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Dynamic LCA of a single-family house, equipped with a micro-cogeneration unit, using a variable share of biomethane

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Abstract. The current study presents the $CO_{2\text{-eq}}$ emissions of the operational energy use of a single-family house, equipped with a micro-cogeneration unit. A back-up boiler and electricity from the grid cover the remaining energy demand, not covered by the micro-CHP. Two different technologies are evaluated, i.e. ICE and fuel cell systems, operating with a variable share of biomethane, while two different substrates were considered for the biomethane generation. A dynamic LCA was applied for the electricity mix, coming from the grid, using different time steps. The results show that producing biomethane from biowaste compared to conventional natural gas is beneficial, in terms of $CO_{2\text{-eq}}$ emissions, independently of the micro-CHP technology, while the total $CO_{2\text{-eq}}$ emissions of the fuel cell technology are higher than those of the ICE, independently of the substrate and the biomethane share.

1. Introduction

The revised Swiss Federal Energy Act in 2017, concerning the building sector, aims at promoting the energy efficiency of buildings and appliances, the decentralized renewable energy production in parallel with the nuclear energy phase-out [1]. An efficient energy technology, also promoted at the EU level [2], which is consistent with the aforementioned goals are the residential micro-cogeneration units that provide a combined production of electricity and heat. The benefits linked with this technology are: (i) the avoided environmental impacts linked to the separate heat and power production [3], (ii) the primary energy savings, due to the high exergy efficiency [4], [5], (iii) the stability of the power of the grid [6], [7] since the micro-CHP units operate in a flexible way, contributing, thus, to the reduction of the winter peaks [8] and the electricity imports, (iv) the introduction of power-driven systems in urban zones [9], (v) the optimal management of the existing natural gas grids and the future network's convergence [10], [11].

The residential micro-CHPs, typically, have a maximum electrical capacity of 50kWe, [2] and they can be separated in two categories, depending on the power production modes, i.e. using thermodynamic cycles or other mechanisms [5], [12]. The most used technologies, belonging to the first group are the internal combustion engines (ICE), the microturbines and the Stirling engines, [5], while the most used type of the second category include the fuel cells micro-CHP. These micro-CHP systems mostly function with natural gas (around 45% of the energy carriers used in micro-CHPs in EU [13]), while the renewable sources, such as biomass, biogas, solar or geothermal, cover around 30% in EU, [13].

Martinez et al. [5] argues that combining the micro-CHP technology with renewables is an '*efficient way to introduce renewables to residential buildings*'. Different studies discuss the environmental gains of the micro-CHP units, combined with renewables, as for example [14], [15]. In [16] the authors concluded that using a micro-turbine with biogas can lead to a 20% reduction of $CO_{2\text{-eq}}$ emissions compared to a gas boiler. Biomethane can be a favourable solution, combined with the cogeneration systems, while different studies discuss the direct and indirect CO_2 emissions of the biogas [17],[18]. However, there are multiple discussions in the scientific community, concerning the allocation method for its production, as summarised in [19].

Thus, the aim of this study is to continue in this direction and position the micro-CHP systems in terms of their environmental performance, by comparing the $CO_{2\text{-eq}}$ emissions of an ICE and a fuel cell micro-CHP, with a traditional gas boiler, using different shares of biomethane and by considering additionally the impacts of the electricity consumption mix, using a dynamic LCA (i.e. hourly, daily, monthly and yearly time steps) for the electricity imports and the domestic production. The $CO_{2\text{-eq}}$ emissions of the biomethane were calculated for two substrates, used in Switzerland for its production, i.e. biomethane produced from manure and biowaste.

2. Methodology

2.1. System configuration of the case studies

The case study concerned an SFH, located in the canton of Neuchâtel (NE). The measured annual heat and electricity demand profiles were provided by Viteos [20], for 2018. The system configuration of the case study is presented in Figure 1. The scenarios examined include a) a traditional gas boiler covering 100% of the heating and domestic hot water (DHW) needs, while 100% of the electricity needs were covered by the grid (reference scenario), b) an ICE micro-CHP, which covered on average 69% and 70% of the heating and electricity demand, respectively and c) a fuel cell unit that covered 13% and 99.5% of the heating and electricity demand, respectively. The design of the ICE micro-CHP was based on the following two criteria, 1) it should cover at least 60% of the energy for heating and DHW, according to the standard solution of the CHP technology, as set by the MuKEn, [21] and 2) it should operate for approximately 3500 hours [22], so that the overproduction during the 3500 hours is equal to the heat demand beyond the 3500 hours limit. Concerning the fuel cell system, it was designed for covering 3500 hours of the annual electricity demand. The remaining electricity and heating demand are covered by the grid and a back-up gas boiler, respectively.

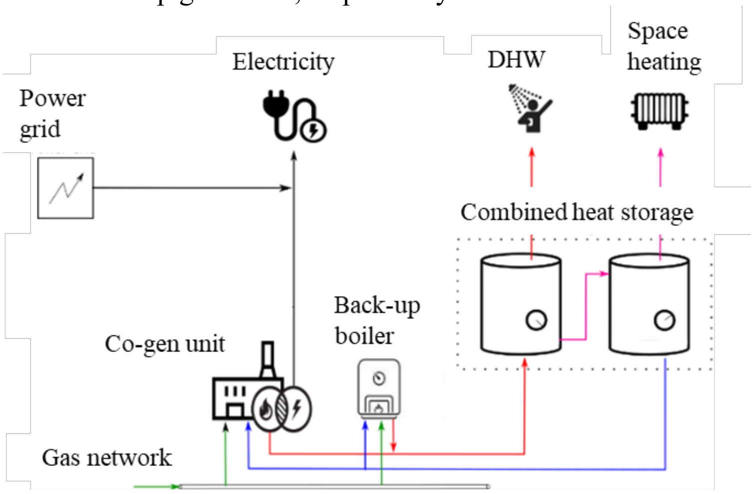

Figure 1: System configuration of the case study, for the micro-CHP scenario

2.2. Life cycle analysis of the operational energy of the case studies

The perimeter for the LCA calculation, concerning the operational energy of the case study is presented in Figure 2. Hence, it is necessary to determine the CO_2 impacts of a) the biogas production, taking two different substrates (manure and biowaste), b) the biogas purification, for the biomethane production, so that it can be injected to the gas network, c) the network of natural gas, d) the losses of the conversion from high to low pressure gas, e) the electricity mix, f) the heat production of the gas back-up boiler, g) the two micro-CHP systems.

2.2.1. LCA of gas, biogas and biomethane

The ecoinvent database v3.4 [23] was used to define the $CO_{2\text{-eq}}$ impacts of the case study. In Switzerland, there are five ways for the biogas production, i.e. from sewage sludge, manure, biowaste, industrial waste water and landfills, while the biggest part of the production (more than 90%) comes from the three first substrates, [24]. The impacts of the biogas are defined differently for these substrates, according to the ecoinvent v3.4. The biogas from sewage sludge and biowaste are considered as waste and have thus no upstream impacts, while the biogas produced from manure has a 1.92 $kgCO_{2eq}/m^3$, since manure is considered as a recyclable co-product [25]. The assumption, concerning the biogas allocations strongly influences the results, as shown in [26]. Thus, it was decided to take both of these assumptions into consideration, in order to evaluate the allocation method of the biogas for two different substrates, i.e., manure and biowaste, using a micro-CHP technology.

The chosen biogas purification procedure was the Pressure Swing Adsorption (PSA), modelled in the ecoinvent database, in order that the biogas reaches a 96% methane in volume, for its injection to the gas network. Concerning the gas network, it was assumed that it operates with different shares of biomethane, namely 0% (i.e., 100% natural gas), 10%, 20% and 100%. The losses from the high to low pressure were also taken into account, i.e. leakage rate of 0.72%, [23].

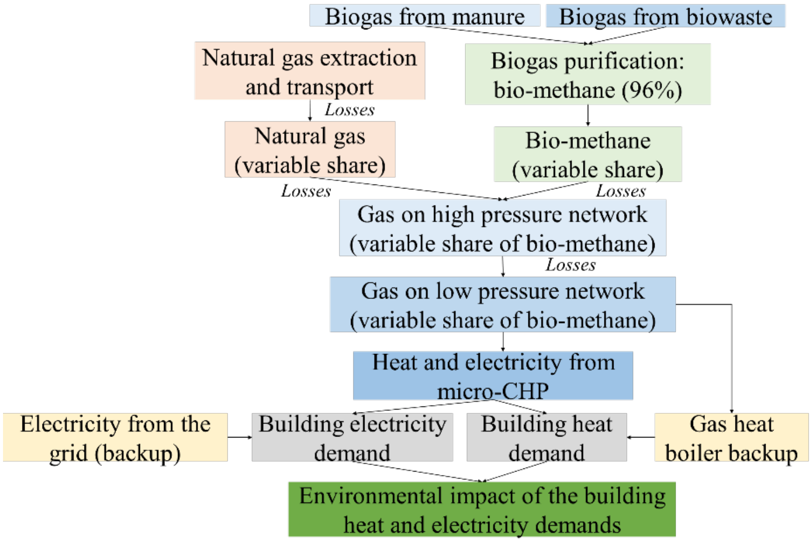

Figure 2: LCA perimeter of the case studies

2.2.2. LCA of the electricity mix

The Swiss electricity mix for four time steps (annual, monthly, daily, hourly) was built by gathering data for the national production, the imports-exports among the neighboring countries, the grid distributions and conversion losses. The transparency platform ENTSO-E, which provides hourly data of the electricity production for the European countries, was combined with the gross exchanges provided by Swissgrid (separating imports and exports) and the grid losses provided by the Swiss Federal Office of Energy (SFOE) so that the Swiss electricity consumption mix at the building level could be defined. A temporal aggregation was performed, in order to calculate the different time steps, while a matrix-based calculation procedure was applied, in order to calculate the impacts of the different electricity production means (i.e. nuclear, fossil fuels, hydro, etc.) and the different imports from the neighboring countries. In the end, the $CO_{2\text{-eq}}$ emissions of the Swiss consumption mix were calculated for 2017 and 2018, Figure 3.

2.2.3. LCA of the ICE, fuel-cell micro-CHP and back-up boiler

The impacts of these two technologies are based on ecoinvent v3.4. The factors of the exergy allocation of the micro-CHP units have been adapted, according to the technical characteristics of the micro-CHP, i.e. their corresponding thermal and electricity efficiencies. In addition, the $CO_{2\text{-eq}}$ emissions of the micro-CHP were calculated for the different shares of biomethane, i.e. 0%, 10%, 20% and 100%.

Concerning the back-up gas boiler, it was considered that it operates with the same variable share of biomethane. Hence, its $CO_{2\text{-eq}}$ were calculated, considering the aforementioned shares. More details of the current methodology can be found in [27].

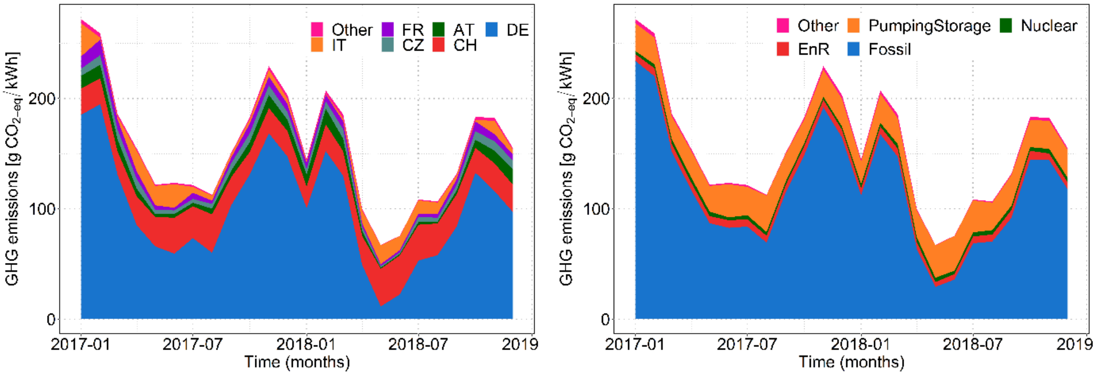

Figure 3: CO_2-eq emissions of the Swiss electricity mix per country and energy source, monthly time step ('Other' includes other countries and other energy source).

3. Results and Discussion

The $CO_{2\text{-eq}}$ emissions of the reference scenario (gas boiler for heating and DHW and electricity from the grid) were 1'460 $gCO_{2\text{-eq}}$/kWh and 10'470 $gCO_{2\text{-eq}}$/kWh, for the electricity and heating demand, respectively. The LCA of the operational energy for the two micro-CHP technologies and the two assumptions of the biogas production are presented in Figure 4. These results correspond to the annual CO_2 emissions of the electricity, heating and total energy demand of the case study, under an hourly time step. Comparing the biogas allocations, it can be noted that the impacts strongly depend on the assumptions, concerning the allocations. As expected the most favourable biogas production, for both micro-CHP technologies and the different energy demands is the biogas produced from biowaste, as the allocation method in ecoinvent v3.4 considers it as a waste. For both technologies, the total $CO_{2\text{-eq}}$ emissions for the biogas coming from biowaste are approximately 70% lower than those when using biogas from manure, that is considered as a co-product in ecoinvent v3.4.

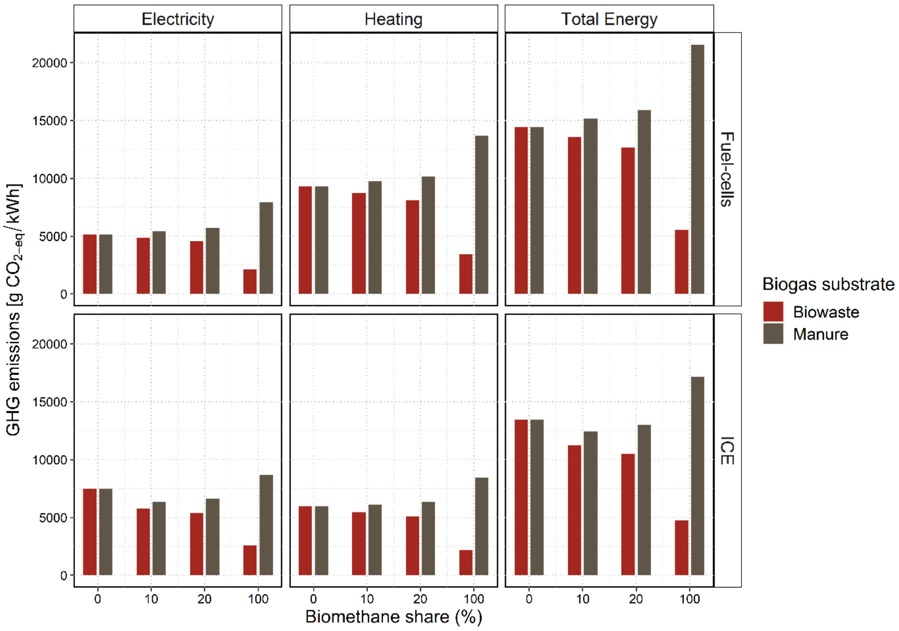

Figure 4: CO2 emissions of the Swiss electricity mix, monthly time step

Concerning the fuel cell micro-CHP, the $CO_{2\text{-eq}}$ emissions of the total energy demand, when using biogas from manure with 100% biomethane are approximately 50% higher than those from 100% natural gas. On the contrary, looking at the ICE, this difference is less pronounced for the manure substrate, i.e. 27% higher $CO_{2\text{-eq}}$ emissions than those coming from 100% natural gas. For the biogas coming from biowaste, the $CO_{2\text{-eq}}$ emissions between the biogas with 100% biomethane are approximately 65% lower than the 100% natural gas, independently of the micro-CHP technology. Comparing the two micro-CHP technologies, it can be concluded that the ICE presents a better performance than the fuel-cells micro-CHP, looking at the total $CO_{2\text{-eq}}$ emissions. The $CO_{2\text{-eq}}$ emissions of the ICE are 20% and 15% lower than those of the fuel-cells, for the biogas coming from manure and biowaste, respectively. Concerning the $CO_{2\text{-eq}}$ of the electricity, for the case of the fuel-cells, the $CO_{2\text{-eq}}$ emissions are 21% lower than for the ICE, for the biowaste substrate and 100% biomethane. For the heating demand the $CO_{2\text{-eq}}$ emissions of the ICE for 100% biomethane and both substrates are approximately 38% lower than those of the fuel cell system.

By comparing the impacts of the micro-cogeneration units for the electricity demand, to those of the grid, it can be seen that the annual carbon emissions of the grid are lower, independently of the biomethane share. This result can be explained, by the low annual carbon intensity of the Swiss electricity mix, [27]. However, it should be noted that during the winter months, when the electricity imports are higher (mainly from Germany and from its fossil fuel thermal plants, see Figure 3) the difference of the $CO_{2\text{-eq}}$ impacts between the grid and the micro-CHP generated power significantly diminishes, for the biowaste substrate and both micro-CHP technologies. Thus, depending on the period of the year, the micro-CHP technology can become competitive, compared to other technologies, a fact that can be revealed only when a dynamic LCA is used for the electricity of the mix. Concerning, heating the micro-CHPs (0% biomethane) perform better, in terms of $CO_{2\text{-eq}}$ emissions, with the ICE technology having approximately 50% less impacts than the gas boiler.

4. Conclusions

In this study, two micro-CHP technologies were examined, for an SFH case study, operating with different biomethane shares, i.e. 0, 10%, 20% and 100%. Additionally, two biogas substrates were examined, i.e. biowaste and manure. The following conclusions could be drawn: a) evaluating the $CO_{2\text{-eq}}$ emissions of the biomethane, using biowaste as substrate, is always beneficial, compared to the natural gas for both micro-CHP technologies, b) evaluating the CO_2 emissions of the biomethane, using a manure substrate, is more beneficial for the ICE system than for the fuel cell system, c) the overall performance of the ICE for the different biomethane shares and both substrates is better than that of the fuel cell. However, the latter presents a slightly better environmental performance for the electricity demand than the ICE, d) both micro-CHP technologies present a better environmental performance than the traditional gas boiler, in terms of CO_2 emissions for the heating demand.

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