



Material and energy flows of industrial biogas plants in Switzerland in the context of the circular economy

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ABSTRACT

Today, biomass is one of many countries most important renewable energy sources. Anaerobic digestion (AD) is a promising alternative to treating organic wastes from both energy and nutrient perspectives. Here, we develop a material flow model to assess the current utilization of wet biomass in industrial AD installations from mass, energy, and nutrient perspectives in Switzerland. We then identify how the current situation fits into the circular economy concept and develop quantitative scenarios for the future of industrial AD. The nutrient transfer coefficients through AD are $>74\%$. In the future, this could replace up to 14,000 t/a of chemical fertilizers, saving up to 40,000 t/a of CO₂-eq. Today, however, 70 t/a plastic ends up in the fields after AD, which should be improved if AD is to increase in the future. Thus, increased AD of organic wastes could reduce dependence on fossil fuels while promoting a circular economy.

1. Introduction

Decreasing our reliance on fossil fuels due to their impact on the climate is one of the greatest challenges of our time. In parallel, finite natural resources and increasing amounts of waste have led to the concept of the circular economy gaining importance during the last decade. Today, biomass is one of the most important renewable energy sources in many countries, while biowaste management is still often tackled in a sub-optimal way (BiPRO/CRI, 2015; Zeller et al., 2020). To achieve the objectives of the EU's long-term policy targets "Low Carbon Roadmap" (Commission, 2011), "Energy Roadmap 2050" (Commission, 2012a), and "Bioeconomy Strategy" (Commission, 2012b), enhanced use of biomass is required, both for energy and material use (Kalt et al., 2012). Besides the EU, many countries, including Switzerland, are developing and implementing renewable energy and bioeconomy strategies (SFOE, 2020; SFOE, 2018; SFOE, 2009). For a long time, organic waste management has been seen as an "end of pipe" strategy. In this regard, a bio-based circular economy considers organic wastes and residues as potential resources that can be used to supply fuels, nutrients, and chemicals needed by society. This is particularly relevant as, by 2050, the amount of waste produced worldwide is expected to increase from 2.0 billion tonnes to 3.4 billion tonnes (Kaza et al., 2018), while the world energy demand should increase by 50 % (EIA, 2021).

Anaerobic digestion (AD) technology is an attractive way of treating wet organic wastes from energy and nutrient perspectives. AD already plays an important role in the agro-industrial sector in Switzerland, displacing emission-intensive waste management strategies such as landfilling (Moretti et al., 2018) or incineration. However, it was estimated that about 1 million tonnes of municipal green waste, in addition to about 420,000 t nowadays, could be potentially recycled by AD technologies by 2050 (Burg et al., 2018a; Burg et al., 2019). In this context, and to facilitate targeted resource and energy policy measures, profound knowledge of the current biomass utilization is of crucial importance (Kalt et al., 2012). Generally, the biomass in AD is utilized to produce renewable energy, while less attention and research is given to its utilization in terms of nutrient recovery. Hence, proper quantification of resource flows, including materials, substances, and energy, through industrial AD systems is necessary to enhance the biological cycle in a circular economy (Sherwood, 2020).

An effective tool for such quantification and system understanding is the Material, Substance, and Energy Flow Analyses (MFA, SFA, and EFA), in which the state and changes of flows and stocks are systematically assessed in a system determined in space and time (Brunner and Rechberger, 2020). In MFA, the material sources, pathways, and final sinks are connected through the applications of mass balances for inputs and outputs of the system defined. Eventually, a complete set of

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information is depicted through MFA, making it an attractive tool for supporting resource management and policymaking decisions.

Previous work showed Switzerland's different mass and nutrient flows at the country level (Baier and Baum, 2006; Binder et al., 2009; Heldstab et al., 2013). However, what remains still unknown is the detailed specific flows going through AD that can be valorized within a circular economy, looking simultaneously at biomass, energy, and nutrients. Indeed, AD promotion relies not only on the valorization of the generated energy but also on the produced digestate and its quality. Many contaminants can hinder the use of the nutrients in the digestate, such as pathogens, plastics, or heavy metals. On the one hand, previous studies showed that neither heavy metals (Baier et al., 2016) nor pharmaceutical residues were an issue. On the other hand, plastic has not been quantified for biogas installations in Switzerland.

The overall aim of our study is to explore the role of AD technology in the advancement of a bio-based circular economy. This improved understanding will help plan the better use of sustainable biomass in Switzerland and elsewhere but also enable policymakers to produce more effective policy instruments and engagement strategies. Indeed, goals have been set for 2050, but the way to reach them is still open, and several scenarios are possible. More specifically, the following research objectives were set: (i) assess the current utilization of wet biomass in industrial AD installations from mass, energy, and nutrient perspectives, including contaminants such as plastics, (ii) identify how the current situation of AD installations fits into the concept of circular economy and contributes to mineral fertilizers substitution, and (iii) develop quantitative scenarios for the future of industrial AD in Switzerland.

2. Materials and methods

Our proposed methodology includes four steps (Fig. 1). First, the data regarding quantities and characteristics of the biomass was collected, and the system boundaries were defined (Section 2.1). Second, a model was created on the software STAN (Section 2.2) to conduct a material flow analysis (MFA), multiple substance flow analysis (SFA) for dry mass content (DM), nutrients (total nitrogen N_{tot} , phosphorus P_2O_5 , potassium K_2O), carbon and plastics, and an energy flow analysis (EFA) to simulate the status for the year 2018 (Baseline). Third, a sensitivity analysis was performed on selected parameters (Section 2.3). Fourth, the material flow model was used to develop future scenarios (Section 2.4).

2.1. Data and system boundaries

2.1.1. System boundaries

In Switzerland, there were over 430 biogas facilities in 2018 (SFOE, 2019), whereby sewage sludge plants represented almost two-thirds of the installations, followed by agricultural and industrial plants. Biogas plants are industrial according to the legal ordinance on spatial planning when <50 % of agricultural residues are processed in these facilities (The Swiss Federal Council, 2000). This study was conducted for industrial biogas plants in Switzerland nationwide for the year 2018 (Baseline). In that year, 35 industrial biogas plants were identified, and 32 were analyzed in this study located in 13 different regions. Three industrial plants were not considered here due to a lack of data, whereby they were comparatively small and negligible in the quantity of biomass they process. All biogas plants treat organic waste by using AD to produce biogas and by-product digestate. However, different patented technologies that use distinct AD treatment processes are available today. In Switzerland, industrial biogas plants utilize Kompogas (INOVA., 2021) as the most prevalent digester technology, in addition to Valorga, Eisenmann (Liesch and Müller, 2007) and Bekon (BEKON, 2022). Accordingly, the biogas plants were grouped into three types: Type 1 (plug flow reactor Kompogas; 22 biogas plants). Type 2 (Eisenmann and Valorga technologies; 5 plants); Type 3 (Bekon technology; 3 plants) (See Supplementary Information (SI) for details on technology).

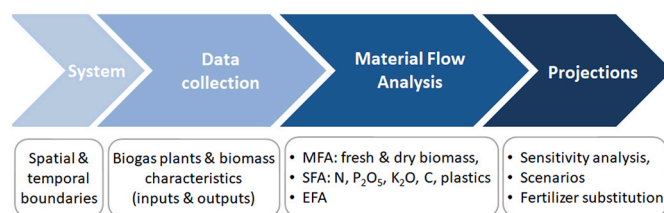


Fig. 1. Flow chart of the methods and processes followed in the present study.

2.1.2. Feedstock composition and material quantities

Data for material quantities inputs and outputs were collected through the national monitoring database (CVIS, 2020) and complemented with direct information from the biogas plants. The material arriving at biogas plant facilities is weighed and recorded in tonnes of fresh mass (FM). Data for the output material are measured in mass (tonnes) or volume (m^3). For the volume conversion to mass, densities of different outputs were identified in the literature (see Supplementary Information SI). 49 biomass streams were identified and grouped into three general categories to describe their origin:

- **Agricultural residues:** this category consists mainly of animal manure that can be either in a solid form, including excrement and bedding material, or in a liquid form with excrements and additional water. A small amount of agricultural crop residues and intermediate crops is also used.
- **Green wastes from municipalities and landscape maintenance:** this stream represents the separately collected biogenic wastes from households, landscape maintenance, and horticulture companies.
- **Industrial biowaste:** this category refers to all biogenic wastes from the industry (mainly food production), restaurants, and catering - when these are not collected at the municipal level.

The waste streams are highly heterogeneous and can vary in their physical and chemical properties.

2.1.3. Nutrients, carbon, and plastic concentrations

For 49 different types of substrates fed into the biogas plants, data from different existing databases and literature were collected for dry weight contents (DM), nutrients (total nitrogen N_{tot} , phosphorous P_2O_5 , and potassium K_2O), carbon C, and plastic contents; all expressed in tonne per tonne dry weight. The nutrient concentration in the outputs, such as digestates (solid and liquid) and composts, is regularly measured by the biogas plants and authorities (CVIS, 2020). After obtaining the nutrient concentrations, the nutrient flows in tonnes from dry matter were calculated as follows:

$$\text{nutrient mass}_{(\text{tonne})} = \text{fresh mass}_{(\text{tonne})} \times \text{DM content}_{(\%)} \times \text{nutrient concentration}_{(\%DM)}$$

Plastic content in the input is expected to come largely from green waste, with an average concentration of 0.1 % (± 0.1 %) (Hüsch et al., 2018). This plastic comes from the sub-optimal waste sorting by individuals and retailers who put it in municipal green waste (e.g. out-of-date food with plastic wrapping). The output plastic concentrations were calculated according to Kawecki et al. (2021). We assume that plastic is transferred to solid digestates and composts only and not into liquid digestate. Plastic concentration in digestate was 0.052 % of the fresh mass, for compost agriculture 0.024 %, and for compost gardening 0.011 % (Kawecki et al., 2021). Microplastics were not considered here due to a lack of data.

2.1.4. Energy content and biogas production

The primary energy of the biomass was calculated based on the dry matter's lower heating values (LHV). The values used in this study were

collected from literature for each substrate. STAN calculated the energy content in biogas based on the LHV attributed to the incoming biomass, digestates, and composts. Also, the primary energy in biogas was estimated using the biogas production declared by each biogas plant. Data on secondary energy carriers, including electricity, heat, and biomethane production from biogas processing, was acquired mainly from the national recording database (CVIS, 2020) and complementary biogas plants. This data represents the energy output after conversion and was allocated to the different biomass feedstock according to their primary energy inputs.

2.1.5. Emissions

Emissions of gases such as vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) take place during AD and composting. They were calculated based on emission factors from the quantity of biogas produced following Burg et al. (2018b), with a flat loss factor of a maximum 2 % emission of the annual quantity of biogas produced for the fermentation process and an additional flat loss factor of maximum 3 % emission of the annual quantity of biogas produced for digestate maturation fields (Biomasse Schweiz, 2012).

2.2. Modeling of flows

Based on the defined system boundaries and the data acquired, a material flow model was created using STAN 2.6 (Cencic and Rechberger, 2008) with the IMPL2013 calculation method extension to perform the MFA, SFAs and EFA. These analyses were conducted using Brunner and Rechberger (2020) approach by creating a material flow balance for flow quantification. According to them, “An MFA delivers a complete and consistent set of information about all flows and stocks of a particular material over time within a spatially defined system. Through balancing inputs and outputs, the flows of wastes and environmental loadings become visible, and their sources can be identified.” A static analysis approach was used to examine the material and substance flows for a particular spatial (Switzerland) and temporal (the year 2018) system boundary. The primary model included three subsystems for each type of AD installation determined in the previous section. Each subsystem's number of processes and flows was adapted as needed. Using the layer feature in STAN, eight levels were created to separately analyze each of the following flows: feedstock (fresh tonnes, FM), dry weight (DM), total nitrogen (N_{tot}), phosphorous (P_2O_5), potassium (K_2O), organic carbon (C), plastics, and primary energy. All flow analyses were conducted by identifying a factor based on multiplying the concentration times the dry matter content. These factors were the input values in STAN to calculate the total material flows based on the fresh mass flows in tonnes at the biomass level following a static MFA. STAN also calculated some flows, when necessary, e.g., missing data such as the carbon and nitrogen emissions values in composting.

2.2.1. Mineral fertilizers substitution

The quantities of nutrients were used to estimate how much mineral fertilizers could be replaced using fermentation products. The greenhouse gas (GHG) emissions and energy consumption reduction when corresponding amounts of mineral fertilizers are produced were calculated (see SI) (Amenume and Capel, 2014; Daniel-Gromke et al., 2015). This was done for the total produced digestate and only considering the nutrients from the non-agricultural biomass. Indeed, manure and agricultural by-products would also have been applied to agricultural fields without the fermentation process. For nitrogen, the availability was assumed to be 65 % of the total nitrogen N_{tot} for the liquid digestate and 20 % for solid digestate and composts (AGRIDEA, 2020). As P_2O_5 and K_2O are already the forms that are available to the plant, a 100 % availability is expected (AGRIDEA, 2020), which would not have been the case for P_{tot} and K_{tot} .

2.2.2. Uncertainties

Uncertainties were estimated at around 1.5 % for the inputs, 7 % for output flows, and 4 % for the liquid digestate that is measured more precisely (Trachsel, 2021); considering that some mass losses can occur during the separation of digestate and transferring of solid digestate with forklifts (CVIS, 2020). The uncertainties associated with the nutrient, carbon, and energy flows were calculated from the literature ranges for the concentrations, thus estimating the standard deviation and standard error. Error propagation was then applied for the calculated quantities through multiplication. For instance, when calculating the nutrient flows, the masses are computed by multiplying the fresh mass flows with dry matter content (%) and nutrient concentration (% DM). Therefore, the uncertainty in fresh mass, dry matter content, and nutrient concentration were considered by computing the relative uncertainty and using propagation using the equation below (Fantner, 2013). The uncertainty values were introduced into the STAN models, which then adjusted these values considering data reconciliation and error propagation.

$$\text{Relative uncertainty } \Delta z/z = \Delta x/x + \Delta y/y + \dots$$

where: z = new calculated quantity; x, y = measured quantities; $\Delta z, \Delta x, \Delta y$ = uncertainties in the respective quantities z, x, y

2.3. Sensitivity analysis

A sensitivity analysis was conducted for certain parameters to understand their influence on the flows and overall results when these values change. The different nutrient contents of total nitrogen N_{tot} , phosphorous P_2O_5 , and potassium K_2O in green waste were insufficient and lacking in the literature, particularly for Switzerland. On the contrary, many values for dry matter content of green waste were available, but they were highly variable, emphasizing the heterogeneity nature of such waste stream (Warning, 2018).

As the largest input quantity was green waste and the literature values for its characteristics are highly variable, we chose to select this input parameter and vary its main characteristics (dry mass, nutrients) (details in SI). We thus varied the dry matter contents of all green waste inputs (+ and – 5 %) and the nutrient contents (+ and – 10 %) to reflect this variability found in literature values.

2.4. Scenarios

In addition to the sensitivity analyses, we calculated the MFA, SFA, and EFA for four future development scenarios. Although there is high uncertainty regarding their likelihood, these scenarios represent guideposts that can help practitioners and policymakers make decisions in the short term. The scenarios were defined using literature sources and several experts' judgments.

2.4.1. Scenario “sustainable”

In a previous study (Burg et al., 2018a), the potential of the different biomass types that could be sustainably used for AD was estimated compared to the quantities already processed in industrial biogas plants. The rest of the organic waste is mostly treated in municipal incinerators, and a smaller part is composted. Using the ratio between the already used and the sustainable potential, we calculated the quantities of industrial and green wastes that could be additionally treated in industrial biogas plants. For the biomass of agricultural origin, it is not foreseen to be primarily used in industrial installations but rather in dedicated agricultural facilities and the proportion of manure, so the agricultural residues were kept at the same percentage of total biomass processed.

2.4.2. Scenario “2050”

According to Burg et al. (2019), both available biomass quantities and composition will change in the future. We expect a slight decrease in

the sustainable potential of industrial biowastes (1.8 PJ primary energy instead of 2.7 PJ today) but a large increase of green wastes from household and landscape maintenance mainly due to improved separate collection and population growth (7.8 PJ instead of 5.8 PJ today). Indeed, a higher AD treatment of biowastes, often incinerated together with municipal waste today, is expected. Again, the agricultural residues were kept at the same percentage of total biomass processed.

2.4.3. Scenario “no manure”

The quantities of manure to be exploited are still very high, but its use is generally of little interest to the industrial biogas plant. Hence, a system where this biomass type is only treated in agricultural biogas plants (based on dedicated, supportive measures) could evolve. Thus, we proposed a scenario where all the liquid and solid manure inputs have been removed from the industrial biogas system and transferred to the agricultural system. The other biomass inputs are kept at their 2018 levels.

2.4.4. Scenario “manure 20”

Industrial biogas plants usually process much lower manure amounts than the other biomass inputs. Indeed, transport and gate fees are costly for the farmers, and manure is of little energetic interest for industrial biogas installations. However, manure could compensate (quantity-wise) for the decrease in green waste inputs from garden and landscape maintenance in winter. As manure has a low energy content, there would not be an interest in processing very large quantities for the industrial installations. However, the farmers may be interested as they often lack sufficient manure storing space in winter when they cannot spread the manure on the fields. After discussing with experts, we propose a scenario where the industrial biogas plant processes 20 % of agricultural inputs yearly. The agricultural inputs were increased accordingly for the three types of installations.

3. Results

3.1. Material flows

Fig. 2 shows the results of the material flow analysis of the 32 industrial biogas plants and their post-composting sites in Switzerland, illustrated as a Sankey diagram for 2018 (Baseline).

Around 745,378 (± 2 %) tonnes of biomass were received at the facilities from the three major streams in 2018. The largest contributing biomass stream was green wastes (61 % of the total incoming material), followed by industrial (28 %), and agricultural residues (11 %), mainly from animal manure. Type 1 processed over 70 % of the total fresh biomass input, followed by Type 2 (19 %) and Type 3 (9 %).

The mass transfer coefficient from the total incoming biomass into the produced biogas represented only 9 %, while a significant amount of digestates and composts were produced as by-products of the process. The general uncertainty for the biomass flow was 2.3 % for the Type 1 installations, 1.8 % for Type 2, and 2.4 % for Type 3. These different uncertainties are due to the number and homogeneity of the installations within each category.

3.2. Substance flow analysis

The installations are processing in total 223,793 (± 5 %) dry tonnes of feedstock with 85,531 (± 16.4 %) tonnes carbon, 3230 (± 6.6 %) tonnes potassium K_2O , 4023 (± 5.3 %) tonnes total nitrogen N_{tot} , and 1516 (± 6.3 %) tonnes phosphorous P_2O_5 . As green waste was the most dominant incoming stream, a crucial amount of nutrients came from it (almost 70 % for K_2O and around 50 % for N_{tot} and P_2O_5). Regarding the input of agricultural residues, it represented 16 % for P_2O_5 , 12 % for K_2O , and 10 % N_{tot} . This is a non-negligible contribution compared to the fresh mass input (9 %, Section 3.1).

The SFA results for the nutrients showed good transfer and recovery of nutrients, highlighting the importance of AD technologies in conserving the nutrients and closing the loops. The results transfer coefficients of nutrients to biofertilizers were 74 %, 78 %, and 86 % for nitrogen, phosphorus, and potassium, respectively, as summarized in Table 1. In 2018, around 340 t of plastics came into the system, mainly through municipal green waste, and 70 t ended up in the soil via digestates and composts. The rest was sent to the municipal incinerator. The uncertainties around plastic quantities are quite high, at 19 %.

3.3. Energy flows

The total primary energy in the incoming biomass was estimated to be 3223 TJ (± 4.9 %) for 2018. 59 % of this primary energy came from green wastes from municipalities and landscape maintenance, 34 %

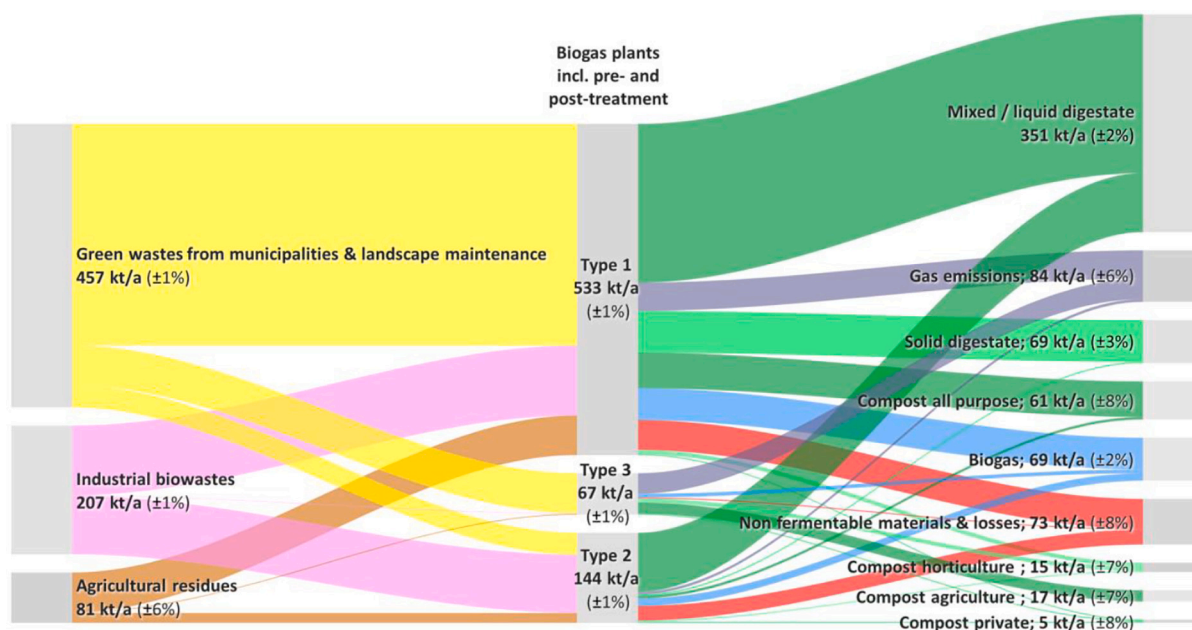


Fig. 2. Sankey diagram of major material flows through industrial biogas plants (including post- and pre-treatments) in kilotonne (kt) per year fresh mass, partly separated depending on the three plant types.

Table 1

Transfer coefficients into the final outputs of biogas plants from initial input expressed in percent of input toward the four output categories. These are calculated for each layer by dividing a specific output (total biogas produced, total fertilizers comprising liquid and solid digestate as well as all compost types), gas emissions from the fermentation and compost maturation, all non-fermentable materials, and losses (such as minerals or storage losses) by the total input value. See all details in the supplementary information excel file.

Type 1–24 plants	Biogas	Fertilizer	Gas emissions	Non fermentable materials & losses
Fresh mass	10 %	73 %	8 %	9 %
Dry mass	30 %	57 %	1 %	12 %
Energy	37 %	44 %	1 %	18 %
Carbon	42 %	45 %	2 %	12 %
Potassium	0 %	83 %	0 %	17 %
Nitrogen	13 %	80 %	1 %	6 %
Phosphorus	0 %	76 %	0 %	24 %
Plastics	0 %	35 %	0 %	65 %

Type 2–5 plants	Biogas	Fertilizer	Gas emissions	Non fermentable materials & losses
Fresh mass	8 %	72 %	3 %	16 %
Dry mass	32 %	49 %	2 %	17 %
Energy	45 %	35 %	1 %	18 %
Carbon	41 %	36 %	3 %	20 %
Potassium	0 %	93 %	0 %	7 %
Nitrogen	11 %	65 %	2 %	22 %
Phosphorus	0 %	82 %	0 %	18 %
Plastics	0 %	2 %	0 %	98 %

Type 3–3 plants	Biogas	Fertilizer	Gas emissions	Non fermentable materials & losses
Fresh mass	9 %	37 %	52 %	2 %
Dry mass	31 %	43 %	22 %	4 %
Energy	43 %	50 %	3 %	4 %
Carbon	38 %	38 %	21 %	3 %
Potassium	0 %	97 %	0 %	3 %
Nitrogen	16 %	50 %	31 %	3 %
Phosphorus	0 %	92 %	0 %	8 %
Plastics	0 %	8 %	0 %	92 %

All - 32 plants	Biogas	Fertilizer	Gas emissions	Non fermentable materials & losses
Fresh mass	9 %	70 %	11 %	10 %
Dry mass	30 %	54 %	3 %	12 %
Energy	39 %	43 %	1 %	17 %
Carbon	41 %	43 %	4 %	12 %
Potassium	0 %	86 %	0 %	14 %
Nitrogen	13 %	74 %	3 %	9 %
Phosphorus	0 %	78 %	0 %	22 %
Plastics	0 %	20 %	0 %	80 %

from industrial wastes, and 7 % from agricultural residues. The primary energy leaving the system was mainly distributed between biogas (39 %) and untapped energy remaining in the digestates and composts (43 %). 17 % was contained in the non-fermentable materials and wastes fraction, whereas the emissions losses were only 1 %. The transfer coefficients for primary energy from the total incoming energy are shown in Table 1.

Depending on the facilities, the biogas was either processed through a combined heat and power plant (CHP) to produce electricity and heat or upgraded to produce biomethane (See Table S3.1 for secondary energy generation according to the surveyed installations). For the overall 25 biogas plants, total electricity production accounted for 11 %

(340,921 GJ) of the energy contained in the overall input feedstock, while about 6 % (186,645 GJ) could be sold in the form of heat. In addition, 14 % (438,631 GJ) of the total primary energy was transformed into biomethane in 7 biogas plants with upgrading facilities.

The primary energy in biogas using the LHV approach and mass balance underestimated the biogas energy for some biogas plants and overestimated for others compared to the data provided by the plant operators. However, the total amount was comparable with the energy in biogas estimated from electricity production (1242 vs. 1313 TJ). The secondary energy carriers after biogas processing are shown in SI.

Additionally, the results of biogas production compared to the theoretical biogas yields indicated that the energy utilization potential was not fully reached, which is common in biogas plants compared to laboratory analysis. In addition, the quantities of CH₄ and CO₂ dissolved in the digestate were not considered separately as these are small. Biogas was converted into secondary energy carriers, namely electricity, heat, and/or biomethane (Fig. 3).

3.4. Sensitivity analysis

The sensitivity analysis results are shown in SI for the different chosen parameter categories. For example, an increase of 5 % of green waste dry mass leads to an increase of N_{tot}, P₂O₅, K₂O, and C quantities by 7 to 8 %, where the uncertainty of the STAN model is only around 2 to 3 %. A decrease of 5 % of green waste dry mass leads to a decrease of 10 % for the same nutrients. Plastic has high uncertainty, making irrelevant all the observed differences in the sensitivity analysis.

The change in dry mass and nutrient quantities is as expected (the higher the value given, the higher the value of the flows). However, whereas increasing the input by +10 % leads to almost +10 % in the flows, a reduction of −10 % leads to only −6 %. Regarding the dry matter content, there was a greater decrease in quantities of N_{tot}, P₂O₅, K₂O, and C when a low dry matter content was chosen for the green waste compared to a slight increase when a high dry matter content was applied.

3.5. Scenarios

In addition to the sensitivity analysis, we ran four different scenarios. Regarding biomass quantities, No Manure leads a reduction of −8 % tonnes fresh mass whereas Manure 20 to +12 % tonnes fresh mass (Fig. 4). Removing manure as input to the biogas plants (No manure) has a much smaller effect on carbon, dry mass, and primary energy (between −4 and 7 %) compared to the effects on nitrogen, phosphorous, and potassium (between −8 and −13 %). Similarly, extended manure utilization (Manure 20) leads to an increase of 9 % for carbon, dry mass, and primary energy but up to 10 to 17 % for the nutrients.

Both the Sustainable and the 2050 scenarios almost double all the values. The Sustainable potential is always slightly higher than the 2050 scenario due to the expected slight decrease in the number of animals and the reduced waste production expected in Switzerland by 2050.

3.6. Mineral fertilizers substitution

The estimated quantities of nutrients in the produced fertilizer from the biogas plants (after removing agricultural inputs) were used to estimate the GHG emissions and energy consumption reduction when corresponding amounts of mineral fertilizers are produced. For the baseline, it was estimated that it corresponds to 343 TJ of energy and 26,000 t of CO₂-eq for about 7708 t of nutrients (Table 2). These values go up to 704 TJ of energy and 54,000 t of CO₂-eq for about 16,000 t of nutrients in 2050.

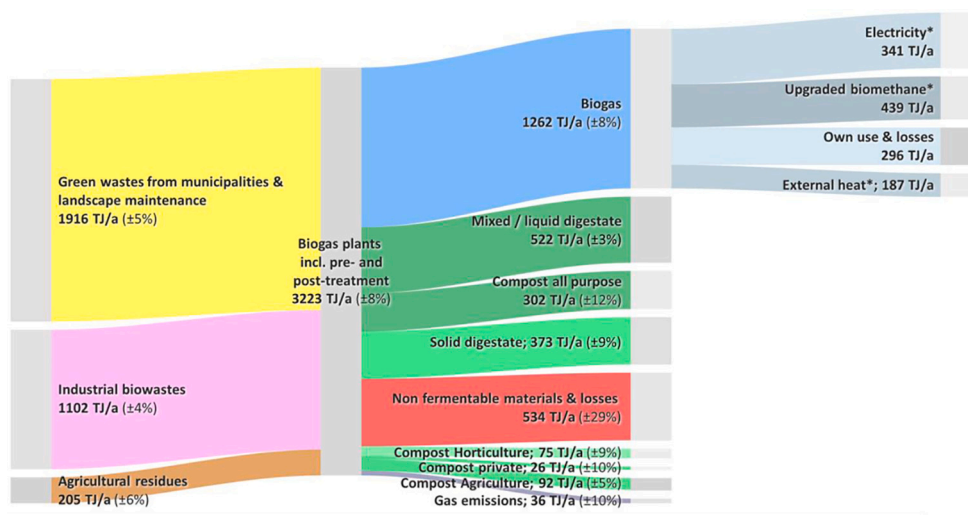


Fig. 3. Sankey diagram of major energy flows through industrial biogas plants in terajoule (TJ) per year. Secondary energy carriers (*) as reported by the biogas plants.

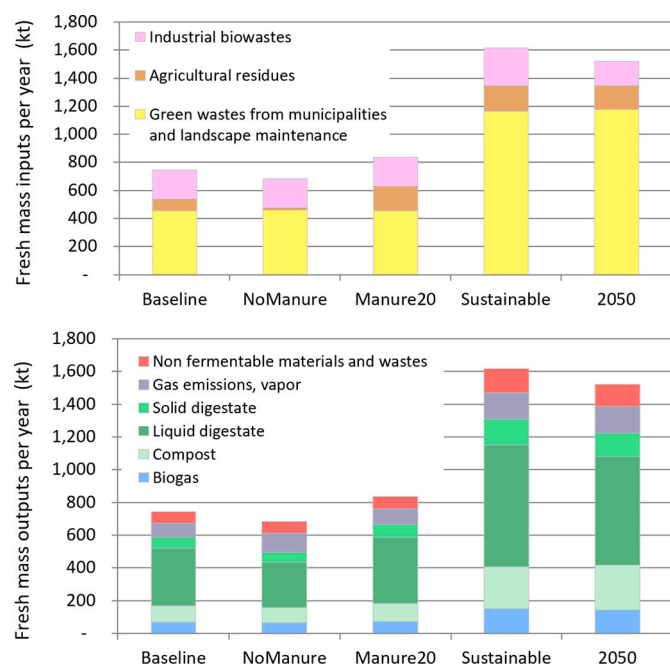


Fig. 4. Fresh biomass inputs and outputs (tonnes and composition) for the Baseline compared to the different scenarios.

Table 2

Fertilizer substitution potential regarding GHG emission (t CO₂-eq) and energy (terajoule TJ) avoided compared to the mineral fertilizer production.

	Nutrients	Mass (dry tonnes)	Mass without agricultural inputs (dry tonnes)	GHG savings (t CO ₂ -eq)		Energy savings (TJ)	
				Total	Without agricultural inputs	Total	Without agricultural inputs
Baseline	N	4023	3606	25,785	23,112	314	282
	P ₂ O ₅	1516	1275	1788	1504	26	22
	K ₂ O	3230	2827	2141	1874	44	39
	Total	8769	7708	29,715	26,491	385	343
Sustainable	N	8233	7300	52,776	46,795	644	571
	P ₂ O ₅	3180	2610	3752	3,079,812	55	45
	K ₂ O	7316	6359	4850	4216	100	87
	Total	18,729	16,270	61,379	54,091	800	704

above the transfer coefficients of each element in this study. However, this can be explained by the fact that they surveyed and measured the inputs and outputs of three individual biogas plants. The nitrogen is harder to compare as they had measured organic nitrogen (transfer coefficient 34–75 %) and mineral $\text{NH}_4\text{-N}$ (transfer coefficient 121–326 %). Zabaleta and Rodic (2015) found it would only be possible to recover 49 % nitrogen and 83 % phosphorus. Nutrient recovery from biowastes could allow biofertilizers to replace part of the mineral fertilizers to reduce GHG emissions, energy consumption, and the use of primary resources. However, these efforts for replacement can be jeopardized when a large amount of foreign matter, such as plastics, ends up in digestates and composts.

The different installation types analyzed showed unique characteristics regarding used feedstock and produced fertilizers. For instance, specific inputs or feedstock were used in Bekon technologies (Type 3, three installations), while a broader range of inputs were utilized in other types. The main reason is that Type 3 main goal is to produce high-quality composts and energy as an important yet secondary output. This is well visible in the specified fertilizer outputs, which all have compost quality rather than mainly digestate, as for Type 1 and 2 (see Section 3.3).

4.2. Method limitations, uncertainties, and sensitivity analysis

One limitation of the study is that precise information regarding substrate characteristics and flows was missing. Indeed, specific biomass waste characteristics for Switzerland are not established, especially for municipal green waste, the largest waste stream. Therefore, the literature and databases were based on other European countries, although these characteristics can vary strongly depending on the local consumer behavior and management practices. Green wastes are very heterogeneous, and the variation seen also represents reality. Moreover, the digestate and compost characteristics varied widely even at the same biogas plant throughout the year. We used static MFA, but a dynamic MFA would enable the estimation of seasonal and geographical differences in biomass nutrient content. The model kept the uncertainty fairly low at the general input and output level (<8 % apart from the carbon (16 %) and plastic (18 %) flows). However, within the model, the uncertainties per flow could be highly variable, indicating that caution is always needed when interpreting the results.

The sensitivity analysis for the parameters investigated showed changes in the output results on a similar scale to the change in the inputs. This indicates the importance of characterization of all input specifications, particularly green waste, in terms of dry matter content and nutrients.

4.3. Opportunities and future perspectives

The transition toward a circular economy is attracting more and more attention in policymaking, including in European countries (Vanhamäki et al., 2020). The Swiss government also strengthened the core strategy of the Circulating and Ecological Economy in its recent waste legislation and biomass strategy (BAFU, 2016; Federal Council of the Swiss Confederation, 2016). Hence, the country has initiated a national-wide waste separation program to be deployed in the coming years, generating large volumes of additional biodegradable waste. It is expected that biomass utilization will play a key role in the energy transition (SFOE, 2020).

Both scenarios, Sustainable and 2050, show what happens when an increased amount of biowastes are treated through AD rather than burnt in incinerators, as is often the case today: the produced biogas quantity and the nutrient amount both double.

As these additional biomass inputs do not come from agriculture, they represent a new source of organic fertilizer not used today (the ashes of the incinerators are landfilled). Hence, this additional amount of produced fertilizer can substitute net imports of fertilizers. By 2050,

this could replace 14,000 dry tonnes of mineral fertilizers, saving about 500 TJ of primary energy and avoiding the emissions of 40,000 t $\text{CO}_2\text{-eq}$, in addition to a produced biogas quantity of about 1300 TJ. It should be noted that, on the one hand, there are also some GHG emissions from operating biogas plants (e.g., transport of biomass, leakages) and, on the other hand, substitution effects at the fuel level. This should also be considered to find the overall GHG balance throughout the whole process. The values above are to be compared with the 119,330 TJ gas imports per year in Switzerland and the 210,000 t of fertilizers sold (Scharfy and Anspach, 2022). With the lowest price at 33 CHF/100 kg and the most expensive around 50 CHF/100 kg (Scharfy and Anspach, 2022), this is equivalent to a minimum of 4,290,000 CHF per year and up to 6,500,000 CHF.

These values correspond to the best-case situation as many factors may affect the nutrient availability in the digestate, such as soil humidity, pH, or the proportion of the different nutrients. Compared to mineral fertilizers that the plant can absorb straight away, it can be assumed that the needed amount of nutrients from digestate-based fertilizer would be increased. The proportion of the nutrients in the digestate is also not well adapted to all crops. Indeed, the amount of N_{tot} may be too low in comparison to P_2O_5 and K_2O (Sogn et al., 2018), which would lead to a need for additional N_{tot} being added from other sources.

Although the quantity of nutrients processed seem low compared to the needs of the agriculture in Switzerland, AD has an important role in closing the material cycles, as these are domestic resources that do not depend on the world economy or politics. Regarding the financial aspect, the prices are highly volatile and serve here as basic benchmarking.

The inclusion or exclusion of manure in the industrial biogas system will depend on how the administrative and legal framework evolves: There is a huge overall unused energy potential (Burg et al., 2018a), but the energy content per volume is relatively low in comparison to other biomass inputs, making it logistically more challenging to use manure in joint AD facilities (Schnorf et al., 2021). However, after fermentation, the digestate is easier to spread on the field, emits fewer odors, and the contained nutrients are easier for plants to take up. Thus, it would be beneficial if manure was treated in (industrial or agricultural) AD before being spread onto the fields.

4.4. Further benefits and challenges

The use of biomass for biogas production has impacts on different sectors. For example, a biogas plant using biowaste as input can provide electricity for households and heat for a nearby industry or greenhouse. The material output from the biogas plant can be used in agriculture, thus reducing the use of mineral fertilizer (e.g., compost) or water demand (e.g., liquid digestate).

Investing in additional treatment of biomass through AD will lead to less dependence on fossil fuels and cleaner energy. However, the quality of biofertilizers is more variable than standardized chemical fertilizers and can be reduced by contaminants such as plastics. Thus, quality control measures are necessary to attract potential buyers, e.g., farmers. The quality regarding larger plastics is already high, as they are sorted out when the biowastes arrive and in the compost afterward. There is also a development toward more mechanized options to treat the biomass before it is added to the digester. This is very important for buyers and the environment, as visible pieces of plastics, in addition to their chemical pollution, are detrimental to the general landscape and the fertilizer price. Also, some biowastes may contain pathogens, antibiotics, pharmaceutical residues, or heavy metals, which must be controlled. Some studies investigated the pathogenic properties of fermentation products, which demonstrated a killing effect of dangerous human, veterinary, and plant pathogens during fermentation (Fuchs et al., 2014). Regular testing of inputs and output for heavy metals in Switzerland has also indicated a good quality (Baier et al., 2016). The

problem of micro-plastic was not considered here due to lack of data, but they are causing concern as new environmental pollutants. However, some studies have shown a high potential for the biodegradation of micro-plastics in conventional AD reactors, adding again to AD's advantages (Nielsen et al., 2019). Nevertheless, in a circular economy where the same material is recirculated many times, the possibility of accumulating unwanted substances in the loop must be considered and addressed.

Ongoing climate policy could also strongly impact the promotion of AD in Switzerland and other countries. To achieve the goals of the Paris Agreement regarding the climate, Switzerland must fully exploit the potential of all its renewable energies, including biomass, by 2050. Indeed, the Energy Perspectives 2050+ for Switzerland (SFOE, 2020) indicated several possible scenarios to reach net zero by 2050 regarding the energy provision, all including full utilization of sustainable domestic biomass. Thus, a program to support the use of available biomass for energy needs to be developed that is as comprehensive as possible and more advanced than today. Indeed, the quantities of unused biomass are so large today that there is still a great deployment potential for AD in Switzerland. AD can help to mitigate climate change, and a higher percentage of total biomass processed will lead to less GHG emissions.

Technical advancements may also play an important role in future development (Burg et al., 2021). For example, these new technologies could imply a higher production of biogas with the same amount of processed biomass through more efficient AD digestion at the pre-processing or digestion steps (Burg et al., 2021). Another avenue would be to improve post-treatment, such as methanisation, to obtain final products with a higher value. Also, other technologies could be used in an industrial setting to promote energy and nutrient recovery from biomass, such as biochar or hydrothermal gasification.

A next step we would suggest is to approach the problem at the business scale to identify the best management methods for the practical operation of biogas plants. Today, economic viability is the main issue for extending AD. Indeed, the energy prices until now have been insufficient to support AD, as the installations are expensive to build and run. The economic viability of industrial biogas plants depends on the gate fees they are charging. An additional income linked to fertilizers production would be an asset.

The future development of industrial AD is hard to predict and depends on many factors. Industrial AD installations will likely treat an increased biowastes amount from the growing population and improve green waste sorting (Burg et al., 2019). Additionally, looking at other installation types, AD for wastewater treatment is now more and more standard as a means to stabilize raw sludge. The picture for the agricultural biogas plants is far less positive: based on today's regulations and framework conditions, only about 10 new plants every 10 years are expected (SFOE, 2019). Although any projections are uncertain, they can guide decision-makers: if more AD is wanted, then some initiatives need to change the conditions under which AD is being developed. For example, legal aspects could change to facilitate or even make the AD of biowastes mandatory. Also, simplification and harmonization could reduce the administrative hurdle to building new installations.

Some decades ago, AD and composting were considered competitive methods in the sense that one excluded the other. Today, AD and composting have been successfully coupled in many plants bringing the benefits both technologies can provide to society (Jensen et al., 2017). From the perspective of a circular bioeconomy, this integration leads to the generation of renewable energy and the production of organic fertilizer to be used for food production, leading to important environmental and economic gains.

5. Conclusions

Here we investigated the current industrial biogas plants in Switzerland and analyzed the effects of potential future changes.

Increasing organic waste quantities processed through AD can promote energy autonomy and nutrient recovery while reducing greenhouse gas emissions. Biogas plants are excellent examples from energy and resource perspectives for a circular economy, yet this technology is underused. A thorough understanding of material and energy flows in biogas plants is the base for optimizing the system, leading to a more economical operation and better ecological performance. The additional benefits of an improved nutrient cycle will also improve economic viability.

CRedit authorship contribution statement

Gillianne Bowman: Conceptualization; Funding acquisition; Formal analysis; Investigation; Methodology; Software; Visualization; Writing- Reviewing and Editing. **Lana Ayed:** Data curation; Methodology; Investigation; Validation; Writing- Original draft preparation. **Vanessa Burg:** Conceptualization; Funding acquisition; Formal analysis; Investigation; Methodology; Validation; Visualization; Project administration; Supervision; Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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