/kWh) than the actual situation (143.58 g CO2eq/kWh). As it was expected, the benefit of the simulation is also fading through time because of the growing part of new renewable electricity generation in Germany. Indeed, the benefit of the deployment of CHP fuelled with natural gas decreases gradually. Indeed, it even become a drawback in 2019, as the EF of the CHP simulation is 1.07% higher than the actual EF.

Year	$EFCons_{CH}$ (g CO2eq/kWh)	$EFCons_{CH}^{New}$ (g CO2eq/kWh)	Variation (%)
2016	143,58	133,76	-6.83
2017	150,83	140,84	-6.62
2018	118,18	114,36	-3.23
2019	94,36	95,37	1.07

Table 2: Actual emission factor of the electricity consumed and results of the CHP simulation

The deployment of the CHP fuelled with natural gas would allow to reduce the impact of the imports from Germany on the carbon footprint of the electricity consumed in Switzerland (see figure 9). Indeed, from 74% (figure 5), it would decrease to reach 52% for the year 2016. The electricity imports from Germany would decrease from 19% (figure 5) to 12% in 2016.

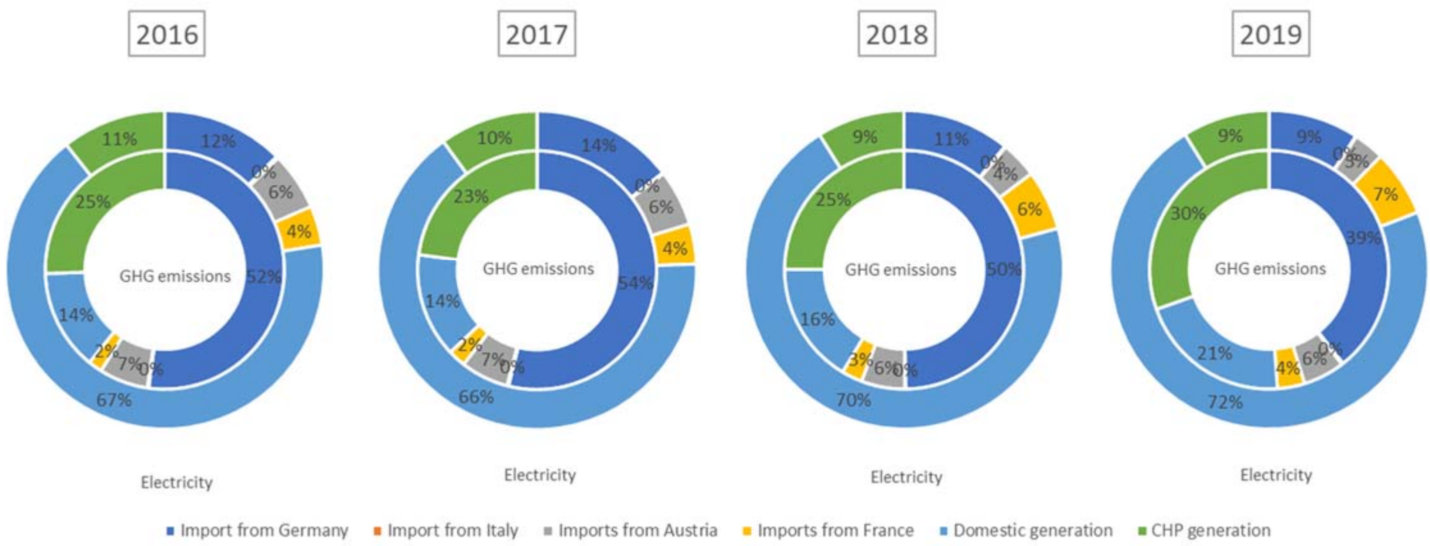

Figure 9: Source of the electricity consumed in Switzerland and its related GHG content after the CHP simulation

The figure 10 shows how the deployment of CHP would actually help reduce the peaks of the carbon intensity of the electricity consumed in Switzerland in winter.

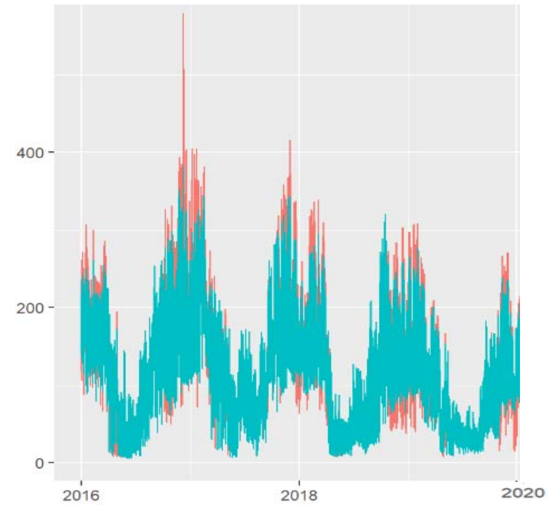

Figure 10: Actual hourly emission factor of the electricity consumed in Switzerland (in red) and hourly emission factor after the simulation (in blue) - (in g CO2eq/kWh)

10. Conclusion

This paper applied an hourly approach to evaluate, for the years 2016 to 2019, the hourly carbon footprint of the electricity consumed in Switzerland. We measured, the impact of the electricity imports from neighbouring countries and simulated how the deployment of CHP fuelled with natural gas would impact this carbon footprint. The geographical scope of this analysis was Switzerland with its direct neighbours (Germany, France, Italy and Austria). It demonstrates that, the Swiss growing dependency on electricity imports during winter has, indeed, a non-negligible impact on the environment. More precisely, it is heavily impacted by imports from Germany and its coal-based power production. Indeed, for the year 2016, imports from Germany accounted for 19% of the electricity consumed in Switzerland while they accounted for 74% of its GHG content. This impact on the carbon footprint of the electricity consumed has decreased through time (from 74% in 2016 to 65% in 2019) due to Germany increasing new renewable energies generation. However, this downward trend should be taken with caution as Germany intend to reach its total coal phase out only by 2038 (BMWi, 2019). In addition, Switzerland has only recently started its nuclear phasing-out process. Indeed, Mühleberg nuclear power plant was the first nuclear power plant to be permanently shut down the 20th of December 2019. Eventually, Switzerland will have to be able to replace 40% of its electricity production. It is probable that, until the development of renewable energies and the reduction in consumption fully compensate the missing electricity production, imports in winter will increase.

The natural gas-fired CHP solution examined in this study could represent a less-carbon intensive alternative. Indeed, it would allow to reduce the carbon footprint of the electricity consumed in Switzerland by up to 6.83%. In addition, being based on existing technology and infrastructure (gas grid), this solution could be deployed in a very short span. This aspect is of particular importance because CO2 emissions shall start to diminish before 2030 if we want to limit global warming to 1.5C° (IPCC, 2018). The necessity to act before 2030 is an aspect that has been neglected in the Energy Strategy 2050 whose objectives are more farsighted. Policy-makers should examine the fact that natural gas could play a temporary role in the energy transition. Another aspect highlighted in this study is the importance of taking into consideration spatial and temporal sensitivity of the carbon content of the electricity consumed. Indeed, as seen in the results, imports from neighbouring countries strongly impact the carbon footprint of the electricity consumed. Moreover, the range between which the carbon footprint varies through time is huge: it can be 113 times higher in winter than in summer. It is essential for policy-makers to take into consideration those two aspects when designing new energy policies. Further research in this area could be carried out in order to investigate the feasibility and the costs of deploying such a solution. In addition, the effect of the nuclear phase-out on the hourly carbon footprint should be explored.

11. Acknowledgement

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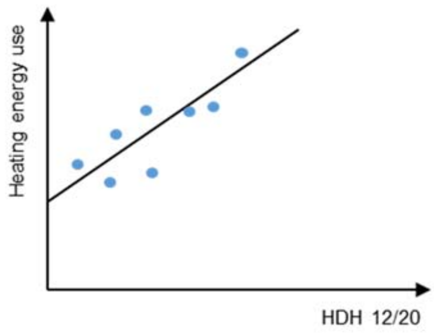
13. Appendix 1- ENTSO-E generation categories

Biomass,
Fossil Brown coal/Lignite
Fossil coal-derived gas
Fossil gas
Fossil Hard coal
Fossil oil
Fossil oil shale
Fossil peat
Geothermal
Hydro pumped storage
Hydro Run-of-River and poundage
Hydro water reservoir
Marine
Nuclear
Other
Other renewable
Solar
Waste
Wind offshore
Wind onshore

14. Appendix 2 – Additional natural gas consumption for heating purposes models

Heating Signature

$$Y_t = \beta_0 + \beta_1 \, HDH_t + \varepsilon_t$$
$$\hat{Y}Heat_t = Y_t - \beta_0$$

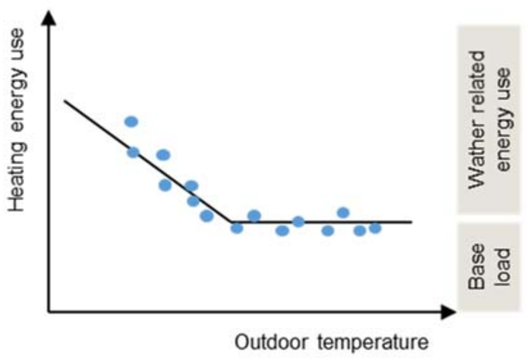


Symbols

Y_t	*natural gas consumption*
$\beta_0, \ldots, \beta_1$	*regression coefficients*
HDH_t	*heating degree hour*
ε_t	*error term*
$\hat{Y}heat_t$	*estimated natural gas consumption for heating purposes*

Piecewise linear relationships in segmented regression models

This method allows us to identify a the "real" breakpoint, the outside temperature after which natural gas consumption is not related to.



$$Y_t = \beta_0 + \beta_1 \, Temp_t + \beta_2 \, (Temp_t - \psi)_+ + \varepsilon_t$$
$$\hat{Y}Heat_t = \beta_0 + \beta_1 * \psi$$
$$\hat{Y}Heat_t$$

Symbols

Y_t	*natural gas consumption*
$\beta_0, \ldots, \beta_2$	*regression coefficients*
$Temp_t$	*outside temperature °C*
ψ	*breakpoint*
ε_t	*error term*
$\hat{Y}heat_t$	*estimated natural gas consumption for heating purposes*

We performed a breakpoint analysis with the R Package "segmented" (Muggeo, 2003, 2008). It calculates multiple linear regressions for data with dependent variables that can be expressed by two or more straight lines with different slopes linked at a breakpoint and calculates these breakpoints.

Appendix 3 – Conditional attribution of the simulated CHP electricity produced