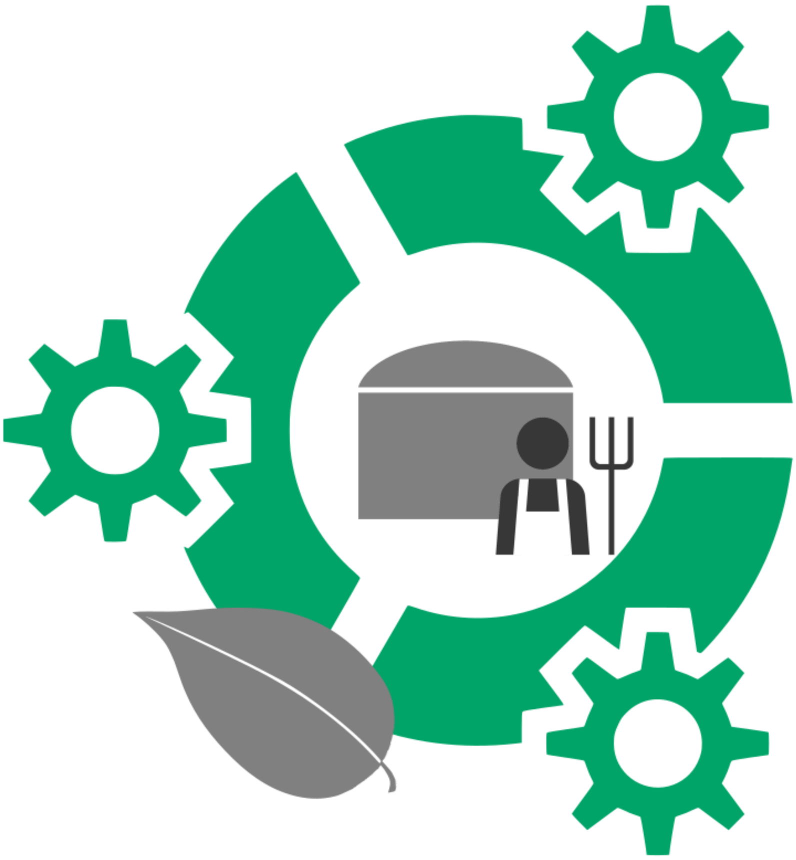
Final report dated 23.08.2022

Bioenergy and circular economy:

the biogas plant as a hub



Source: ©Vanessa Burg 2020

Date: 1st of July 2022

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:

Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL
Zürcherstrasse 111, 8903 Birmensdorf, Switzerland, www.wsl.ch

Ökostrom Schweiz
Technoparkstrasse 2, CH- 8406 Winterthur, www.oekostromschweiz.ch

Authors:

Vanessa Burg, Eidg. Forschungsanstalt WSL, vanessa.burg@wsl.ch

Gillianne Bowman, Eidg. Forschungsanstalt WSL, gillianne.bowman@wsl.ch

Victor Anspach, Ökostrom Schweiz, victor.anspach@oekostromschweiz.ch

Deborah Scharfy, Ökostrom Schweiz, deborah.scharfy@oekostromschweiz.ch

Lana Ayed, Eidg. Forschungsanstalt WSL

Christian Rolli, Eidg. Forschungsanstalt WSL

SFOE project coordinators:
Sandra Hermle, sandra.hermle@bfe.admin.ch

SFOE contract number: SI/501989-01

Zusammenfassung

Biomasse spielt in einer Kreislaufwirtschaft eine wichtige Rolle, sowohl in Bezug auf die Material- als auch auf die Energieversorgung. Das heutige Agrar- und Ernährungssystem basiert jedoch in der Regel auf linearen Flüssen (z. B. Einfuhr von Ressourcen, fossilen Brennstoffen und Mineraldüngern), während ein zirkulärer Ansatz bevorzugt werden sollte. In dieser transdisziplinären Studie wird die Produktion von Biogas als erneuerbare Energiequelle und von Gärresten, die als organischer Dünger verwendet werden, aus der Perspektive der Kreislaufwirtschaft bewertet. Sie untersucht die derzeitige Nutzung von Biomasse in landwirtschaftlichen und industriellen anaeroben Vergärungsanlagen in der Schweiz in Bezug auf Masse, Nährstoffe (C, N, P, K) und Energieströme. Dabei quantifizieren wir das System und mögliche Vorteile im Detail und untersuchen zukünftige Entwicklungen von Biogasanlagen anhand verschiedener Szenarien. Unsere Ergebnisse zeigen, dass die landwirtschaftliche und industrielle anaerobe Vergärung erheblich gesteigert werden könnte. So könnte bis 2050 mindestens die doppelte Menge an Biogas geliefert und gleichzeitig erhebliche Mengen an Mineraldünger und Treibhausgasemissionen einspart werden. Somit könnte eine verstärkte anaerobe Vergärung von organischen Rückständen und Abfällen die Abhängigkeit von fossilen Brennstoffen und Ressourcenimporten verringern und gleichzeitig die Kreislaufwirtschaft fördern.

Résumé

La biomasse a un rôle important à jouer dans une économie circulaire, aussi bien en termes d'approvisionnement en matières qu'en énergie. Cependant, le système agroalimentaire actuel est typiquement basé sur des flux linéaires (par exemple, l'importation de ressources, de combustibles fossiles et d'engrais minéraux), alors qu'une approche circulaire devrait être privilégiée. Dans cette étude transdisciplinaire, la production de biogaz comme source d'énergie renouvelable et de digestat, utilisé comme engrais organique, est évaluée du point de vue de l'économie circulaire. Elle analyse l'utilisation actuelle de la biomasse dans les installations de digestion anaérobie agricoles et industrielles en Suisse en termes de masse, de nutriments (C, N, P, K) et de flux énergétiques. Nous avons quantifié en détail le système et ses avantages et examiné les développements futurs des installations de biogaz en utilisant différents scénarios. Nos résultats démontrent que la digestion anaérobie agricole et industrielle pourrait être largement augmentée, car elle pourrait fournir au moins deux fois plus de biogaz d'ici 2050, tout en économisant des quantités importantes d'engrais minéraux et d'émissions de gaz à effet de serre. Ainsi, l'augmentation de la digestion anaérobie des résidus et déchets organiques pourrait réduire la dépendance aux combustibles fossiles et l'importation de ressources, tout en favorisant l'économie circulaire.

Summary

Biomass has a central role to play in a circular economy, both in terms of material and energy supply. However, today's agro-food system is typically based on linear fluxes (e.g., import of resources, fossil fuels, and mineral fertilizers), when a circular approach should be privileged. In this transdisciplinary study, the production of biogas as a renewable energy source and digestate, used as an organic fertilizer, is assessed from the circular economy perspective. It investigates the current utilization of biomass in agricultural and industrial anaerobic digestion plants in Switzerland in terms of mass, nutrients (C, N, P, K), and energy flows. Indeed, the system and its benefits were quantified in detail and examine future developments of biogas plants using different scenarios. Our results demonstrate that agricultural and industrial anaerobic digestion could be largely increased, as it could provide at least twice as much biogas by 2050 while saving significant amounts of mineral fertilizer and GHG emissions. Thus, increased AD of organic residues and wastes could reduce dependence on fossil fuels and resources import while promoting a circular economy.

Main findings

- Nowadays, the agricultural and industrial biogas plants in Switzerland process 1.9 Mt of biomass per year (62% agricultural and 38 % industrial), leading to a yearly biogas production of 2,579 TJ and a quantity of fertilizer of 1.6 Mt.
- The fertilizers contain about 11’000 tonnes of N, P, and K, thus saving about 40’000 to CO2-eq and 510 TJ energy.
- If the full sustainable potential was used, these advantages could be increased more than twofold.
- With increasing prices of mineral fertilizers and recognition of the many opportunities they represent, there is today a strong incentive to increase the commercialization of digestate products.
- There is a need for better data regarding the feedstock input and outputs characteristics as well as precise emissions measurements at the biogas plant level.

Contents

1 Abbreviations

AD	Anaerobic Digestion
C	Carbon
CH_4	Methane
CHP	Combined heat and power
DM	Dry Matter
EFA	Energy Flow Analysis
eq-CO_2	CO_2 equivalents
FM	Fresh matter
GHG	Greenhouse gas
K_2O_5	Potassium
LHV	Lower heating value
LSU	Livestock unit
MCF	Methane conversion factor
MFA	Material Flow Analysis
MJ	Megajoule
MM	Manure management
N	Nitrogen
N_2O	Nitrous oxyde
oDM	Organic Dry Matter
P_2O_5	Phophorus
PE	Primary Energy
PJ	Petajoule
SFA	Substance Flow Analysis
t_{DM}	Tonne of feedstock dry matter
t_{FM}	Tonne of feedstock fresh matter

2 Glossary

Anaerobic digestion: Decomposition of a biodegradable feedstock organic matter when exposed to an environment without oxygen (European Biomass Industry Association, 2022). Anaerobic digestion produces two main products: digestate and biogas.

Biogas: A mixture of gases produced by microorganisms performing anaerobic digestion. It primarily consists of methane (CH_4) and carbon dioxide (CO_2) and may contain small amounts of hydrogen sulfide (H_2S), moisture, and siloxanes.

Biowastes: All organic waste capable of undergoing anaerobic or aerobic decomposition, such as industrial, food, or green wastes that are collected separately.

Circular economy: A model of production and consumption which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended, and waste generation is minimized (European Parliament, 2022).

Digestate or fermentation slurry: Digestate refers to the product which has undergone anaerobic digestion. It is liquid with a certain amount of solids, depending on the input biomass.

Digestate separation: The digestate can be separated into solid and liquid fractions, which improves its possible further processing and usability as a fertilizer.

Liquid separated digestate: Liquid separated digestate: refers to the liquid digestate fraction after the digestate separation. While digestate as such is liquid, the liquid separated digestate contains even fewer solids.

Liquid manure or slurry: Type of livestock waste that is in liquid form, collected in liquid manure pits and usually mixed with water. Before dilutions, liquid manure has a dry matter content between 4% and 9% (GRUDAF, 2009).

Manure: Composed of animal feces and urine and may contain livestock bedding, additional water, and wasted feed.

Solid manure: Type of livestock waste that is in solid form, collected in the stables, with a dry mass content between 20% and 65% (GRUDAF, 2009).

Solid separated digestate: refers to the solid digestate fraction after the process of digestate separation. It contains most solids and can be used like solid manure or compost.

3 Introduction

3.1 Background information and current situation

Swiss biomass could make a significant contribution to implementing the energy transition. Biomass has many advantages, as it can be used for electricity, heat, and as a fuel for transport. Being easily storable, biomass is also fully considered in the energy landscape of 2050 for process heat and heavy freight (SFOE, 2020). In previous studies, we have examined the energy potential with regard to sustainability criteria of woody and wet biomass (Burg et al., 2018a; Thees et al., 2017) and found that wet biomass could supply an additional 30 PJ of energy per year. Most of this remaining potential (26 PJ) lies in animal manure and communal green waste (3.3 PJ). Organic industrial waste and organic domestic waste are already collected and transformed into energy. Wet biomass is processed in anaerobic digestion plants (AD), where anaerobic micro-organisms decompose the organic fraction of wastes while producing biogas. Simultaneously, the resulting nutrient-rich digestate serves as a fertilizer for local agriculture. Furthermore, AD of animal manure is a promising strategy to reduce greenhouse gas emissions originating from manure (Burg et al., 2018b). So far, however, AD technology has only been used to a limited extent - especially in agriculture - due to the low profitability for the plant operator.

The use of wet biomass has been shown to have many further positive externalities that can be monetized. As subsidies for energy from anaerobic digestion are decreasing throughout Europe, innovative solutions are needed and are being searched for (Enea Consulting, 2019). In the agriculture sector, using digestate instead of unfermented slurry limits water pollution and reduces the use of mineral fertilizers. The digestate can also be sold as compost and fertilizer for hobby gardeners and agriculture. However, the quality and recognition of these products are still a problem, even though the avoided fertilizers' imports and additional revenues from selling the products of biomass transformation could diversify agricultural revenues and create resilience (Enea Consulting, 2019). Then, the GHG emissions saving can be recognized through CO_2 certificates and thus add an additional income to the energy side. Other positive externalities of AD technology that are more difficult to quantify and monetize but are still important for society include, e.g., energy independence, soil quality preservation, and job creation (Enea Consulting, 2019).

Today's agro-food system is typically based on linear fluxes (e.g., import of resources, fossil fuels, and mineral fertilizers), while a circular approach should be privileged. In order to promote the many positive externalities of AD and justify the political support for this technology, it is, therefore, necessary to investigate its many advantages compared to the current situation. Through an extensive survey in which 200 farmers took part, we found that they have a generally positive attitude towards AD. However, there are some concerns regarding digestate handling (Burg et al., 2021b). This reluctance shows the need to look into this issue more closely and to create a better information basis.

To analyze the system's circularity, Material Flow Analysis (MFA) was shown to procure indicators facilitating decision-making (Tanzer and Rechberger, 2019; Virtanen et al., 2019). Tonini et al. (2014) further notify that material-, substance-, and energy flow analysis (MFA, SFA, EFA) were useful to assess mass, energy, and substance flows in different urban systems, including waste management and bioenergy. They can also serve as a basis for life-cycle assessments and are a complementary tool for environmental management strategies (Tonini et al., 2014). However, MFA/SFA are rarely used in the regional context, as it is challenging to gather regional-level information (Virtanen et al., 2019). Studies having regional or national boundaries focus on only one or a few nutrients (Binder et al., 2009; Coppens et al., 2016).

3.2 Purpose of the project

Bioenergy systems fit into the context of the circular economy, in which, according to the European Commission, "...the value of products, materials, and resources in the economy is maintained as long as possible and the generation of waste is minimized" (European Commission, 2015). Restorative, it aims to keep the material and its components at their highest utility and value (Figure 1) (Fagerström et al., 2018), which includes using by-products from one production process as secondary raw material in another. Being a country with only little raw material resources, Switzerland has pursued the circular economy approach since the mid-1980s. The circular economy is part of the country's green economy and sustainable development plan, which considers the limited supply of natural resources (FOEN, 2020). However, certain materials require more resources and energy when recycled than using primary raw materials.

There are two reasons why biogas production is strongly linked to the circular economy: First, it is an important step in a cascading use of biomass. Second, the AD process allows the creation of value from waste. Accordingly, material flows, previously regarded as residues/waste from industrial processes, agriculture, and other human activities, can be processed through the biogas plant and used both as useful energy sources and in the form of nutrient-rich fertilizers. In fact, the nutrients contained in organic domestic or industrial wastes, such as nitrogen, phosphorous, potassium, and other minerals, are returned in the digestate, while they would be lost in traditional waste combustion.

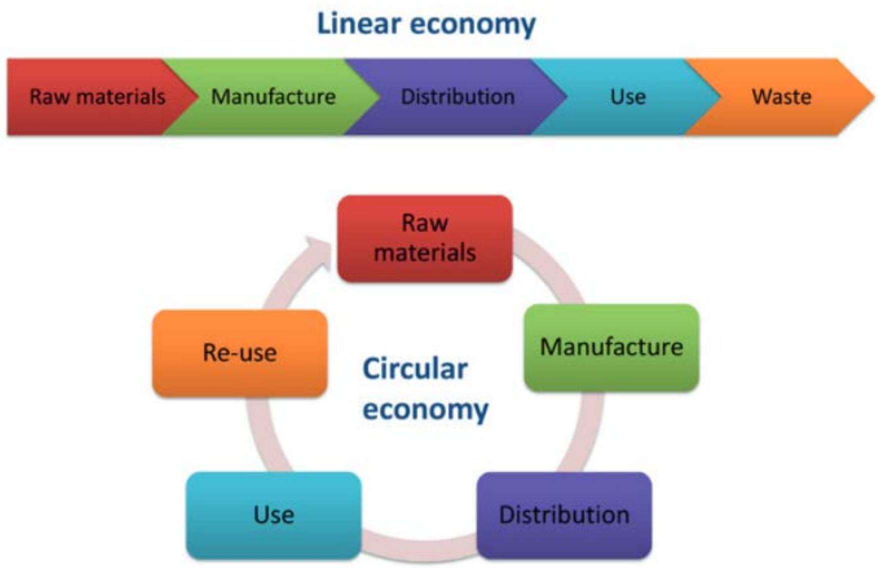


Figure 1: Differences between the linear and the circular economy, from Fagerström et. al (2018).

For these reasons, we would like to examine the Swiss bioenergy system in the circular economy context. The amount of energy going back to the local community in the form of electricity, heat, or fuel through anaerobic digestion will be investigated. Moreover, the reduced GHG emissions of biogas projects are compared to conventional waste treatments (including operating energy consumption, emissions of conventional energy substitution, and excrement discharge) to examine the possible advantages of the technology.

The production of mineral fertilizers is based on fossil fuels (N-fertilization on Haber-Bosch process) or exhaustible natural resources (phosphate rock), and it is also highly energy consuming (Chojnacka et al., 2019). Therefore, the replacement of fossil-based fertilizers resulting from the production of digestate will be assessed in terms of GHG avoided and avoided nutrients imports.

Economically, the current bioenergy system in the agricultural sector is living from the sales of electricity and waste heat. Agricultural biogas plants also benefit from CO_2 reduction attestations when participating in a climate protection project. The digestate, either solid or liquid, has, however, no economic value so far. Up to now, the animal manure used in the biogas plants is cost-free, and the farmers receive the same amount of nutrients in the form of digestate back as initially brought, also at no cost. There are only a few cases of digestate being sold. The project aims to estimate the value and economic potential that digestate has and can achieve in the future when more biogas plants will be present and more digestate will be available. The digestate market can be agricultural, horticultural, and also address private "hobby gardeners".

For this purpose, the nutrient balance of the current bioenergy system needs to be assessed at the national level. Possible scenarios for the future and substitution effects (replacement of mineral fertilizers, CO_2 equivalents) should also be analyzed. **We want to show whether and to what extent**

AD can lead to improved resource cycles. This will provide a reference for future research and a basis for practical optimization and political measures.

3.3 Objectives

The proposed study aims to investigate for Switzerland how and to what extent AD fits into the concept of the circular economy and to assess what impact it could have on the current nutrient and carbon cycle. The current utilization of biomass, focusing on industrial-commercial and agricultural biogas plants (without sewage sludge), will be analyzed in a Material Flow Analysis (MFA) and a substance flow analysis (SFA), which will provide a quantitative understanding of the current system. Further potential added values for the biogas plants will be examined.

More specifically, this study has the following objectives:

1) Show the current utilization of wet biomass in anaerobic agricultural and industrial digestion plants in Switzerland in a material flow model.
2) Investigate the mass, nutrient, and energy balance from biomass in AD installations on a national scale and demonstrate how it fits into the circular economy concept.
3) Understand the substitution effect of mineral fertilizers to bio-fertilizers from digestate and show how it contributes to closing the cycles. The substitution potential of artificial fertilizers will be assessed quantitatively, monetarily, and qualitatively.
4) Consider the economic aspects and possible other positive externalities (e.g., energy. GHG emissions mitigation) of the use of biomass in anaerobic digestion.
5) Examined possible future developments of agricultural and industrial biogas plants based on scenarios.
6) Finally, recommendations are derived in considering the entire bioenergy system, and approaches for system improvement are presented.

4 Procedures and methodology

This study focuses on the energetic utilization of the wet, fermentable biomass and the associated nutrient flows. This biomass includes agricultural and anthropogenic residues/waste such as animal manure, green wastes, and organic industrial wastes (Burg et al., 2018a; Thees et al., 2017). Sewage sludge and other specific biomass types, such as slaughterhouse waste, which for hygienic reasons cannot be reused per se even after fermentation and require more complex treatment, are not treated here (Der Schweizerische Bundesrat, 2015). Therefore, the material flows of two biogas plant categories are investigated here: industrial-commercial fermentation and agricultural fermentation (co-fermentation), whereby different fermentation products are generated depending on the feedstock used.

4.1 Model and system boundaries

The model reflects the Swiss industrial and agricultural biogas system and excludes sewage sludge. In 2018, the Swiss renewable energy statistics reported 111 agricultural and 28 industrial biogas plants (BFE, 2019a). These plants mainly differ in the origin of feedstock they process and the technology used. However, it is sometimes difficult to distinguish them, and their definition is linked to the amount of co-substrates used in the fermenter and the zone it is built (The Swiss Federal Council, 2000). In order to receive the agricultural supportive bonus and feed-in tariffs, 80% of the processed material has to be of regional and agricultural source (BFE, 2015). However, biogas plants are generally called *agricultural* when 50% of the mass of the treated material originates from farms. Furthermore, this 50% should be from the biogas site or neighboring farms (15 km driving radius). This part should also represent at least 10% of the energy production from the plant. The origin of the remaining substrates should remain within a driving distance of fewer than 50 km (The Swiss Federal Council, 2000). For this study, all plants processing more than 50% non-agricultural substrates were considered *industrial.* Thus, 32 industrial plants were obtained (see 4.2).

The model is presented and calculated on the software STAN (short for substance flow Analysis), which is a software frequently used for this purpose (Binder et al., 2009; Coppens et al., 2016; Jensen et al., 2017; Tanzer and Rechberger, 2019; Tonini et al., 2014). The developers of STAN (Cencic and Rechberger, 2008) describe MFA as a "systematic assessment of flows and stocks of materials within an arbitrarily complex system defined in space and time." The model and the equations can contain known, measured, and constant variables. Measured data always hold uncertainties, which are associated with the samples (e.g., existing digestate analyses) or with the analytical concentration of the chemicals, e.g., 10% for C and N, 2.5% for P, and 6.2% for K (Cencic and Rechberger, 2008; Tonini et al., 2014). There are also other possible methods to estimate the uncertainty and resolve contradictions in the measured data, e.g., by using means and standard deviations (Cencic and Rechberger, 2008) or uncertainty intervals (Coppens et al., 2016). Examples of the STAN models used are given in the Appendix.

The system boundaries are limited to the inputs and the outputs into biogas plants and might include pre- and post-processing steps of the feedstock when necessary (Figure 2). The way the output flows, also called export flows in STAN, may influence other sectors, such as crop or livestock production, which are not considered here.

First, the model for the mass/substance flow analysis of the two different biogas plant types must be described separately. Both types use different technologies and, therefore, require different processing steps. The inputs in industrial biogas plants are mostly solid, with substrates having dry matter (DM) contents reaching 45% (BAFU, 2016). Even if the processes are similar, it is possible to distinguish the plug-flow (Kompogas), the silo-like (DRANCO, Valorga), and the box procedure (BENKO), all of which might require additional pre-processing steps (BAFU, 2016). Agricultural plants use mostly liquid substrate inputs as the DM input of the fermentation mix should not exceed 15% (BAFU, 2016).

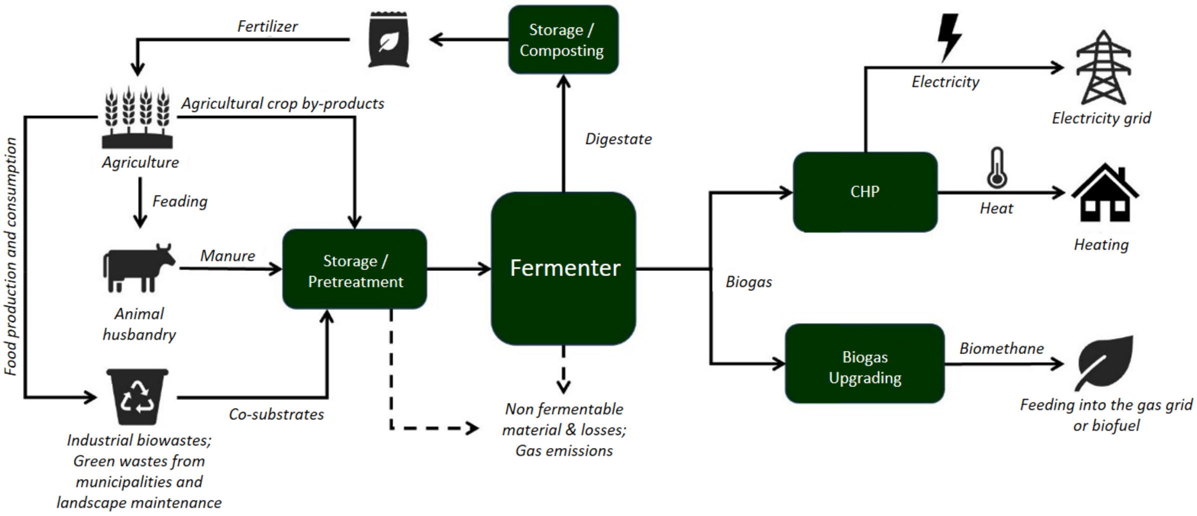


Figure 2: Schematic representation of the most important flows in agricultural biogas plants.

4.2 Data

The analysis mentioned above requires data on material flows. In total, the data of 93 biogas plants could be used, which were classified into 61 of agricultural and 32 of industrial type. One major source of information is procured by the association *Inspektorat für die Kompostier- und Vergärbranche der Schweiz*, which was commissioned to establish the control of the composting and anaerobic digestion plants for several cantons (CVIS, 2020; Schleiss, 2020). The dataset of the Inspektorat shows the material inputs (in tonne of fresh matter, t_{FM}) and outputs (in m^3) of 57 agricultural and 30 industrial biogas plants for the year 2018 in a semi-anonymized way. Data for previous years (2010-2019) are available and are used to complement missing values, as some plants are surveyed every second year only. Hence, two agricultural plants are issued from the year 2019. Furthermore, information on previous years will also be used to calculate uncertainty parameters. The data from the four remaining agricultural plants and two industrial plants originated from the cantonal authorities and were completed according to the federal manure-exchange list Hoduflu (BLW, 2019). For industrial biogas plants, primary data from the plants themselves complement the initial dataset. For data privacy reasons, more specific and comprehensive datasets could not be accessed (e.g., FOEN, Ökostrom Schweiz). Information regarding energy flows could also be obtained from the Inspectorate, the cantonal authorities, and the plants. Where necessary, direct calculations are made based on each feedstock's organic content and potential methane yield based on literature values (KTBL, 2013; Thees et al., 2017).

4.3 Nutrients, Carbon and Plastic Concentrations

For the different types of substrates fed into the biogas plants, data from several public and private databases and literature were collected for nutrients (nitrogen N, phosphorous expressed as P_2O_5, and potassium, expressed as K_2O), carbon (or C/N ratio), and plastic contents (see additional Excel file). The nutrient concentration in the outputs digestates (solid and liquid) and composts are measured by the industrial biogas plants on a regular basis and a few times a year in the agricultural plants (CVIS, 2020). After obtaining the nutrient concentrations, the nutrient flows in tonnes from dry matter were calculated as follows:

$$nutrient\ mass_{(tonne)} = fresh\ mass_{(tonne)} \times DM\ content_{(\%)} \times nutrient\ concentration_{(\%DM)}$$

Plastic was only considered for the industrial biogas plant in the STAN model, and the content in the input was assumed to come mostly from municipal green wastes, with an average of 0.1% (± 0.1%) (Hüsch et al., 2018). The output plastic concentrations were calculated according to Kawecki et al. (2021). Plastic is assumed to be transferred into solid digestates and composts and not into liquid digestate. Plastic concentration was 0.052% of the fresh mass in the solid digestate, 0.024% for compost delivered to agriculture, and 0.011% for compost for gardening (Kawecki et al., 2021). Plastics are not much of an issue for the agricultural biogas plants as very little municipal green waste is processed there. Thus, it was not included in the STAN as a layer. However, a simple estimation was performed considering only the input from municipal green wastes as the total amount of plastic included in the agricultural system.

4.4 Energy Content and Biogas Production

The primary energy of the biomass was calculated based on dry matter's lower heating values (LHV) from the literature. STAN calculated the energy content in biogas based on the biogas yield attributed to the incoming biomass, digestates, and composts (see additional Excel file). Data on secondary energy carriers, including electricity, heat, and biomethane production from biogas processing, was acquired mainly from the national recording database (Schleiss, 2020).

4.5 Emissions

Emissions of gases such as vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ammonia (NH3) take place during storage, anaerobic digestion, and composting. If the biogas installation is operated following the Quality Management Biogas Handbook (Biomasse Schweiz, 2012), a flat loss factor of a maximum 2% emission of the annual quantity of biogas produced can be expected at the fermenter level (BAFU, 2015). Moreover, an additional flat loss factor of a maximum 3% emission of the annual quantity of biogas produced can be assumed for digestate maturation taking place before it is spread onto the fields. These emissions are taken as upper limit boundaries. Vapor losses from the fermenter and the storage after fermentation were also considered (Baier, 2022). Based on this, STAN calculates an equilibrium for the model and its uncertainty.

4.6 Flows modeling

Based on the defined system boundaries and the data acquired, several material flow models were created using the software 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 (2016) approach by creating a material flow balance for flow quantification.

Using a static analysis approach, the material and substance flows were examined for a particular spatial (Switzerland) and temporal (the year 2018) system boundary.

For the industrial biogas plants, the main model included three subsystems for each type of anaerobic installation determined in the previous section (see example in Appendix). For the agricultural biogas plants, only one system was used. In each subsystem, the system boundary was adapted, depending on the considered processes to analyze, with a varying number of processes and flows. Using the "level" feature in STAN, seven levels were created to analyze each of the following flows separately: goods (biomass), nitrogen (N), phosphorous (P_2O_5), potassium (K_2O), organic carbon (C), plastics (only for the industrial plants), and energy. The SFA was conducted for the nutrients and carbon levels 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 flows based on the fresh mass flows in tonnes at the biomass level. STAN also calculated some flows when necessary e.g., missing data such as the carbon and energy flows in biogas and nitrogen emissions values in composting.

4.7 Scenario development and analysis: agricultural biogas plants

Starting from the base model, which relies on data from 2018 (Baseline), various scenarios for the future of agricultural biogas plants were elaborated. For this purpose, interviews were conducted with nine experts from different disciplines using the Wild Card method (see scientific publication Burg et al., Submitted)). The term Wild Card refers to a plausible future event that is estimated to have a low probability, but a high impact should it occur (Barber, 2006). Such incidents might constitute turning points in the evolution of a certain trend. The exercise of imagining Wild Cards is an effective way to encourage respondents to think differently.

4.7.1 Scenario A1: Continued Support

The first scenario was defined to provide a reference scenario for the year 2050 to remain coherent with the Swiss Energy Perspective 2050+ (SFOE, 2020). Through several interviews (Gisler, 2021; Meier, 2021; Scharfy, 2021), it was estimated that a doubling of plants in 10 years is realistic if continued support is granted to promote agricultural biogas such as simplified permit procedures (Meier, 2021). Based on the 2018 flows model and the expected development until 2050, this doubling was converted into a new construction rate:

$$\frac{+100\%}{10\ a} = +10\%\ per\ Year \rightarrow 2050 - 2018 = 32a \rightarrow 32a * 0.1 = 3.2 = \underline{+320\%}$$

This increase corresponds to a system with approximately 460 agricultural biogas plants in 2050. Based on the 2018 flows model and the expected development until 2050, this doubling was converted into a diffusion rate (460/111=4.14). All input flows were increased by this factor, similarly to the extrapolation for the already existing plants in the Baseline model.

4.7.2 Scenario A2: Sustainable Manure Potential

This scenario is based on the complete utilization of the sustainable potential of manure for energy, according to Burg et al. (2018a). The co-substrates were also increased by splitting their remaining sustainable potential between industrial and agricultural biogas plants, considering their share today to avoid double counting in both types. Indeed, the amount of biomass available in Switzerland and the proportion of the biomass treated today in each type of installations is known (Burg et al., 2018a). Hence, the industrial biowastes were multiplied by 1.33, whereas cattle manure was multiplied by more than 20 (see all values in Burg et al. (Submitted)). The amounts of energy, carbon, and nutrients per tonne of fresh matter (FM) were held constant for all flows since it is primarily their amounts that change, not their composition.

4.7.3 Scenario A3: Sustainable Food System

Nutrition in Switzerland is likely to change in the future, which could directly influence agricultural production (Müller, 2021; Ow, 2021) and thus the availability of substrates for agricultural biogas plants. Less meat consumption influences the amount of manure produced, which makes up a large part of the input. Zimmermann et al. (2017) analyzed and compared four nutrition scenarios under different framework conditions, where environmental impacts were reduced by running a model with an objective function for minimizing environmental factors. For the present study, the Sustainable Food System scenario using the "FoodWaste" nutrition scenario was used as it has the lowest environmental impact and, with the maximum possible reduction in food waste, is closest to a closed-loop system. This scenario provides significantly different future bio-resource potential values compared to a previous projection study where disruptive changes were excluded (Burg et al., 2019). This scenario was applied to scenario A2 as a combination would make sense from a sustainability point of view.

4.7.4 Scenario A4: Technical Change Separation

Following the experts' discussions, efficiency improvement at different technical levels can be expected. One suggestion was the development of manure separation following the ongoing project NETZ. The project aims to achieve higher exploitation of the biomass potential by separating raw manure into liquid and solid fractions and subsequent separate fermentation (Hersener, 2021; Meier et al., 2016; Nägele, 2021; Nägele et al., 2021).

The separation values of the pressing screw come from the final report LEVER (Treichler et al., 2016), but no carbon data was collected. The ratios had to be calculated based on a European study (Webb et al., 2013) where the DM content in the liquid fraction is reduced by 40-45% and the C content by 45-50%. The 39% reduction in DM content in the liquid fraction is similar to the LEVER data (Treichler et al., 2016). Only input flows that occur directly on farms with less than 10% dry matter content are fed into the separator. These criteria apply to the two flows of cattle slurry and cattle manure. The raw slurry was estimated from these two flows with the average values weighted by quantity. Subsequently, from this raw slurry, using the relative data from Treichler et al. (2016) and Webb et al. (2013), the values of separated slurry solids and thin slurry were calculated.

4.8 Scenario development and analysis: industrial biogas plants

The scenarios were defined using literature sources and several experts' judgment. Although there is high uncertainty concerning their likelihood, these scenarios represent guideposts that can help practitioners and policymakers make decisions in the short term.

4.8.1 Scenario I1: Sustainable

In a previous study (Burg et al., 2018a), the potential of the different biomass types that could be sustainably used for anaerobic digestion was estimated compared to the quantities already processed in industrial biogas plants. The rest of the organic waste is mainly treated in municipal incinerators, and a smaller part is composted. Using the ratio between the already used and the sustainable potential, the quantities of industrial and green wastes that could be additionally treated in industrial biogas plants was calculated. 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 (SM).

4.8.2 Scenario I2: 2050

According to Burg et al. (2019a), both quantities and the composition of biomass available in the future will change. a slight decrease in the sustainable potential of industrial biowastes is expected (1.8 PJ primary energy instead of 2.7 PJ today) but a considerable 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 much higher biowaste treatment through anaerobic digestion is expected, which today is mostly incinerated with municipal waste. Again, the agricultural residues were kept at the same percentage of total biomass processed.

4.8.3 Scenario I3: No Manure

The quantities of manure to be exploited are still very high, and its use is generally of little interest to the industrial biogas plant. A system where this biomass type is only treated in agricultural biogas plants (based on dedicated, supportive measures) could evolve. Thus, a scenario was proposed, 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.

4.8.4 Scenario I4: Manure 20

Industrial biogas plants usually process lower amounts of manure than the other biomass inputs, especially as transport and gate fees are costly for the farmers and its use is of little energetic interest for the industrial biogas installation. However, manure could compensate (quantity-wise) for the decrease in green waste inputs from garden and landscape maintenance in winter. A scenario where the industrial biogas plant process 20% of agricultural inputs was proposed. The agricultural inputs were increased accordingly for the three types of installations.

4.9 Uncertainties

Uncertainties were estimated from 1% to 3% for input material flows from industrial sources but 7% for agricultural inputs, 4% for liquid digestates, and 6% for solid digestates; taking into account that some mass losses can occur during the separation of digestate and transferring of solid digestate with forklifts. 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). As for the energy flows, the uncertainty in the fresh mass and dry matter content was considered. The uncertainty values were introduced into the models. STAN then adjusts these values taking into account data reconciliation and error propagation.

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

where: z = new calculated quantity; x, y = measured quantities;

Δz, Δx, Δy = uncertainties in the respective quantities z, x, y

5 Results and discussion, Flow analysis

5.1 Industrial biogas plants

5.1.1 Material flows

Figure 3 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). Examples of the STAN models used are given in the Appendix.

Around 745,000 (±2%) tonnes of biomass were received at the facilities coming from the three major streams in 2018. The most significant contributing biomass stream was green wastes with 61% of the total incoming material, followed by industries at 28%, and 11% from agricultural residues, mainly animal manure. Type 1 processes 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 from 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 slightly different uncertainties are due to the number and homogeneity of the installations within each category.

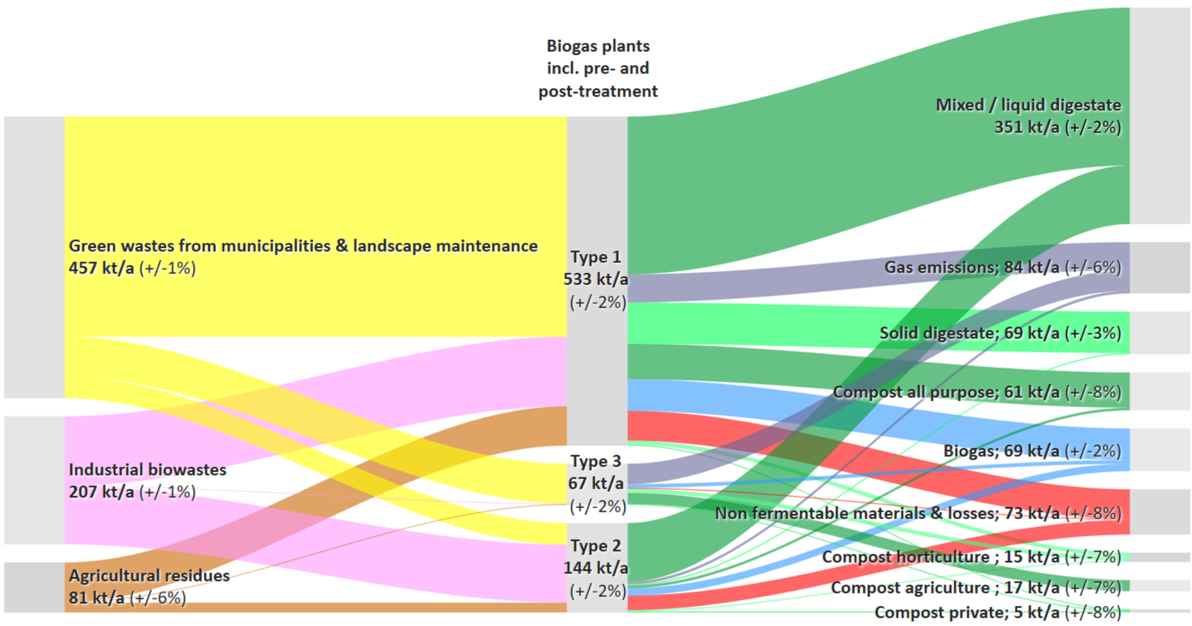


Figure 3: Sankey diagram of major material flows through industrial biogas plants (including post- and pre-treatments) in kilotonne (kt) per year fresh mass, partly separated depending on the three plant types.

5.1.2 Substance flow analysis

The installations are processing in total 223,793 (±5%) dry tonnes of feedstock with 85,531 (±16.4%) tonnes carbon, 3,230 (±6.6%) tonnes potassium K_2O, 4,023 (±5.3%) tonnes nitrogen N and 1,516 (±6.3%) tonnes phosphorous P_2O_5. As green waste was the most dominant incoming stream, a significant amount of nutrients came from it (almost 70% for K_2O and around 50% for the N and P_2O_5). Regarding the input of agricultural residues, it represented 16% for P_2O_5, 12% for K_2O, and 10% for N. This is a non-negligible contribution compared to the fresh mass input (9%, chapter 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 (and Bowman et al. (Submitted)). In 2018, around 340 tonnes of plastics came into the system, mainly through municipal green waste, and 70 tonnes ended up in the soil via the digestates and composts. The rest was sent to the municipal incinerator. The uncertainties around plastic quantities are quite high, at 19%.

Table 1: Transfer coefficients in the final output of industrial biogas plants from initial input expressed in percent of input toward the four categories.

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%

5.1.3 Energy Flows

The total primary energy contained in the incoming biomass was estimated to be 3,223 TJ (±4.9%) for 2018. 59% of this primary energy was coming from green wastes from municipalities and landscape maintenance, 34% 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 in a facility to produce biomethane. For the 32 biogas plants, total electricity production accounted for 12% of the energy contained in the overall input feedstock, while about 6% could be sold in the form of heat. In addition, 11% 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 (1,242 vs. 1,313 TJ).

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. Biogas was converted into secondary energy carriers in the form of electricity, heat, and/or biomethane (Figure 4). The secondary energy carriers after biogas processing are shown in Appendix.

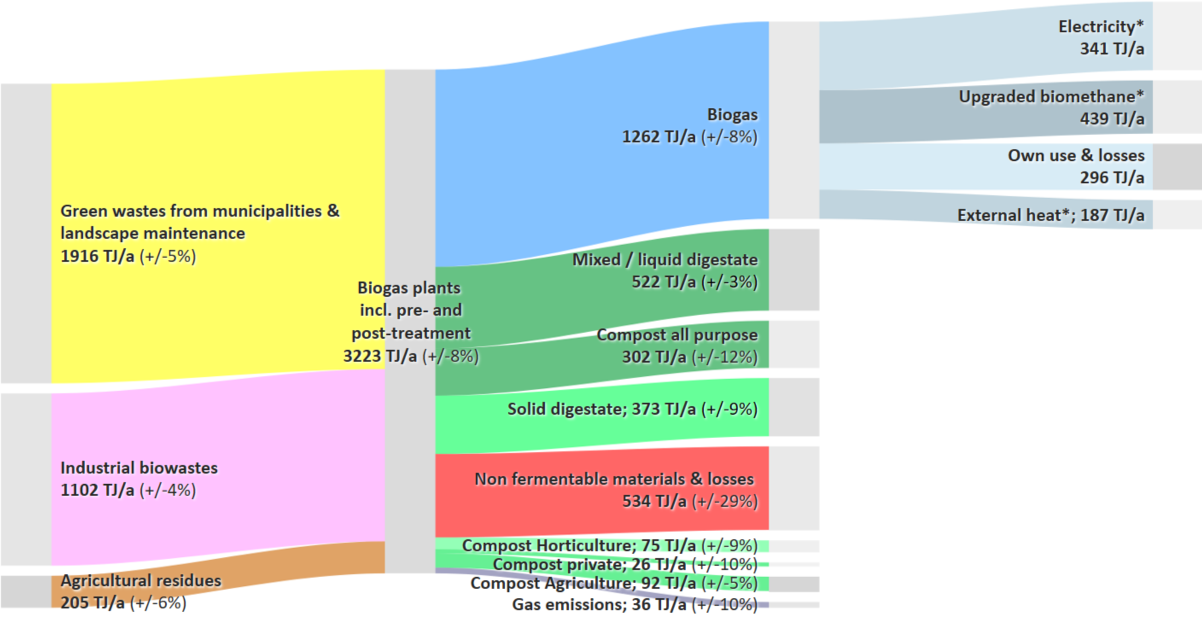


Figure 4: Sankey diagram of major energy flows through industrial biogas plants in terajoule (TJ) per year. Secondary energy carriers (*) as reported by the biogas plants.

5.1.4 Sensitivity Analysis

The sensitivity analysis results are shown in the scientific publication (Bowman et al., Submitted) for the different parameter categories chosen. For example, an increase by 5% of green waste dry mass leads to an increase of N, P_2O_5, K_2O, and C quantities by 7-8%, where the uncertainty of the STAN model is only around 2-3%. A decrease of 5% of green waste dry mass leads to a reduction 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 a +10% in the input leads to almost +10% in the flows, a reduction of -10% leads to a reduction of only about 6% of the flows.

However, with regards to the dry matter content, there was a greater decrease in quantities of N, P_2O_5, K_2O, and C when a low dry matter content was chosen for the green waste compared to the slight increase when a high dry matter content was applied.

5.1.5 Scenarios

In addition to the sensitivity analysis, four different scenarios were examined (Figure 5). Regarding biomass quantities, The No Manure scenario leads to -8% tonnes fresh mass, whereas the Manure 20 scenario to +12% tonnes fresh mass. 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%). The effect can also be found when increasing manure quantities (Manure 20) with up to 9% increase for carbon, dry mass, and primary energy but up to 10-17% 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.

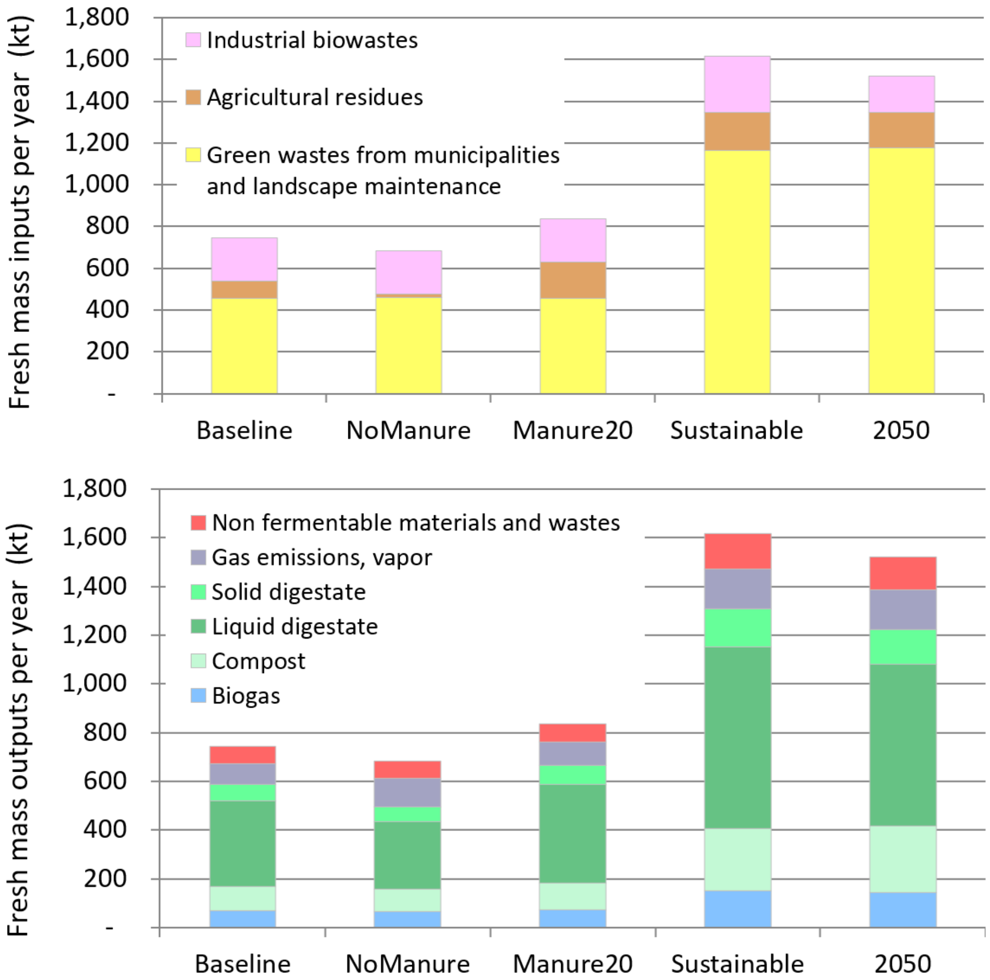


Figure 5: Fresh biomass inputs and outputs (tonnes and composition) for the Baseline compared to the different scenarios.

5.1.6 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 around 343 TJ of energy and 26,000 tonnes of CO_2-eq for about 7,708 tonnes of nutrients (Table 2). These values go up to 704 TJ of energy and 54,000 tonnes of CO_2-eq for about 16,000 tonnes dry tonnes of nutrients (N, P_2O_5, K_2O) in 2050.

Table 2: Fertilizer substitution potential regarding GHG emission (t CO_2-eq) and energy (terajoule TJ) avoided compared to the production of mineral fertilizer for the industrial biogas plants.

	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	4,023	3,606	25,785	23,112	314	282
	P_2O_5	1,516	1,275	1,788	1,504	26	22
	K_2O	3,230	2,827	2,141	1,874	44	39
	Total	**8,769**	**7,708**	**29,715**	**26,491**	**385**	**343**
Sustainable	N	8,233	7,300	52,776	46,795	644	571
	P_2O_5	3,180	2,610	3,752	3,079,812	55	45
	K_2O	7,316	6,359	4,850	4,216	100	87
	Total	**18,729**	**16,270**	**61,379**	**54,091**	**800**	**704**

5.2 Agricultural biogas plants

5.2.1 Material flows

Figure 6 shows the results of the MFA representing the situation of agricultural biogas plants in Switzerland for 2018, illustrated as a Sankey diagram (Baseline). According to the model, around 1.2 (±6%) megatonnes (Mt) of FM were brought to agricultural biogas plants in Switzerland in 2018. The largest contributing biomass stream came from agricultural residues (83%), mainly from animal manure representing 79% of the total incoming material, followed by industrial biowastes 14%, and only 3% from green wastes from municipalities and landscape maintenance. This resulted in 1.09 (±5%) Mt of fertilizers, or 90% of the input (see Figure 6). The non-fermentable materials and losses (14,700 (+/-9%) t) was about 1% of the total. The gas and vapor emissions represent 2% of the outputs. Examples of the STAN models used are given in the Appendix.

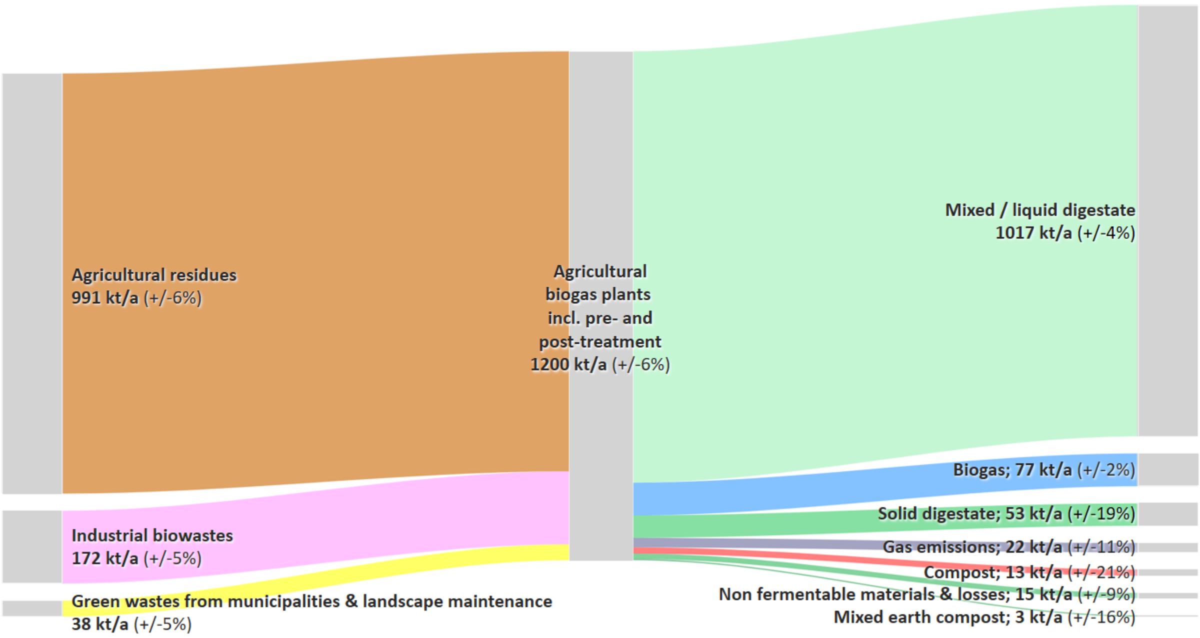


Figure 6: Sankey diagram of major fresh mass flows through agricultural biogas plants in kilo tonnes per year (kt / a).

5.2.2 Substance flow analysis

The 111 installations process in total 164,034 (±7%) dry tonnes of feedstock. In total, the input material contained 78,880 (±5%) tonnes of carbon, 5,318 (±8%) tonnes t nitrogen N, 2,783 (±10%) tonnes phosphorous P_2O_5, and 5,485 (±9%) tonnes potassium K_2O. As agricultural residues were the most dominant incoming stream, a crucial amount of nutrients came from it (76% for K_2O, 78% for P_2O_5, and 67% for N). Regarding the input of industrial biowastes, it represented about 12% for K_2O, 14% P_2O5 and 25% for N).

The SFA results showed high transfer and recovery of nutrients. Indeed, transfer coefficients of nutrients to biofertilizers were 83%, 87%, and 83% for N, P_2O_5, and K_2O, respectively (Table 3, see also scientific publication (Burg et al., Submitted)). Moreover, 48% of the carbon is transferred to the biogas and 42% to the fertilizers. Furthermore, approximately 170 (+/-6%) tonnes of plastics came into the system in 2018. This amount is expected to be partly reduced through sorting within the installations.

Table 3: Transfer coefficients in the final output of agricultural biogas plants from initial input expressed in percent of input toward the four categories (tonne).

	Total input	Biogas	Emissions	Fertilizer	Non fermentable materials & residues
Fresh mass (t)	1,200,011	77,172	22,239	1,085,889	14,712
Transfer coefficient		6.4%	1.9%	90.5%	1.2%
Carbon (t)	78,880	38,197	4,019	33,274	3,390
Transfer coefficient		48.4%	5.1%	42.2%	4.3%
Dry Mass (t)	164,034	75,500	7,198	74,529	6,807
Transfer coefficient		46.0%	4.4%	45.4%	4.1%
Energy (GJ)	2,819,623	1,317,599	127,746	1'247,872	126,406
Transfer coefficient		46.7%	4.5%	44.3%	4.5%
Potassium (t)	5'485	0	0	4,547	938
Transfer coefficient		0%	0%	82.9%	17.1%

Nitrogen (t)	5,318	750	85	4,431	52
Transfer coefficient		14.1%	1.6%	83.3%	1.0%
Phosphorus (t)	2,783	0	0	2,417	366
Transfer coefficient		0 %	0%	86.8%	13.2%

5.2.3 Energy Flows

In the incoming biomass, the total primary energy (PE) contained was 2,819 TJ (±8%) in 2018 (Figure 7). More than 80% of the biomass comes from agriculture, but only about 51% of this PE was gained from it. 41% of the PE comes from industrial wastes and 8% from green wastes. Regarding the outputs, the primary energy was mainly distributed between biogas (47%) and digestates and composts (44%), representing untapped energy remaining in the output biomass.

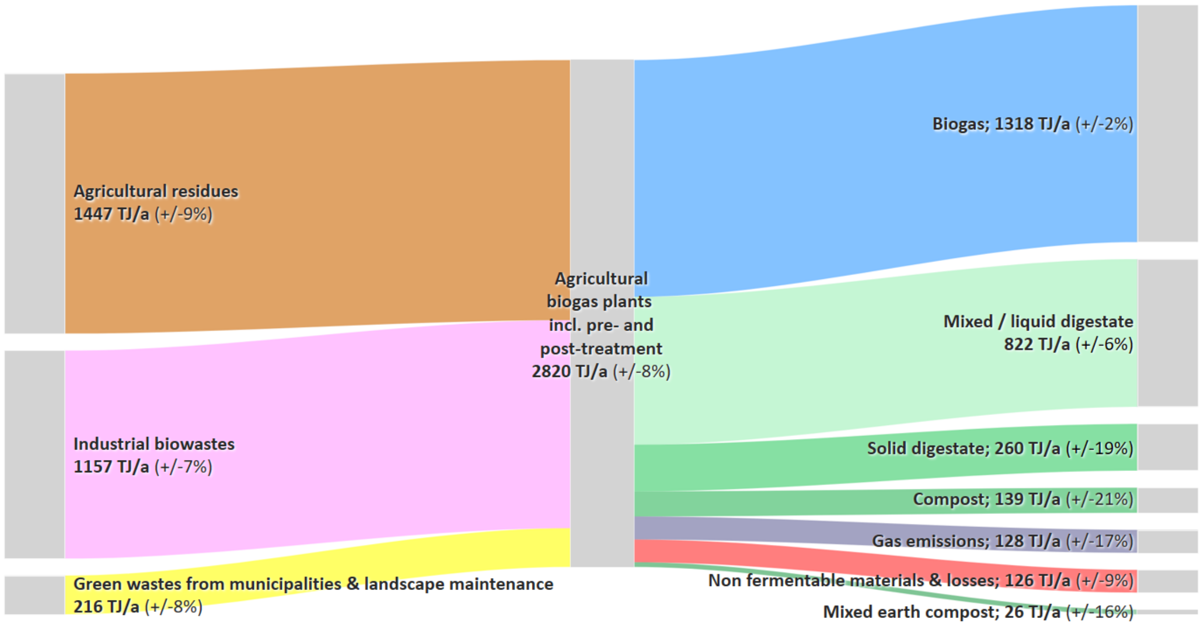


Figure 7: Sankey diagram of major energy flows through agricultural biogas plants in terajoule (TJ) per year.

From the data of the installations, an estimated 69x106 m^3 biogas was produced, leading to approximately 137,800 MWh of electricity and 59,700 MWh of heat sold in 2018. A small part of the biogas was converted into biomethane and injected into the grid. Because the installations sell these energy products and have to report them to authorities, a high level of accuracy is expected, which is then reduced through the up-scaling.

5.2.4 Sensitivity Analysis

The sensitivity analysis results are shown in (Burg et al., Submitted) for the different parameter categories chosen. The changes in fresh biomass were less than the 5% uncertainty of the model. However, an increase or decrease of 3% of the DM of agricultural residues leads to an increase or decrease twice as large for DM and C in the model. Increasing or decreasing by 5% the quantity of nutrients N, P_2O_5, and K_2O from liquid manure had an effect of less than 5% on the amounts of the final nutrients, which was smaller than the variation of the system (between 8-10% uncertainty).

5.2.5 Mineral fertilizers substitution

Today, co-substrates substitute 3,716 tonnes of fertilizers (1,769 N, 623 P_2O_5, 1,325 K_2O), equivalent to saving almost 13,000 t CO_2-eq from mineral fertilizers (Table 4). The highest values for the Sustainable Manure Potential scenario represent more than 15,000 tonnes of fertilizers and around 40,000 t CO_2-eq emission saving. One important point to consider is that, depending on the literature, the nitrogen availability of manure can be increased between 5 and 20% after digestion. This suggests that, in addition to the mineral substitution calculated here for co-substrate only, 5 to 20 % should be added on the part of the digestates, which could add as a maximum the equivalent of 354 tonnes (Baseline) up to 1,026 tonnes (Sustainable Manure Potential) of nitrogen available to the plants coming from non-agricultural inputs.

Table 4: Substitution potential from N, P_2O_5, K_2O for the agricultural Baseline situation.

Nutrients	**Dry mass (t)**		**GHG savings (t CO_2-eq)**		**Energy savings (GJ)**	
	Total	**Without agricultural inputs**	**Total**	**Without agricultural inputs**	**Total**	**Without agricultural inputs**
N	5,318	1,769	34,086	11,336	416,005	138,360
P_2O_5,	2,783	623	3,284	734	48,707	10,896
K_2O	5,485	1,325	3,636	878	75,694	18,279
Total	**13,586**	**3716**	**41,007**	**12,949**	**540,407**	**167,536**

5.2.6 Scenarios

In addition to the sensitivity analysis, different scenarios were examined, four of which presented here in comparison to the Baseline (more in the scientific publication).

Material flow

With continued measures to support the diffusion of agricultural biogas, an expansion of +320% is envisioned by 2050, i.e., the operation of approximately 450 biogas plants processing 5.1 (±6%) Mt of FM per year (Continued Support Scenario). Around three-quarters of this FM comes from manure and only 2% from agricultural by-products from crop cultivation. Industrial bio-wastes and green wastes from municipalities and landscape maintenance account for 17% of the FM but 52% of the primary energy. The shares of inputs by origin remained constant compared to the Baseline (Figure 8).

If the entire estimated Sustainable Manure Potential is exploited in Switzerland, 23.53 (±4%) Mt/a of FM can be used, which corresponds to an increase by a factor of 19.6 compared to today. The increase is strongest for agriculture residues, mostly manure, from 83% (Baseline) to 98% (Figure 8). The increase is much smaller for the green wastes and industrial bio-wastes, leading their relative share to decrease from 3% and 15% (Baseline) to 1% each.

A change in the food system towards more sustainability and the associated reduced livestock farming and food waste would decrease the estimated sustainable biomass potential in Switzerland. This also changes the composition of the substrates.

In the Technical Change Separation scenario, slurry represents 16.1 (±4%) of the total 21.9 (±4%) Mt/FM fed into the press screw. All the inputs with a DM content greater than 10% are fed directly into the solid fermenter without going through the press screw. After separation, the liquid fraction consists of about 14.2 (±3%) Mt/a of thin slurry with a DM content of about 1%, and the solids weigh about 1.8 (±4%) Mt/a with a DM content of about 12%. The solids are subsequently fed into the regional digester along with the other biomass types. The inputs to the liquid and solid digesters are thus about 57% and 43% of the total fresh biomass inputs.

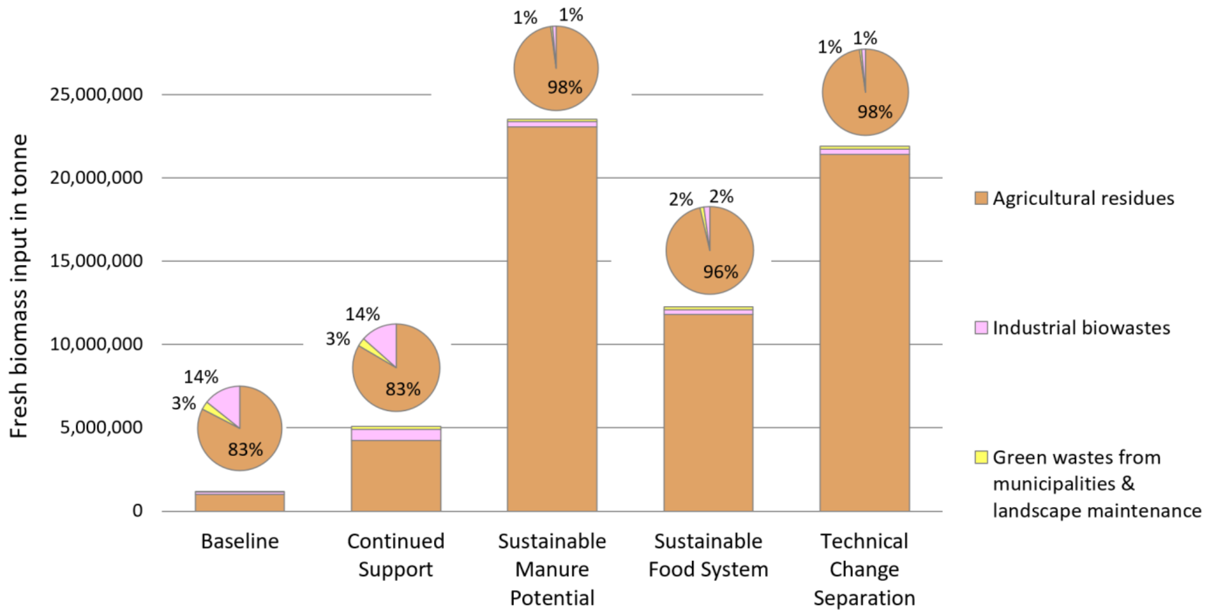


Figure 8: Agricultural biogas plants - Fresh biomass inputs (tonnes and composition) for the Baseline compared to the different scenarios.

Substance flows

Figure 9 shows an overview of the nutrient inputs of the Baseline and the different scenarios. The composition of the flows is comparable for the Baseline, and the scenario Continued Support. The nutrients N, P_2O_5, and K_2O remain predominantly in the digestate (83, 87, and 83%, respectively). As a result, in the Continued Support scenario the total of 4.6 (±5%) Mt fertilizers contains 18,664 (±6%) t/a N, 10,340 (±7%) t/a P_2O_5 and 19,614 (±6%) t/a K_2O. Carbon accounts for 331,933 (±20%) t/a, representing 7% of the processed FM. 48% of the carbon goes into biogas (160,842 (±2%) t/a) in the form of CH_4 and CO_2, and almost 43% (141,493 (±9%) t/a) goes into the fermentation residues, where carbon can be directly returned to agriculture.

In the Sustainable Manure Potential scenario and those based on it (Diet sustainable and Tech sustainable), the share of the agricultural inputs is much higher for all substances, e.g., carbon comes around 95% from agricultural residues compared to about 65% in the Baseline and Continued Support scenario. If all agricultural residues are added together, they account for more than 90% of the N, P_2O_5, and K_2O inputs. If the entire sustainable manure potential in Switzerland is used, there are 74,064 (±7%) t/a of N, 50,475 (±7%) t/a of P_2O_5 and 96,726 (±9%) t/a of K_2O in the digestate annually.

Regarding the scenario Sustainable Food System, it leads to 42,747 (±6%) t/a N, 24,123 (±6%) t/a P_2O_5 and 50,436 (±6%) t/a K_2O in the digestate. Due to the scenario's assumptions, the quantity of nutrients in the system decline, with a reduction of at least a third compared to the Sustainable Manure Potential.

In the Technical Change Separation scenario, the proportion of nutrients in the separated liquid fraction is higher due to the better solubility of nutrients compared to carbon (Baier, 2021). Nevertheless, about two-thirds of the N and P_2O_5 and half of the K_2O still enter the regional solid digester.

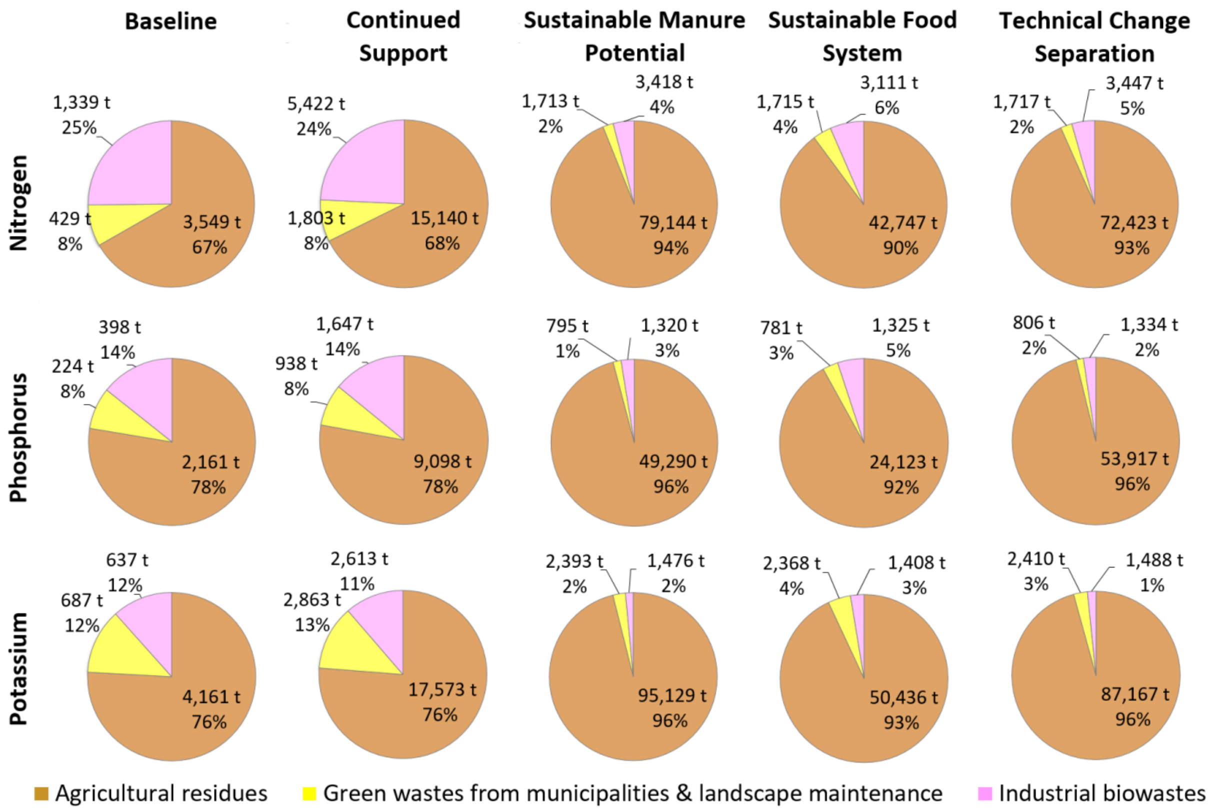


Figure 9: Nutrients (nitrogen N, phosphorus P_2O_5, potassium K_2O) input in tonne and % per scenario.

Energy flows

Figure 10 shows the primary energy content per output for the different scenarios. In the Continued Support scenario, the total primary energy content of the inputs reaches 11.6 (±8%) PJ/a, and with this substrate composition, about 1 GJ of biogas is produced per tonne of FM. Thus, 47% of the primary energy goes into biogas (5.4 (±5%) PJ/a).

If using the full Sustainable potential, biogas production increases from 1.3 (±2%) PJ/a today to 15.5 (±8%) PJ/a (factor of 11.8). Thus, the increase in biogas production is lower than for FM, which increases by a factor of 19.6, and also slightly lower than the increase in primary energy (factor of 12.9).

For the Sustainable Food scenario, there is a decrease in carbon and primary energy by 68% compared to the Sustainable Scenario. Due to this decrease, the biogas' potential is reduced to 10.8 (±7%) PJ/a.

In the Technical Change Separation scenario, due to the higher DM content, the percentage of carbon processed in the solid digesters (85%) is significantly higher, and thus, the biogas yield (91%) compared to the liquid digester.

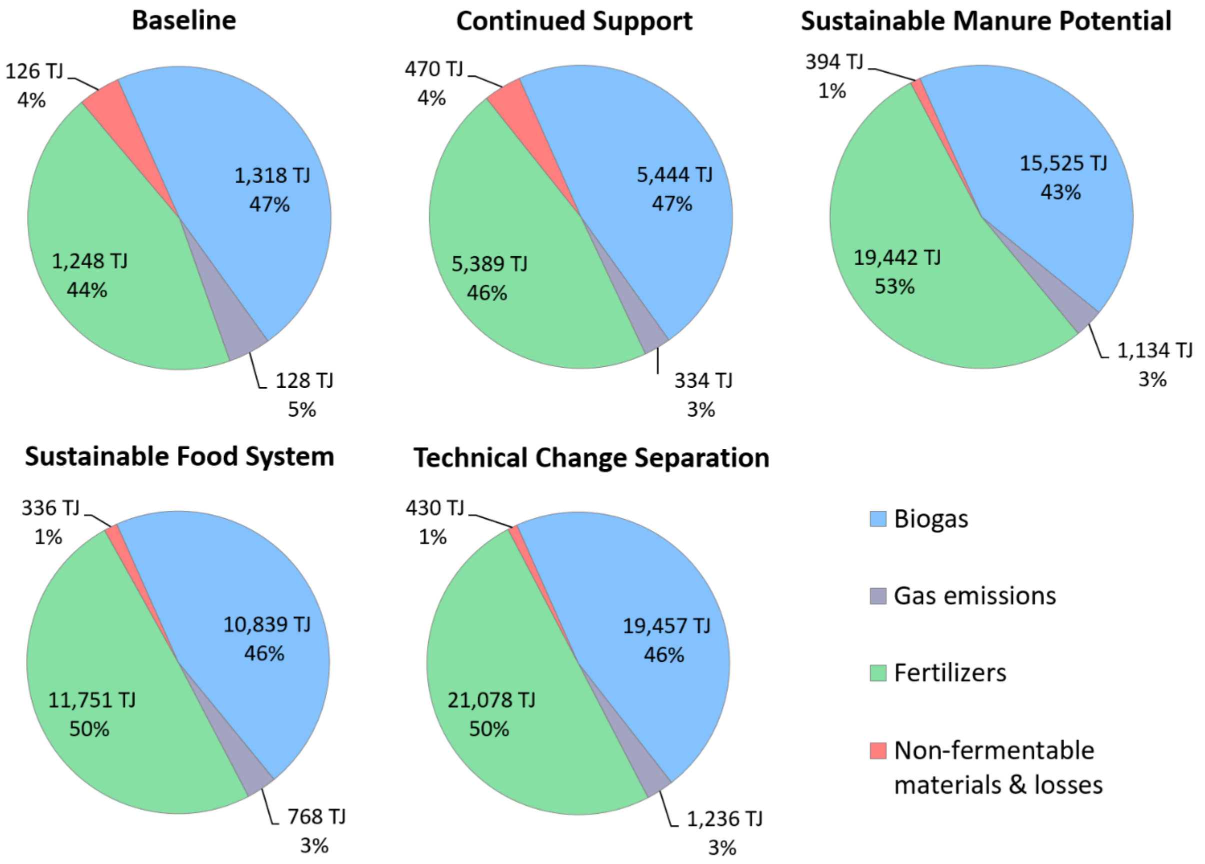


Figure 10: Primary energy in terajoule (TJ) per output for the different scenarios.

5.3 Overview results industrial and agricultural biogas

Overall, industrial and agricultural biogas plants in Switzerland process about 2,000 kt of fresh mass per year (Figure 11), leading to the production of 1,600 kt fertilizers and 2,600 TJ biogas (Figure 13).

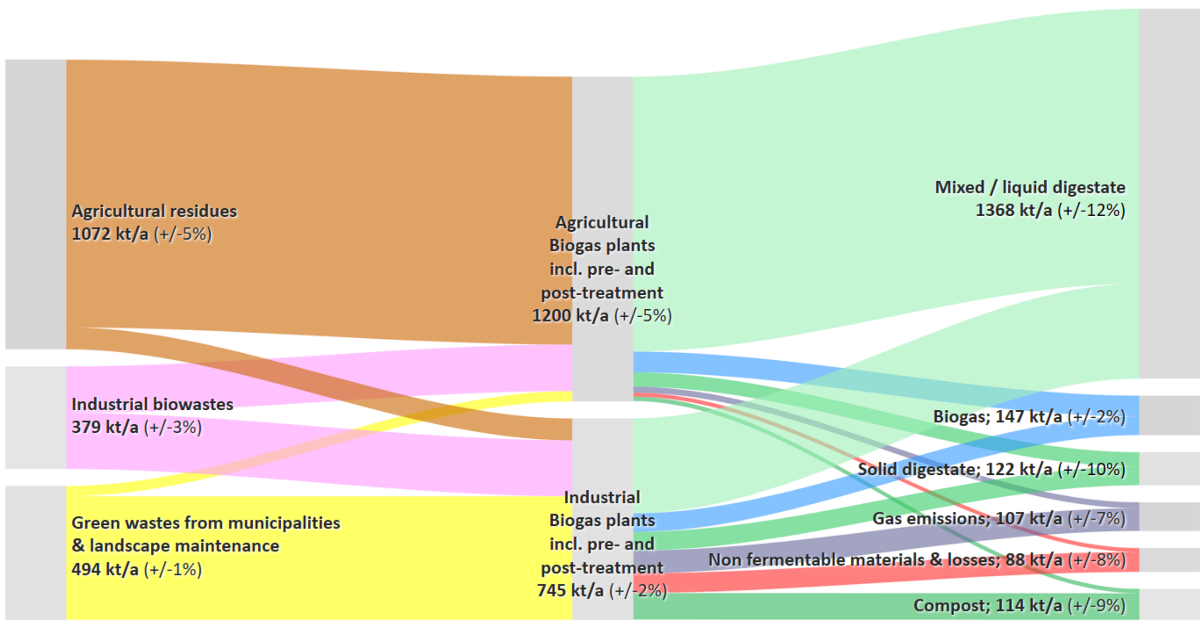


Figure 11: Sankey diagram of major flows through agricultural and industrial biogas plants in fresh mass kilotonne per year (kt/a).

Whereas more fresh mass is treated in the agricultural biogas plants, the industrial biogas plants process more dry mass due to the low dry mass contained in manure, representing about half the inputs of the agricultural biogas plants. Biogas production is correlated more strongly to dry mass than fresh mass (Figure 12).

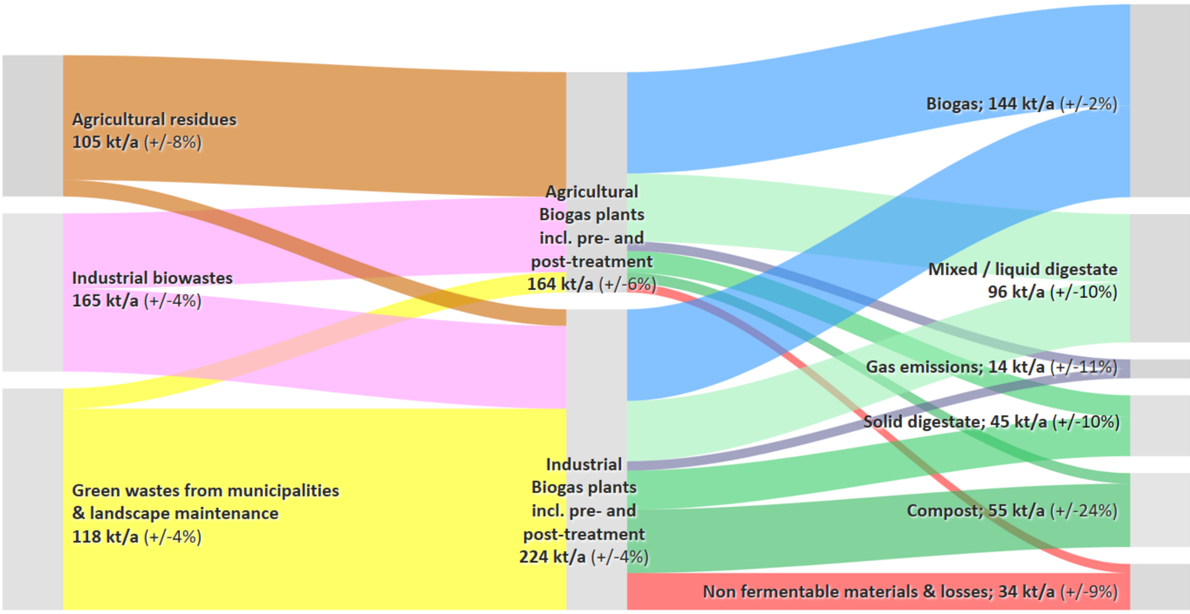


Figure 12: Sankey diagram of major flows through agricultural and industrial biogas plants in dry mass kilotonne per year (kt/a).

The quality of fertilizers leaving both installation types is variable, and the non-fermentable materials represent a higher proportion in the industrial biogas plants. These can take lower quality inputs that they will pass on as they receive a gate fee. Also, part of their non-fermentable material is composed of wood which can be thermally processed in combustion plants and contains a fair content of primary energy (Figure 13).

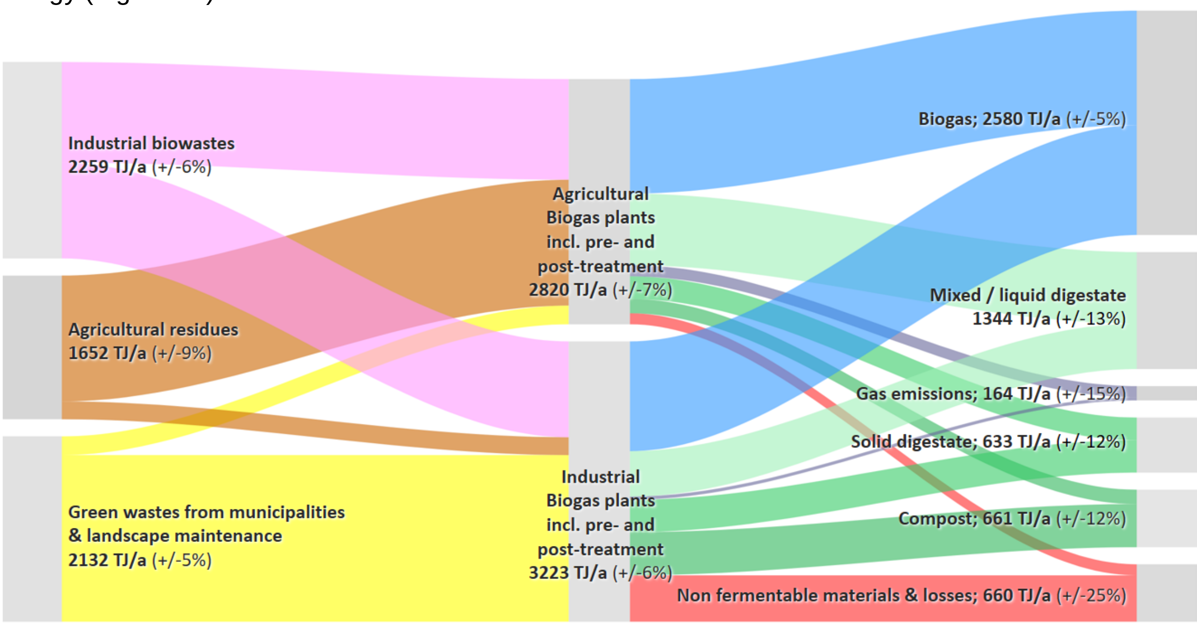


Figure 13: Sankey diagram of major flows through agricultural and industrial biogas plants in primary energy terajoule per year (TJ/a).

The substitution potential of the fertilizers produced is very high, even when the inputs from agricultural residues are excluded (Table 5). Indeed, more than 11,000 tonnes of nutrients were added this way to agriculture in 2018, and almost 30,000 tonnes could be replaced in the future.

Table 5: Overview of industrial and agricultural biogas plants Baseline and Scenario Sustainable regarding nutrients. The amount of N, P_2O_5, and K_2O in the processed feedstock is given. The GHG and energy savings indicate the amounts necessary to produce the same amount as mineral fertilizers. As it is usual practice to bring/let all the agricultural residues on the fields, a distinction is made for the net savings.

		Mass (dry tonnes)		**GHG savings (t CO_2-eq)**		**Energy savings (TJ)**	
	Nutrients	**Total**	**Without agricultural inputs**	**Total**	**Without agricultural inputs**	**Total**	**Without agricultural inputs**
Baseline	N	9,340	5,374	59,872	34,449	730	420
	P_2O_5	4,299	1,897	5,073	2,238	75	33
	K_2O	8,715	4,152	5,778	2,752	120	57
	Total	**22,355**	**11,424**	**70,723**	**39,441**	**926**	**510**
Scenario Sustainable Manure Potential	N	92,508	12,432	592,976	79,685	7,236,	972
	P_2O_5	54,585	4,724	64,409	5,574	955	82
	K_2O	106,314	10,228	70,486	6,781	1,467,	141
	Total	**253,407**	**27,384**	**727,872**	**92,042**	**9,659,**	**1,196,**

5.4 Discussion of flows analysis

Energy generation and nutrient recovery

The results of the flow assessments allow us to gain insights into the actual agricultural and industrial biogas system and its potential role in the transition to a circular economy. The total primary energy contained in the incoming biomass was estimated to be 6,043 TJ (±8%) for the year 2018, with 2'820 (±7.7%) from the industrial and 3'223 (±8%) from the agricultural plants. A large proportion of the energy chemically bound in the input substrates will not be converted into biogas and is retained in the solid and liquid residues.

While the total primary energy contained in the incoming biomass was estimated to be 6,043 TJ (±8%) for the year 2018, about 40% of the input energy was converted into biogas (2,600 TJ (±5%)) and a similar amount remained in the digestates and composts. This biogas amount is similar TJ (±5%)) and a similar amount remained in the digestates and composts. This biogas amount is similar to the values from the official statistics, which recorded about 1,400 TJ gross biogas production for agricultural and 1,300 TJ for industrial biogas plants in 2018 (BFE, 2019a). The different unused energy pathways from the system can be seen as the starting points for process optimization, with measures undertaken to increase the biogas yield of the substrates (e.g. through pretreatment processes), avoid carbon and methane losses (e.g. long storage, leakages), decrease the energy demand of the AD facility, minimize conversion losses and maximize the use of thermal energy (e.g. by using a heat exchanger or heat pump).

The calculated emissions from the biogas plants (including pre- and post-treatment) were a bit higher than some new studies. For example, two measures of an overall loss of 1.5% and 2.7% methane out of the whole methane production for an agricultural biogas plant, including storage, were reported (Scharfy and Anspach, 2021), while here 5% carbon losses were obtained with the STAN model compared to the overall inputs quantities and 11% compared to the produced biogas quantities. It must be noted that measures regarding digestion can be much lower (Scharfy and Anspach, 2021) and that a high variation has been found in different biogas plants (Calbry-Muzyka et al., 2022). The emissions from the post-treatment itself can also be highly variable (Dinkel et al., 2012). Moreover, water inputs and losses throughout the process are also little known and highly dependent on feedstocks and pre- and post-treatments (Baier, 2022). This strongly indicates that to quantify all the explicit material and substance flows, regular, comprehensive measurements at many sites are needed to quantify these emissions. However, our focus was on the material aspects and fertilizer production, in addition to the biogas generation.

Looking at the nutrient flows, a high transfer (>75%) was found from input material into biofertilizer, both in industrial and agricultural plants. This value is likely to be higher as the approximation made here to use averages has reduced our precision, whereas, from the literature for industrial plants, precise measures made for individual plants gave even higher values (Schievano et al., 2011; Zabaleta and Rodic, 2015). Indeed, Schievano et al. (2011) reported a 91-94% transfer of phosphorus and 94-98% transfer of potassium, which is 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 specific biogas plants. In our study, a significant share of the phosphorus and potassium goes into the non-fermentable fraction (mostly wood). The nitrogen is harder to compare as they had measured organic nitrogen (transfer coefficient 34-75%) and mineral $N\text{-}NH_{4+}$ (transfer coefficient 121-326%). (Zabaleta and Rodic, 2015) found it would only be possible to recover 49% nitrogen and 83% phosphorus. In any case, nutrient recovery from biowastes could allow biofertilizers to replace part of the mineral fertilizers to reduce GHG emissions, energy consumption, and 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 in terms of feedstock used and biofertilizers produced. Nutrients and carbon are already well recycled in agriculture as, even without AD, raw manure is spread onto the fields. However, the nutrients and carbon added by the co-substrates are far from negligible. The substitution benefits are both impacting resource preservation and energy savings, thus also having a positive effect on climate change mitigation. Moreover, the carbon staying in the digestate ensures a high humus value for the fertilizers leading to improved soil quality on agricultural land (European Biogas Association, 2015; Schievano et al., 2009).

Method limitations, uncertainties and sensitivity analysis

One limitation of the analysis is that information was missing. Indeed specific biomass waste characteristics for Switzerland are highly variable. The literature and databases were based as much as possible on Swiss values, but some were only found for other European countries. However, these characteristics can vary strongly depending on the local consumer behavior and management practices. Moreover, the digestate and compost characteristics varied widely even at the same biogas plant throughout the year. The model kept the uncertainty fairly low at the general input and output level. 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 significant change in results indicates the importance of characterization of all input specifications.

Opportunities and future perspectives

The scenario Sustainable shows what happens when more bio-wastes and residues are treated through AD rather than burnt in incinerators or for manure directly brought to the fields without digestion, as is often the case today: the quantity of biogas produced and the amount of nutrients more than double. As part of the additional biomass, inputs do not come from agriculture, and they represent a new source of organic fertilizer not used today (the ashes of the municipal incinerators are landfilled). Hence, this additional amount of produced fertilizer can substitute net imports of fertilizers. By 2050, this could save about 1,200 TJ energy (in addition to a produced biogas amount of 18,000 TJ), replace 27,384 dry tonnes of mineral fertilizers and avoid the emissions of 92,000 tonnes of CO_2-eq from mineral fertilizer production. This is to compare with the 119,330 TJ gas import per year in Switzerland and the 210,000 tonnes of fertilizers sold (see section 6 and (Scharfy and Victor, 2022). Although the numbers seem low compared to the needs, this has an essential role in closing the material cycles, as these are domestic resources that do not depend on the world economy or politics.

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).

Although a significant increase in biogas production is already envisaged in the Continued Support scenario, only one-third of the sustainable potential is used. Potential restrictions on the use of the more limited co-substrates, and possible changes in the food system, e.g., leading to a strong diminution of available manure, must also be considered. However, the margin compared to the current situation is so large that there is, in any case, a great deployment potential for agricultural AD in Switzerland. Technical advancements may also play an important role in future development (Burg et al., 2021a). For example, the Technical Change Separation scenario could imply a higher production of biogas with the same amount of processed biomass through more efficient AD digestion in separated liquid and solid systems. Other technological changes that could increase the efficiency and the economic viability of energy from manure can also be envisaged (Burg et al., 2021a).

6 Monetary aspects

6.1 The value of digestates

Digestate, solid separated digestate, and liquid separated digestate are the three common by-products from agricultural biogas plants. They can be used in many different ways in agriculture. In arable farming and grassland, it is thenitrogen availability and organic matter input whichare particularly valued. Agricultural digestate products also have the potential to replace mineral fertilizers, as other organic residues (co-substrates) are co-digested in addition to animal manure, thereby adding valuable nutrients and returning them to the agricultural system. Reducing the used amounts of mineral fertilizers is desirable for many reasons (e.g., resource conservation and soil fertility), also with regards to circular economy. yet, the agricultural digestate products have difficulties in being monetarily valorized.

The mineral fertilizer replacement capacity could be a good argument for a better added-value of digestate products. Indeed, the energy required to produce one tonne of mineral nitrogen is about 600 kWh_{el} (Wilken, 2020). The current handling, shaped by the agricultural and market-specific circumstances, mostly does not explicitly attribute a price to the digestate products. The reasons are, for example, the lack of willingness to pay for animal manure generally, a surplus problem in regions with high animal density, or competition with industrial digestate. The cooperation between animal manure suppliers and biogas plant operators is mostly free of charge. The supplying farmers bring their animal manure to the biogas plant, and the biogas plant operator returns the digestate. This is fair in terms of effort: the biogas plant operator earns money with the energy product biogas, and the supplying farmer can outsource his animal manure and receives back a digestate product with improved plant-growing properties (Ökostrom, 2020).

Nevertheless, it would be desirable for the digestate products to achieve a monetary value corresponding to their fertilizer value. This would allow agricultural biogas plant operators to cushion the high operating costs and improve their value partly. The plant operators could develop another economic income source by selling digestates as fertilizer.

Assuming that the animal manure produced is applied on farms anyway - whether digested or undigested - the digestate of animal manure alone cannot replace mineral fertilizer. On the other hand, considering that nitrogen availability increases with digestion (Jarosch et al., 2018) and that additional macro- and micronutrients are introduced with the co-substrates compared to non-fermented animal manure, digestate products can partially replace mineral nitrogen fertilizer.

Several reasons justify an improved economic valorization of digestate products:

1. The digestate products from agricultural biogas plants offer advantages compared to conventional animal manure of having increased nitrogen availabilities and coming with laboratory-accurate nutrient analyses. The supplying farmer can plan and meet the nutrient requirements of his crops more precisely through the nutrient analyses than with the unfermented animal manure that has not been analyzed for nutrient content.

2. Anaerobic digestion is a time-intensive process - on average, it takes 95 days in agricultural biogas plants (referring to the gas-tight system, also including gas-tight digestate storage) (Stürmer et al., 2021). Due to this retention time, a biogas plant has large digestate capacities. Thus, it can enable animal manure suppliers to outsource storage space and therefore save storage costs. The valorization of digestates could thus be partially marketed by reference to storage time and costs.

3. The replacement of mineral fertilizers with digestate products reduces agricultural nutrient surpluses, increasing with the expansion of anaerobic digestion of animal manure. If the agricultural digestate products had an adequate economic value, agricultural biogas production could also gain additional attractiveness.

4. Digestate products are reliable in availability and stable in price, as they are largely independent of external energy sources and are produced climate-friendly. Moreover, as domestic products, they are

part of the local circular economy. Regarding climate protection and the circular economy, digestate products are preferable to importing mineral fertilizers.

The question of how the goal of improved valorization and value creation can be achieved, is elaborated in the following chapters.

6.2 Questions in the "Monetization" work package

Within the project, the Monetization work package investigated how the economic marketing opportunities for agricultural digestate products can be improved. The aim was to answer the following two key questions:

- Which theoretical economic value can be attributed to agricultural biogas digestates based on their nutrient content and properties?

- Which value creation opportunities are likely to increase the value of agricultural digestate products?

The procedure and results of the investigations are given below.

6.3 Analyses and results

The following data were collected and analyzed to answer the questions:

1. Mineral fertilizer uses and mineral fertilizer prices in Switzerland 2018-2020
2. Evaluation of the nutrient content of digestate products 2018-2021
3. Calculation of theoretical economic digestate prices based on nutrient values
4. Online survey of agricultural biogas plant operators on the value of their digestate products
5. Deriving ideas for adding value to agricultural digestate products
6. Taking into account current political and market price developments

6.3.1 Market analysis of mineral fertilizers in Switzerland

The term mineral fertilizer can be understood in different ways. The term used here refers to mineral or chemical fertilizers, sometimes also called artificial fertilizers or commercial fertilizers. The definition used here is based on the definition from the Fertilizer Law Guide (“Wegleitung Düngerrecht”): "Products whose nutrients have been obtained by extraction or by industrial, physical, and/or chemical processes or are contained in the form of minerals, as well as calcium cyanamide, cyanamide, urea and its condensates and addition compounds." (BLW, 2016).

To obtain data and information on the consumption quantities and prices of mineral fertilizers in the Swiss agriculture, inquiries were made to Landor and Agricura. Agricura is a cooperative which implements compulsory nitrogen storage on behalf of the Confederation (Federal Office for National Economic Supply FONES). Landor belongs to the fenaco cooperative and is the largest fertilizer trader in Switzerland. Further work was done with the information obtained and with literature values. The information from Agridea's business data collection, the REFLEX catalog (Agridea, 2020) was used for mineral fertilizer prices.

In its 2019/2020 activity report, Agricura reports that N fertilizer sales have decreased by 7.8%, P fertilizer sales by 2%, and K fertilizer sales by 11.6% in the last five years. The top ten mineral fertilizers for Switzerland are listed in **Error! Reference source not found.**, according to Agricura's 2019/2020 consumption statistics. The prices for the mineral fertilizers were taken from the REFLEX catalog 2020 (Agridea, 2020).

Table 6: Application quantities of Switzerland's ten most important mineral fertilizer (groups) in 2019-2020 and the nutrient quantities of N, P, K contained. The prices refer to the drop shipment/third-party business and are taken from the REFLEX 2020 catalog.

	Description	Commercial designation	Quantity (t)	Quantity N (t)	Quantity P_2O_5 (t)	Quantity K_2O (t)	Price (CHF/100 kg)
1	Ammonium nitrate with calcium carbonate	Calcium ammonium nitrate	69'934	18'256	0	0	32.20-33.80
2	Compound fertilizer	Nitroplus, Nitrophos Rapide , Suplesan etc.	40'373	5'024	3'306	6'936	52.30
3	Urea	Urea	16'737	7'581	0	0	49.70
4	Other nitrogen fertilizers	Various	14'870	3'583	0	0	
5	P and K fertilizer	Various	12'552	0	1'704	3'108	51-63
6	Ammonium sulphate nitrate	ASS	10'682	2'758	0	0	43.6-45.1
7	Potassium chloride	Kali 60%	7'328	0	0	4'234	51.80
8	Ammonium nitrate	Entec 26%	6'216	1'679	0	0	41.50
9	Nitrate and Phosphate	Various	5'894	1'138	786	0	
10	Ammonium sulphate	Ammonium sulphate	5'189	1'049	0	0	42.0
Sum of the ten most common mineral fertilizer (groups)			189'775	41'068	5'796	14'278	
Total of all mineral fertilizers used			210'099	42'974	9'519	16'469	

A total of 210,099 tonnes of mineral fertilizers were applied in Switzerland in 2019-2020 (Agricura Platform, Activity Report 2019/2020). Concerning the nutrients contained in the mineral fertilizers, in terms of quantity, mainly nitrogen was applied, with a total of nearly 43,000 tonnes. The application quantities of potassium (K_2O) amounted to a rounded sum of 16,500 tonnes, and the phosphorus quantity reached a rounded sum of 9,500 tonnes. The prices for the ten most important mineral fertilizers ranged between CHF 30 and 50 per 100 kilograms. There are seasonal fluctuations in the prices of mineral fertilizers and even daily prices for some fertilizers (e.g., diammon phosphate in 2020). Per 100 kg, the annual fluctuations in mineral fertilizer prices ranged between minus 26% and plus 17% between the years 2018 and 2020 (AGRIDEA, 2020). This shows that changes in prices are common in the fertilizer market.

The price situation for mineral fertilizers has changed significantly in 2021 and 2022. The most recent developments, which became apparent in 2020 & 2021 and are now a reality, are unusual and cannot be compared with previous years, as prices doubled and tripled. Many factors explain this development, e.g., restricted fertilizer supplies from Russia, China, Turkey, and Ukraine, but also increased transport costs and higher energy prices. It was, therefore, necessary to adjust the calculations and recalculate the fertilizer values for the current prices. When recalculating, a tripling of the price for urea and calcium ammonium nitrate as well as a 50% increase in the price of potash was assumed. No adjustment for phosphorus fertilizer prices was considered. The increase in fertilizer prices and the background information were taken from the agricultural press, for example, from here: Fertilizer prices extremely high in 2022: Fertilizer market out of control (Düngerpreise 2022 extrem hoch: Düngermarkt außer Rand und Band | agrarheute.com).

6.3.2 Nutrient contents of agricultural digestate products

To obtain a detailed overview of the nutrient contents in agricultural digestate products, an analysis of the nutrient reports from the legally required laboratory analyses from 2018 to 2021 was performed (using data from the CVIS database of the Inspectorate of the Swiss Composting and Digestate Industry, and additional laboratory analyses of our members, which are collected as part of our monitorings). A total of 429 nutrient analyses from digestates (from 63 biogas plants), 36 nutrient analyses of liquid separated digestate (from 8 biogas plants), and 124 nutrient analyses of solid separated digestate (from 27 plants) were analyzed. There were significantly fewer analyses for liquid separated digestate than for the other digestate products. The nutrient contents of the digestate products are central to determining the economic value, as they are measured by their ability as nutrient suppliers. In the following, the nutrient properties of the digestate products common digestate, liquid separated digestate, and solid separated digestate are discussed.

Digestate

The range of nitrogen content in the digestate is quite broad, ranging from 30 kg N/t dry matter (DM) to 103 kg N/t DM. This is due to the large variety of animal manures, agricultural residues, and co-substrates, which bring different amounts and concentrations of nutrients into the digestate. In the median range (the second and third quartile), the digestates had a nitrogen content between 58 and 76 kg N/t dry matter (see Figure 14). The mean value was 69 kg N per tonne of dry matter. Converted to fresh matter, this results in a concentration of 3.7 kg total N per tonne of fresh matter (FM). This corresponds to the nitrogen content of undiluted and undigested cattle slurry, which is given as 3.9-4.0 kg N per t FM in the GRUD (GRUD, 2017). Converted to a standard dilution of 1:1.5, the diluted slurry contains considerably less, namely around 1.6 kg N per t FM. Table 7 lists the average values of cattle slurry and digestate products for a better comparison.

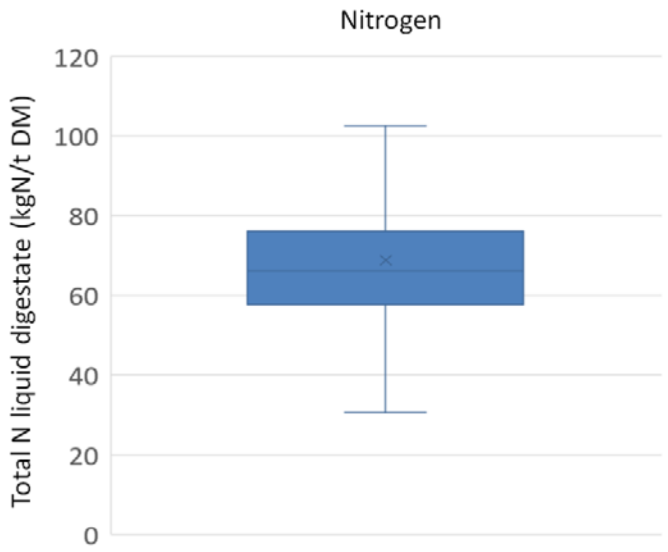


Figure 14: Total nitrogen concentration in agricultural digestates. Boxplot with results from nutrient analyses of the years 2018-2021 (n = 429).

Regarding available nitrogen, measured as ammonium nitrogen, the 2018-2021 digestate products analyses showed an average value of 2.2 kg NH_4-N per tonne of fresh matter. The lowest value measured was 0.31, and the highest was 4.0 kg NH_4-N per tonne FM. Most of the digestates have an ammonium value between 1.5 and 2.6 kg NH_4-N per t FM. This is also within the range of the nitrogen values in the GRUD (2.0-2.8 kg $N_{available}$ per tonne FM) given for undiluted cattle slurry (GRUD, 2017). However, the standard dilution of 1:1.5 reduces the available nitrogen contents to 0.8-1.1 kg $N_{available}$ per tonne FM in the undigested cattle slurry. Thus, the anaerobic digestion of diluted (cattle) slurry with other animal manures and agricultural or other organic residues raises the nutrient contents of the diluted slurry to the level of undiluted (cattle) slurry.

The analyzed digestates showed a mean concentration of 24 kg P_2O_5 per tonne of dry matter. The mean 50% of the digestates had phosphate concentrations of 20-28 kg P_2O_5 per tonne of dry matter (see Figure 15). Digestate with low phosphate concentrations had between 8 and 20 kg P_2O_5 per tonne of dry matter, while digestates with high phosphate concentrations reached 41 kg P_2O_5 per tonne of dry matter. The fluctuations in phosphate concentrations between the different liquid digestate samples were significantly smaller than for nitrogen or potassium.

Digestates showed a mean potassium concentration of 77 kg K_2O per tonne of dry matter. In the middle range (middle 50%), the digestates had potassium concentrations of 62 to 91 kg K_2O per tonne of dry matter (see Figure 15). Digestates with low potassium concentrations had concentrations lower than 62 up to a minimum of 22 kg K_2O per tonne of dry matter. Digestates rich in potassium had concentrations of up to 134 kg K_2O per tonne of dry matter. The range of concentrations was thus greatest for potassium, even more extensive than nitrogen. The reason for this is again to be found in the different inputs of the biogas plants. Potassium is present in various concentrations in food and also in animal manure. Chicken manure, for example, has significantly higher potassium contents than cattle manure (GRUD, 2017).

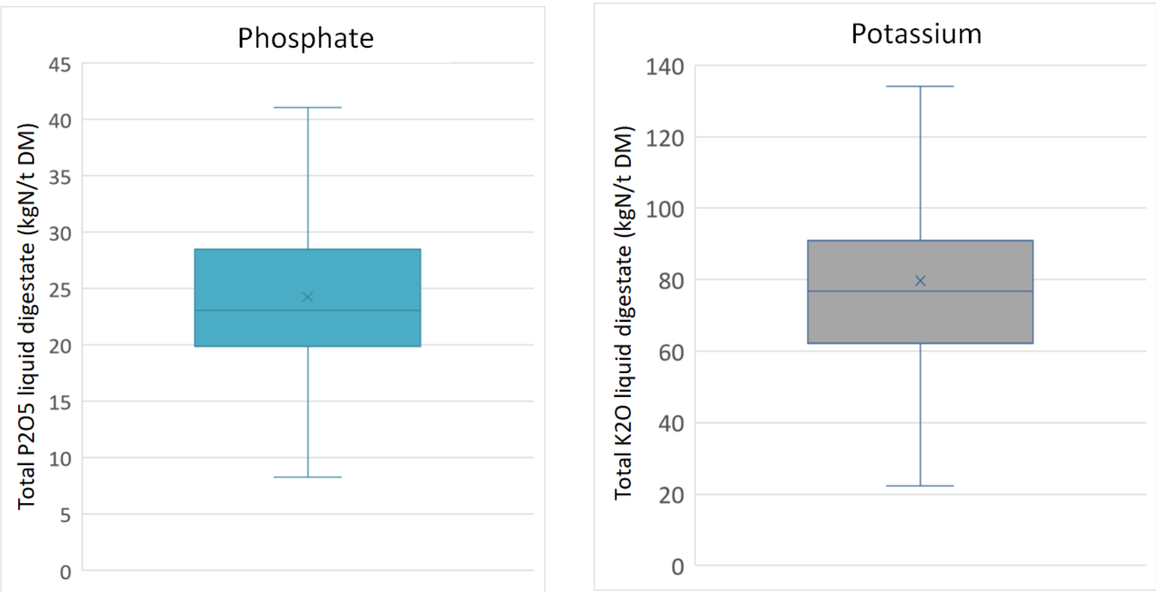


Figure 15: Phosphate and potassium concentrations in digestate from agricultural biogas plants. Boxplots with results from nutrient analyses of the years 2018-2021 (n = 429).

When comparing the mean concentrations of P and K of digestate with the concentrations in undiluted cattle slurry, it can be found that they are similar (see Table 7). However, the ranges of concentrations of N and K in the digestates are quite large. It is, however, essential to know the nutrient analyses of the digestate both for the farmers using the digestate to correctly cover the nutrient requirements of their crops and for the plant operators to classify the economic value of their digestate correctly.

Besides the macronutrients N, P, and K, the question of the C:N ratio also plays a role in fertilizing. Table 7, therefore, also includes the C:N ratio of the digestate products because this provides information about the humus effect of organic fertilizers. Organic fertilizers with a C:N ratio < 10:1 are described as rapidly degradable, i.e. the microorganisms in the soil can easily process the carbon and release the nutrients, i.e. mineralize them. They do not contribute to humus formation. With a C:N ratio > 15:1, a fertilizer is described as a humus-building, as the microorganisms need significantly longer to process the organic matter and release the nutrients. With the digestate products liquid digestate and solid digestate, you have both. You have a fast-acting fertilizer (digestate as well as liquid separated digestate) with a C:N ratio between 4 and 6 and a slow-acting humus-building product (solid digestate) with an average C:N ratio of 23 (Table 7).

Table 7: Nutrient contents of the three most common agricultural digestate products compared to cattle slurry. The nutrient values represent means from (analyses of) 429 digestates, 36 liquid separated digestates, and 124 solid separated digestate samples from the years 2018-2021 and comparative values for cattle slurry from literature, the GRUD (GRUD, 2017).

	Cattle manure undiluted	Digestate	Liquid separated digestate	Solid separated digestate
N (kg /t FM)	3.9-4.0	3.7	4.7	8.1
P_2O_5 (kg / t FM)	1.3-1.7	1.3	1.3	4.2
K_2O (kg / t FM)	4.5-7.5	4.2	5.8	7.8
Ca (kg / t FM)	1.2-1.5	1.5	1.5	5.3
Mg (kg / t FM)	0.4-0.6	0.4	0.4	1.6
S (kg / t FM)	NA	0.4	0.4	1.2
C:N ratio	NA	5.9	4.7	23.1
Dry matter content (%)	9	5.4	5.4	29.0

Liquid separated digestate

Some farms separate the digestate into two fractions: the liquid separated digestate and the solid separated digestate. The two separated fractions, liquid and solid, allow different uses and marketing opportunities. Either the biogas plant operators separate the digestate for their own purposes to optimize the use of the digestate, e.g. when using it on pasture (separation of solids leads to the avoidance of digestate residues staying on top of the grasses) or then for sale. Since fewer nutrient analyses were available for the evaluation of liquid separated digestate than for the common digestate, the average comparison must be interpreted cautiously. The nutrient properties of the liquid separated digestate differed from the non-separated liquid digestate by higher N and K_2O concentrations on average. Due to the higher N concentrations, the C:N ratio of liquid separated digestate is also lower than that of common digestate. There were no differences for phosphate and the other nutrients between the digestates.

Solid separated digestate

Regarding nutrient content, the solid separated digestate is characterized by higher nutrient concentrations per tonne of fresh matter than liquid separated digestate and common digestate. However, since the dry matter of the solid separated digestate is 29%, the nutrient concentrations in relation to the dry matter are significantly lower than in the two other digestate products (which have an average dry matter of 5.4%). Especially N and K_2O are found in lower concentrations in the solid separated digestate than in the liquid separated digestate. The difference is less pronounced for phosphate and the other nutrients (Ca, Mg, S). Therefore, the liquid separated digestates are better suited as a complete organic fertilizer than the solid separated digestate.

The solid separated digestate is particularly suitable for building up humus, similar to compost or undigested manure. According to VDLUFA (VDLUFA, 2014), solid digestate has a humus equivalence (Heq) of 36-50 per tonne of fresh matter. The humus equivalence mainly depends on the dry matter content of organic fertilizer (the higher the DM content, the higher the humus reproduction capacity). Straw, for example, has a humus equivalence of 100 heq/t FM. The C:N ratio of solid digestate was, on average, 23 (see Table 7), which indicates an effect of slow nutrient release in the soil.

6.3.3 Calculation of theoretical fertiliser values

Digestate products are organic compound fertilizers that can be used in agriculture (or horticulture) like conventional animal manure. Based on their nutrient content, a theoretical, economic value can be calculated based on the prices for mineral fertilizers per nutrient content for the main nutrients nitrogen, phosphorus, and potassium. It is referred to as fertilizer value. This method of calculation has been used for several years by the Bundesgütegemeinschaft Kompost e.V. in Germany to describe the quality of digestate products (BGK, 2013), among other things to award digestate products with the RAL seal of quality (RAL Deutsches Institut für Gütesicherung und Kennzeichnung e.V., RAL - Expert für Kennzeichnungen | RAL.DE). For digestate products awarded the RAL quality seal, their fertilizer values are stated in euros (€) in the product properties. The RAL seal of quality is available for liquid and solid digestate products and especially for NAWARO digestate products. Depending on how much biomass the biogas plant processes, 4 to 12 laboratory analyses per year are required to determine the fertilizer value, i.e., every three months or every month (BGK, 2021).

The simplest calculation variant for fertilizer values, according to BGK (BGK, 2013), is as follows:

Fertilizer price from digestate products (CHF/m^3) = $N_{available}$ content (kg/m^3)*N-parity price (CHF/kg) + P_2O_5-content (kg/m^3)*P_2O_5-parity price (CHF/kg) + K_2O-content (kg/m^3)*K_2O-parity price (CHF/kg)

Parity prices are the prices of the corresponding single-nutrient mineral fertilizers per unit of the nutrients. For the parity price of nitrogen, urea is used as a reference in various literature sources. For P_2O_5, it is usually triple superphosphate, and for K_2O it is potash 60% (AGRIDEA, 2020). Depending on this, other nutrients, e.g., lime or sulfur, can be included in the fertilizer value calculation.

In the next step, application costs are also considered in the calculation. Compared to the application of mineral fertilizers, the application of liquid manure/digestate is three times as expensive, and the application of solid manure/digestate is four times as expensive. The additional costs compared to the mineral fertilizer application must be deducted from the fertilizer value when applying the digestate products for a comparable fertilizer value. These additional costs lead to a deduction of CHF 3 per m^3 of manure and CHF 5 per m^3 of digestate, according to AGRIDEA (AGRIDEA, 2020).

In addition to the nutrient content, the humus value can also be priced into the fertilizer value of the digestate products. This is particularly important if the humus balance of a farm is negative and needs to be rebuilt (Reinhold, 2008). The Bundesgütegemeinschaft Kompost e.V. in Germany proposed this: straw can be used as a humus reference. Straw has a humus reproduction capacity of 100 kg humus-C per tonne of straw (VDLUFA, 2014). Depending on the price at which straw is traded, one can assign a monetary value to a unit of humus-C. Humus carbon is the proportion of organic matter in organic fertilizers (according to VDLUFA). For compost, for example, one calculates with a humus reproduction capacity of 40-70 kg humus-C per tonne of fresh matter. For liquid digestate products, 6-12 kg humus-C/t can be expected, and for solid digestate products 36-50 kg humus-C per tonne of fresh matter (BGK, 2013; VDLUFA, 2014). In a 2013 publication by the Bundesgütegemeinschaft Kompost e.V., a straw price of €72.50 per tonne is assumed. In Switzerland, indicative prices of 50 CHF per tonne of straw already removed from the field can be found for 2021 (Stroh - Schweizer Bauernverband (sbv-usp.ch)). The parity price in this country is therefore 0.5 CHF/kg Humus-C.

To calculate the theoretical fertilizer value of the digestate products, the so-called parity prices or pure nutrient prices were first determined from the mineral fertilizer price data, i.e., a price per quantity of nutrient contained (see Table 8). Although, as can be seen in **Error! Reference source not found.**, many different mineral fertilizers are used in Switzerland, it makes sense to derive the parity prices only from the single-nutrient fertilizers. Indeed, for nutrient parity prices from complex fertilizers, a division - to be justified - of the price for the individual nutrients would be necessary. For nitrogen, two parity prices were used for calculations: once with the parity price of 1.10 CHF, derived from urea, and 1.25 CHF, derived from calcium ammonium nitrate. Calcium ammonium nitrate is the most commonly used mineral fertilizer in Switzerland (see **Error! Reference source not found.**).

Table 8: Determination of nutrient parity prices for nitrogen, phosphate and potassium based on mineral fertilizer prices in 2020 and 2022.

Nutrients	Mineral fertilizers	Contained nutrient units (%)	Fertilizer price 2020 (CHF/100 kg)	Parity price 2020 (CHF/kg nutrient)	Fertilizer price 2022 (CHF/100kg)	Parity price 2022 (CHF/kg nutrients)
Nitrogen (N)	Urea	45% N	49.7	1.1	149.1	3.3
	Lime ammonium nitrate	26% N	32.6	1.3	97.9	3.8
Phosphate (P_2O_5)	Triple Super Phosphate	46% P_2O_5	66.9	1.5	66.9	1.5
Potassium (K_2O)	Kali 60%	58% K_2O	51.8	0.9	77.7	1.3

Nutrient contents from actual, laboratory-tested samples from agricultural biogas plants were used to calculate the fertilizer value of digestate, liquid separated digestate, and solid separated digestate. Mean values from laboratory analyses of 429 samples for liquid digestate, 36 samples for liquid separated digestate, and 124 samples for solid separated digestate from the years 2018-2021 from the Ökostrom Schweiz database, supplemented with data from CVIS (Inspectorate System of the Swiss Composting and Digestion Industry) were used. Following the procedure developed by BGK, economic fertilizer values of agricultural digestate products were determined with the help of the nutrient values and availabilities. For the nutrients phosphorus and potassium, 100% plant availability was assumed for all three digestate products (digestate, liquid separated digestate, solid separated digestate). For nitrogen, the availability was assumed to be at 65% for digestates and liquid separated digestates, and 20% for solid separated digestates. These availabilities are used in Switzerland's farm nutrient accounting system (Module 8 of the Suisse-Bilanz, Guideline 1.16, valid from 1.1.2020-31.12.2022. This does not consider farm-specific N utilization rates, which according to the Suisse Balance, leads to a reduction in the nitrogen availability of digestate on open arable land (Arnaudruz et al., 2020).

With the sharp increase in mineral fertilizer prices in 2021, a recalculation of the economic fertilizer values of the digestate products was indicated. The initially calculated values were kept for comparison. Using the BGK method, a gross fertilizer value of CHF 8.3-8.7 per m^3 fresh matter (FM) was calculated with the original fertilizer prices for digestate, depending on whether the parity price of urea or calcium ammonium nitrate was used for nitrogen. Deducting the additional cost of CHF 3 per cubic meter of liquid digestate for application (compared to mineral fertilizer application) resulted in a net fertilizer value of CHF 5.3-5.7 per tonne on average for digestate (see Table 9). Considering the mineral fertilizer prices applicable at the beginning of 2022, the net fertilizer value of digestate increased to 12.5-13.6 CHF/m^3 fresh matter. Using the same procedure, a net fertilizer value of 7.4-7.8 CHF/m^3 was calculated for liquid separated digestate. With the new prices at the beginning of 2022, these values also increased to 16.6-18.0 CHF per cubic meter (see Table 10). The liquid digestate products' financial value also comes primarily from the contents of these two nutrient elements with rising prices for N and K fertilizer.

Table 9: Calculation of economic fertilizer values for digestates based on nutrient contents in fresh biomass and mineral fertilizer parity prices in 2020 and 2022.

Digestate	Nutrient contents	Fertilizer price of the nutrients CHF/t) in 2020	Fertilizer price of the nutrients (CHF/t) in 2022
Nitrogen (kg N/t FM)	3.7*	2.7 (Urea) – 3.0 (Calcium ammonium nitrate)	8.0 (Urea) – 9.1 (Calcium ammonium nitrate)
Phosphate (kg P_2O_5/t FM)	1.3	1.9	1.9
Potassium (kg K_2O/t FM	4.2	3.7	5.6
Fertilizer value liquid digestate (CHF/t FM)		8.3 – 8.7	15.5 – 16.6
Deduction of additional expenses for application costs (CHF/t)		-3.00	-3.00
Effective fertilizer value of liquid digestate (CHF/t FM)		**5.3-5.7**	**12.5-13.6**

* Only the available nitrogen (65% of the total N) is credited with a parity price

Table 10: Calculation of economic fertilizer values for the liquid separated digestate on the basis of nutrient contents and mineral fertilizer prices in 2020 and 2022.

Liquid separated digestate	Nutrient contents	Fertilizer price of the nutrients CHF/t) in 2020	Fertilizer price of the nutrients (CHF/t) in 2022
Nitrogen (kg N/t FM)	4.7*	3.3 (Urea) - 3.8 (Calcium ammonium nitrate)	10.0 (Urea) – 11.4 (Calcium ammonium nitrate)
Phosphate (kg P_2O_5/t FM)	1.3	1.9	1.9
Potassium (kg K_2O/t FM	5.8	5.2	7.8
Fertilizer value liquid separated digestate (CHF/t FM)		10.4-10.8	19.6-21.0
Deduction of additional expenses for application costs (CHF/t)		-3.00	-3.00
Effective fertilizer value of liquid separated digestate (CHF/t FM)		**7.4-7.8**	**16.6-18.0**

* Only the available nitrogen (65% of the total N) is credited with a parity price

For solid separated digestate, the availability of 20% is taken into account for nitrogen, in contrast to digestate or liquid separated digestate, which results from the high C:N ratio and the associated N immobilization in the soil. Accordingly, the potassium and phosphate contents are the most "financially effective" for the solid separated digestate. A gross fertilizer value of about CHF 15 per tonne and a net fertilizer value of CHF 10 per tonne were calculated on average for solid manure (see Table 11). With increased fertilizer prices in 2022, the theoretical fertilizer values of solid manure also increased and can be valued at around CHF 17 net per tonne FM.

Table 11: Calculation of fertilizer values for the solid separated digestate product.

Solid separated digestate	Nutrients content	Fertilizer price of the nutrients CHF/t) in 2020	Fertilizer price of the nutrients (CHF/t) in 2022
Nitrogen (kg N/t FM)	8.1*	1.8 (Urea) – 2.0 (Calcium ammonium nitrate)	5.7 (Urea) – 6.5 (Calcium ammonium nitrate)
Phosphate (kg P_2O_5/t FM)	4.2	6.1	6.1
Potassium (kg K_2O/t FM	7.8	7.0	10.5
Fertiliser value solid digestate (CHF/t FM)		14.9 – 15.1	21.9 – 22.7
Deduction of additional expenses for application costs (CHF/t)		-5.0	-5.0
Effective fertilizer value of solid digestate (CHF/t FM)		**9.9 – 10.1**	**16.9 - 17.7**

* Only the available nitrogen (20% of the total N) is credited with a parity price

The calculation of monetary humus values in addition to fertilizer values is a procedure that has developed from compost quality assessment and illustration. Examples for the calculation of humus values can be found, e.g., in (Reinhold, 2008). A similar approach can be taken for digestate products, as they also have a humus value and add organic matter to the soil. This is particularly relevant for digestate products, as they are sometimes considered less humus effective compared to unfermented animal manure due to the reduced carbon content resulting from digestate.

For the determination of humus values, the application or incorporation of (cereal) straw into the soil is suitable as a reference. For straw, a humus reproduction capacity of 100 humus equivalents (Heq) per tonne of straw is assumed (VDLUFA, 2014). Depending on the market price of straw, a parity price can be established for the humus output. Currently, the market price recommendations are 50 CHF per tonne of straw (AGRIDEA, 2020). The humus value for straw is, therefore, 50 CHF/100 Heq or 0.5 CHF per Heq. For the digestate products solid and liquid digestate, the VDLUFA has determined a humus equivalent value of 7 and 43 per tonne of fresh matter (VDLUFA, 2014). Thus, a calculation with the humus value of straw results in a humus value of 3.5 CHF per tonne for liquid digestate and 21.5 CHF per tonne for solid digestate. If higher application costs for the digestate products compared to straw are taken into account, the humus value for liquid digestate amounts to only CHF 0.2 per tonne. For solid digestate, however, a respectable humus value of 16.5 CHF per tonne would result (see Table 12). A separate calculation for liquid separated digestate was not carried out, as it can be assumed that the humus reproduction performance is comparable to that of digestate.

Table 12: Calculation of the humus value for agricultural digestate products.

	Cereal straw	**Liquid digestate**	**Solid digestate**
Dry matter content (%)	86	5.24	30.0
Humus equivalent per tonne FM (kg Humus-C/t)	100	7	43
Straw price bulk from the field (CHF/t)	50		
Application costs (CHF/t)	1.7	5	6.67
Humus value (CHF/t)	0.5	3.5	21.5
Humus value minus additional costs of spreading compared to direct straw spreading (CHF/t)	**50**	**0.2**	**16.5**

6.3.4 Survey of biogas plant operators

A questionnaire was developed to record the current situation among agricultural biogas plant operators. The questionnaire was used to gather information on the following points relevant to the project:

- Animal manure availability in the region
- Cultivation system (organic or conventional)
- Demand situation for the digestate products
- Internal/external purchase
- Sales opportunities for liquid digestate, liquid separated digestate, solid separated digestate
- Seasonal differences in sales
- Desired price for digestate products
- Mineral fertilizer substitution by digestate products in practice
- Services related to digestate products
- Ideas for better value creation
- Willingness for process changes

The survey was conducted partly orally and partly in writing:
In the first step, five biogas plant operators were interviewed by telephone. In a second step, all biogas plant operators were asked to share their experiences and marketing strategies by means of a digital survey. In total, feedback from 22 plant operators could be used for the evaluation.

When interviewing the plant operators, the first question referred to the demand for their digestate products and whether they find enough customers. The answers were mainly positive, i.e., demand is satisfactory for most plant operators (see Figure 16). Only a small number of respondents said that demand was not high enough and that they would like to have more customers.

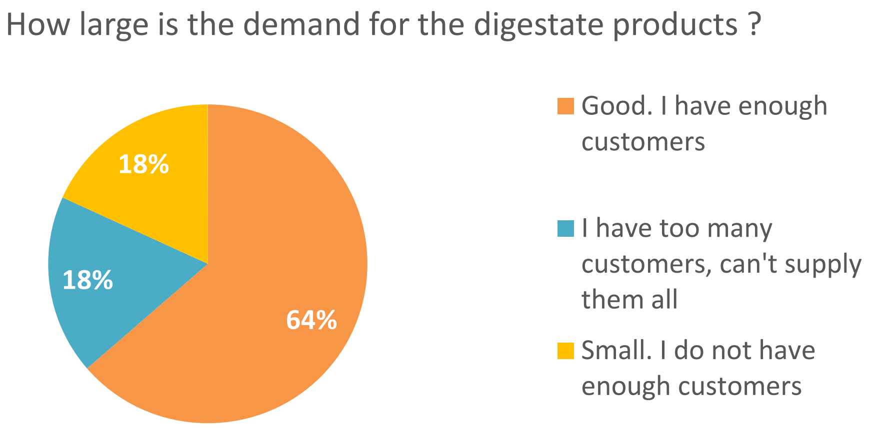


Figure 16: Responses on agricultural digestate products' demand.

In order to better understand the statements on the demand situation, another question was asked about the share between supplying and external, i.e., non-supplying, customers. Results show that almost all plant operators also have external customers, so this seems to be common and probably contributes to the satisfaction of demand. For 9 out of 22 operators, at least two-thirds of the customers for their anaerobic digestion products are supplying farmers, and the external customers are only a small part of the customers (Figure 17). Interestingly, however, there were also a total of 8 plant operators for whom external customers make up a significantly larger proportion of the clientele. At least 25% of the customers are external, and the highest number of customers was 90%.

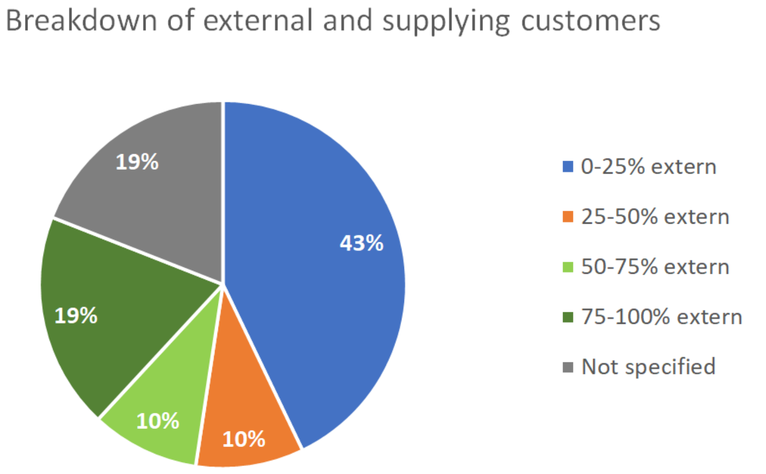


Figure 17: Responses on the importance of supplying and external customers.

The most central question for the plant operators was the question referring to the revenue from the digestate products. First of all, operators were asked whether a direct price could be achieved for the digestate products, independent of additional services such as transport or spreading. The results showed that the vast majority of operators could not obtain revenue for the digestion products alone (Figure 18). 16 out of 22 operators stated that they (have to) deliver their digestion products free of charge. Those who ticked "Yes, but only for transport and/or spreading" are also included in the number of operators who do not receive any revenue for the digestate products. The other operators (6 out of 22), on the other hand, stated that they receive revenue for digestion products, either for the digestion slurry itself or for the separated products, liquid, and solid digestate. From these figures, it can be roughly stated that financial value creation from the digestate products is only realizable for about 30% of the operators.

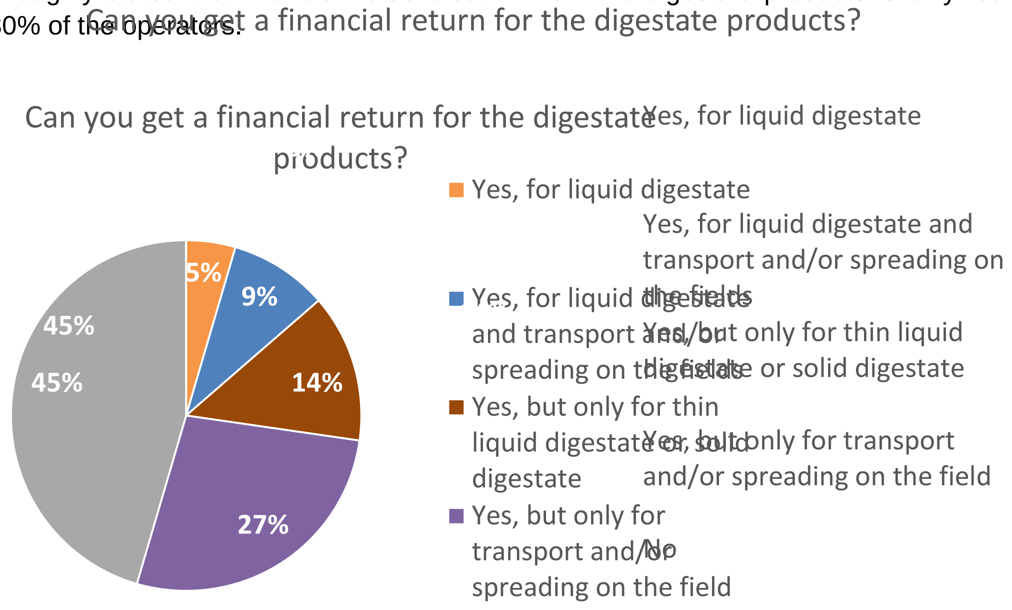


Figure 18: Responses on revenue from digestate products.

When asked about the specific amount of revenue for the digestate products, i.e., what sales price is achievable, only a few responses were received, also due to the small number of operators who effectively generate revenue for their digestate products. Table 13 below lists the stated prices for the three digestate products:

Table 13: Responses to sales prices of digestate products.

Digestate product	Sales price range
Digestate	3.50 – 5.00 CHF/m^3
Liquid separated digestate	5.00 – 7.00 CHF/m^3
Solid separated digestate	8.00 - 12.00 CHF/t

With regards to increasing the added value of digestate products, it was interesting to ask for the desirable prices would for the digestate products. Figure 19 shows the statements for desirable prices per price category and type of digestate product. The desired prices clearly exceed the prices effectively achieved in practice in the case of the highest mentioned desired prices. However, there was also some feedback on desired prices, which lie exactly in the range that can also be partially achieved in practice.

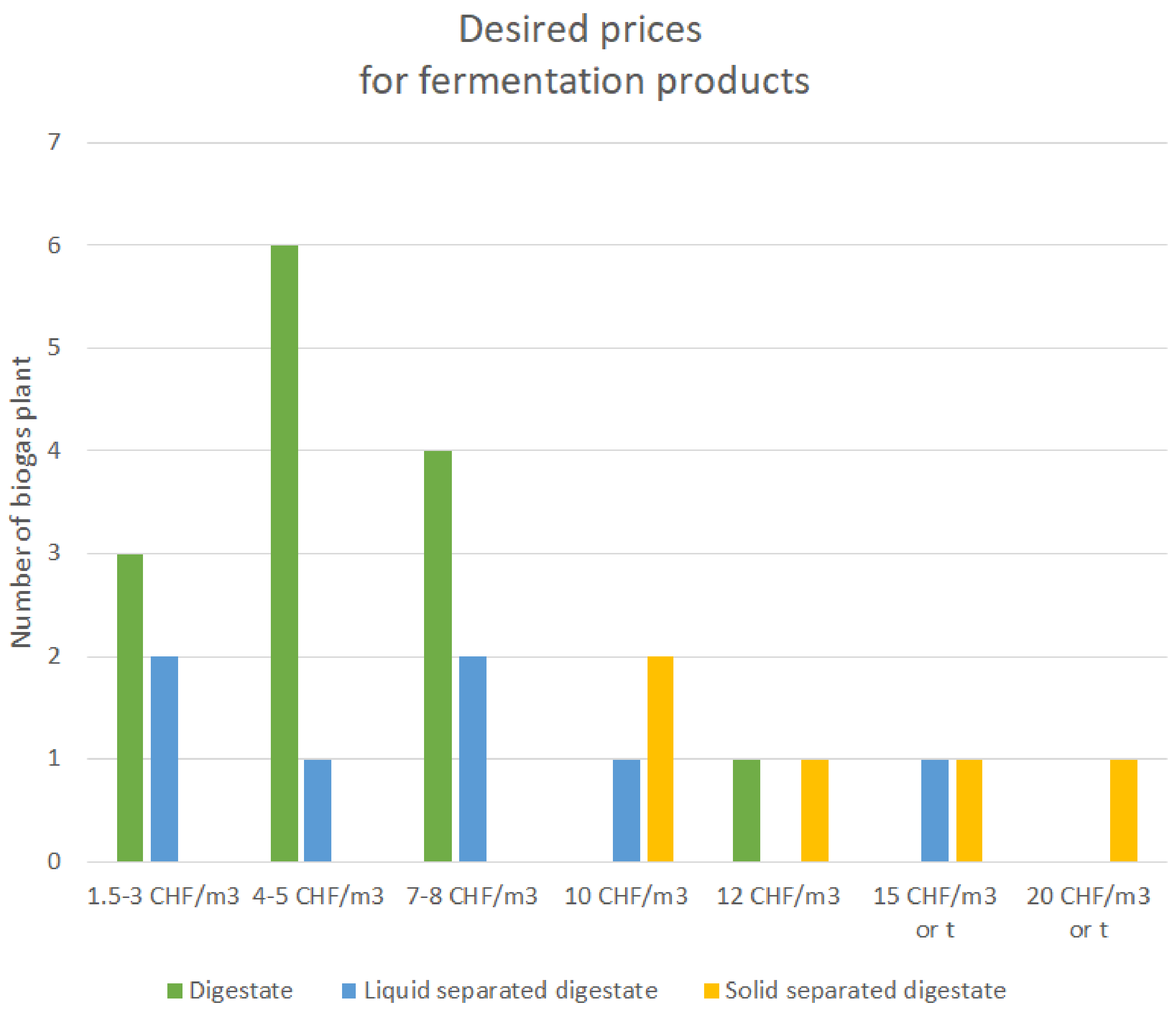


Figure 19: Responses of the interviewed agricultural biogas operators on their desired level of revenue for their digestate products.

6.3.5 Identifying promising value creation opportunities

"The price of digestate products is mainly determined by transport costs to the application sites, the time of year, the nutrient content and the legal situation" is an accurate statement from the publication by Dahlin et al. (2015), which was made in relation to the situation of biogas plants in Germany. However, it actually applies everywhere, although the transport distances in Switzerland are smaller and the nutrient surpluses in the regions are less dramatic compared to Germany.
For Germany, the following prices for digestate products and composts can be found in the literature (from 2015) (Dahlin et al., 2015):
Liquid digestate: from -18 euros per tonne to 5 euros per tonne. The negative prices result mainly when the transport costs of a distance up to 150 km exceed the product costs.
Digestate pellets: from €0 to €200 per tonne (with the normal range going up to €100 and €200 being achieved only for the special chicken house litter pellets)
Agricultural compost: normally €0-7 per tonne. Higher prices (up to €80 per tonne) can be obtained for specially processed compost in the ornamental horticulture sector.

These prices show that unprocessed digestate does not have a high market value in Germany and that its delivery even causes costs for the operator. This is a bad starting position for digestate and does not do justice to the product. So value-added strategies are needed. The low market value is apparently true for the Swiss digestates as well, as our survey has shown, and strategies for better marketing are needed for Swiss digestate producers as well.
In order to identify promising value creation strategies, various sources were looked at and considered, namely literature, biogas conferences, and conversations with plant operators. Looking at neighboring countries, one can discover that the processing of digestate products has already reached a high process level in the meantime. There are several reasons for this. One factor is the lack of market value mentioned above. Another factor is that the spreading of digestate products on agricultural land is seasonally prohibited in Germany with the new fertilizer ordinance (2020). This puts a strain on the storage capacities of biogas plants in winter. An increased need for storage capacities, in turn, leads to a need for compression, i.e., a reduction in water content, which can increase nutrient concentrations. With a concentrated digestate, the nutrients can also be transported more cheaply. This is a problem, especially for large biogas plants in nutrient-intensive, i.e., livestock-intensive regions, because they process large quantities of biomass and accordingly have to "accommodate" large quantities of digestate products.

From solid digestate products, pelleting has been the most common further processing method so far. For liquid digestate products, on the other hand, there are several different processes, some of which build on each other:

1. vacuum evaporation
2. membrane filtration
3. precipitation
4. stripping
5. wastewater treatment

These treatment or processing methods end up with different products (see also Figure 20). In the simpler processes, the processing results in multi-nutrient solutions and water. In the more complex processes, products such as ammonium sulfate solutions (ASL), lime, nitrogen-reduced digestate, magnesium ammonium phosphate, calcium phosphate, or phosphorus-reduced digestate are produced (Wilken, 2020). Vacuum evaporation is e.g. offered by the company Arnold & Partner AG in Switzerland, but is not used in Switzerland so far. According to the company, the financial investment is too big for agricultural biogas plants currently (according to A. Wicki, Arnold & Partner AG, 2022).
There are different needs for nutrients in agriculture. There is the need for mainly nitrogen in the fertilizer product but also the need for P and K as “one-nutrient-Fertilizers”. For the plant operator, however, the question of economic viability comes before any investment. For small biogas plants, special treatment plants for the digestate products are certainly not worthwhile, as the purchase of a separator for small biogas plants is already a financial hurdle. While most of these techniques are

already frequently used in the neighboring countries with a large biogas community, such as Germany and France, they have not been yet established in Switzerland.

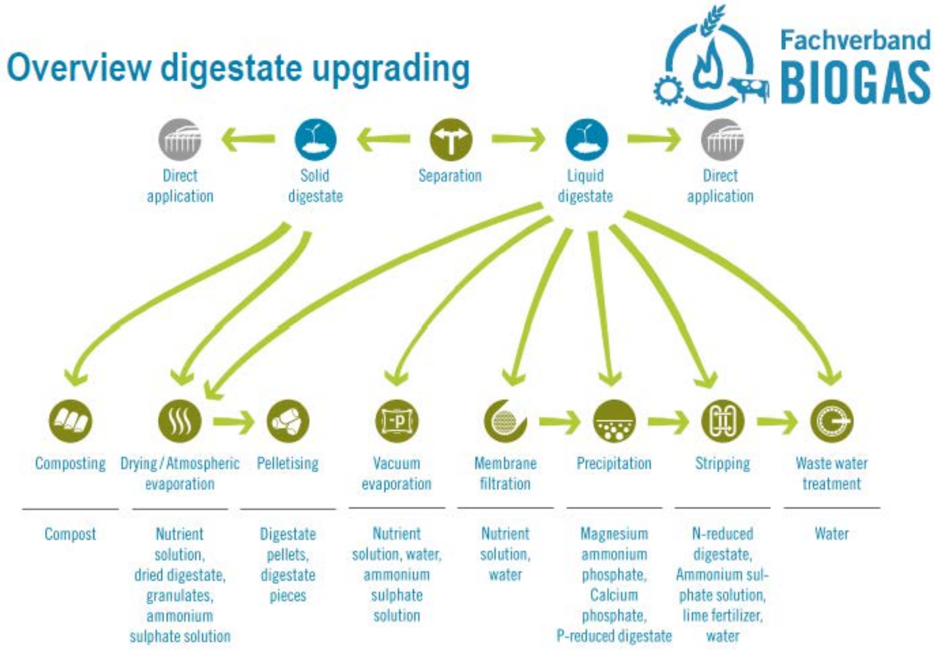


Figure 20: Established process steps for the treatment of digestate products (Wilken, 2020).

Looking at the sales markets, German sales data show that 91.5% of liquid digestate products are sold to conventional agriculture and 7.5% to organic agriculture (Wilken, 2020). The situation is somewhat different for solid digestate. 83% of solid digestate is sold to conventional agriculture, and the rest to hobby horticulture (6.5%).

- Hobby horticulture (6.5%)
- Horticulture (3.5%)
- Landscaping (3.5%)
- Other (3.5%)

The larger non-agricultural marketing share of solid digestate is mainly due to the fact that dry digestate products can be traded and packaged more easily than liquid ones. So digestate products can also be part of the soil for cultures and act as a peat substitute in horticulture. The hobby gardeners are also a target group for the sale of digestate products. If things are to get more creative, digestate products can also be used in landscaping or viticulture.

There have also been studies on marketing opportunities in the hobby gardening sector. There are also various sales aspects to consider in order to achieve sales success. In the publication by (Wilken, 2020), for example, it was examined which possibilities are promising in the marketing of digestate products in Germany. It was found that it is advantageous for the sale of digestate products if the origin, i.e., the biogas plant, is concealed or at least not superficially recognizable. Thus, products are only advertised with the note "made from organic raw materials". Apparently, there are negative associations with biogas production among the German population, probably due to the controversial maize monoculture discussions, and accordingly, there is also a low acceptance of the products. In this respect, it is then also important that the products have little dust and little odor. In addition, it was found that granules are best suited for non-professional use, even better than powder or pellets. With pellets, the "challenge" is that there must be incorporated into the soil because otherwise, the pellets remain on the surface, and the nutrients do not reach the soil, especially in dry conditions.

Nevertheless, there were also biogas producers in the study by Dahlin et al. (2015) who had good experiences with an offer for self-collectors "filling-up with digestate as required". However, this seems to be mainly an offer for biogas plants close to the city, which also have walk-in customers. For remote biogas plants, it will be important to actively "go" to the customers themselves. Positive media coverage is helpful in improving the public perception of digestate products (Dahlin et al., 2015). Public events at the biogas plants, but also the presentation of digestate products at agricultural and horticultural fairs, can be helpful in improving the perception and acceptance. It seems that personal contact between producers and customers or resellers, but also with local authorities and agricultural advisors, is essential for building trust in biogas and digestate products.

It is recommended that garden fertilizers be marketed through nurseries, garden centers, and DIY and garden shops (Kröger et al., 2016). From a legal point of view, the manufacturer in Germany must indicate the type and composition of the raw materials (animal origin versus plant origin), the nutrient content in relation to the fresh and dry matter, the trace elements, heavy metal content, and lime content (CaO) in relation to the DM on the fertilizer products.

Commercialization experience from Germany (Kröger et al., 2016) shows that:

- Filling pelleted digestate in bags is cheaper than filling it in buckets.
- The investment costs for a pelleting station, including a bagging station, are high (50'000-70'000 €). It is recommended to also look into renting a pelleting station to start with.
- The total costs for the production of packed fertilizer bags are most favorable from a production quantity of at least 50 tonnes and onwards.
- The minimum production quantity can be lower if the end product can be sold at a higher price.
- "The higher the prices that can be achieved and the higher the quantity sold annually, the shorter the payback period".
- Long-term purchase agreements with traders or specialist sellers are helpful for securing sales.

The new EU Fertilizer Products Regulation (EU 2019/1009) is intended to make it easier to trade organic fertilizer products such as digestate products within Europe (2019a). Uniform environmental standards for CE marking apply. Minimum nutrient content requirements also apply (1% N - total nitrogen by matter, 1% P_2O_5, 1% K_2O). There must be at least 3% main nutrient content. In addition, a minimum content of 5% organic carbon is also required. These minimum requirements do not seem to be so easy to achieve for liquid digestate products, and concentration is therefore unavoidable. Enrichment with mineral fertilizer is also conceivable. At the moment, therefore, the regulation has primarily achieved a simplification for the trade in solid digestate in the EU. In Switzerland's Fertilizer Book Ordinance, there are no such minimum contents for animal manure/digestion products (2019b). According to the Fertilizer Ordinance (Der Schweizerische Bundesrat, 2001) in Switzerland, liquid digestate products may not have more than 20% dry matter. In addition, there is an obligation to provide proof of nutrient content, dry matter content, and organic matter.

In addition to the use as a fertilizer product, there are also other possible uses for digestate products:

- Use of dried digestate as bedding in animal stables. There is apparently a pelletization option for this, with the result that the pellets are soft and not hard for use as fertilizer.
- Digestate pellets as heating material (instead of wood pellets)
- Peat substitute in garden soil

Producing pellets from digestate is already practiced at some Swiss biogas plants for fertilizer production. The use as animal bedding material and for heating purposes are not applied here. The peat substitution is however an option that could be considered for some biogas producers. While some biogas plants sell solid separated digestate to private persons for gardening purposes, there is currently no commercial application.

With regard to product quality, in addition to the nutrient-related properties as fertilizer products, there are also the quality characteristics "hygienically safe" and "foreign substance controlled". Both are aspects that are also addressed in Switzerland. Since 2019, the digestate products have been subject to random checks for foreign substances. Hygienic controls do not exist for digestate products in this sense - but precautionary measures are taken, the hygienization of sensitive substrates, and there have been studies to investigate the pathogenic properties of digestate products, which demonstrated a killing effect of dangerous human, veterinary, and plant pathogens during digestate (Fuchs, 2015; Fuchs et al., 2014).

Hurdles in the commercialization of digestate products can be, for example, Dahlin et al. (2015):

1. additional human and financial resources are needed for commercialization, which causes additional costs.
2. bureaucratic hurdles exist. In France, for example, fertilizer commercialization requires a (costly and lengthy) permit from the Ministry of Agriculture.
3. distant sales channels cannot be used, as transport distance is an important cost factor.
4. resellers (supermarkets, garden centers) have preferences for selling product pallets and little interest in individual products. The product quantity must also be right for the reseller. In addition, resellers often pocket up to 60% of the sales prices.

In summary, there are still no established recipes for success for digestate products from biogas plants, not even in Germany (Dahlin et al., 2015). Even if the processing technologies are mature, the marketing strategies for digestate products do not seem to be mature yet, and the positioning is still in its infancy. For small biogas plants, however, the recommendation can be derived to initially concentrate on simple processing operations, such as composting or pelletizing digestate products. Or they can join forces with other biogas plants and market their digestate products together in a kind of cooperative.

Looking at greater or improved value creation, the process of quality enhancement is, of course, also linked. In order to determine the willingness of biogas plant operators to optimize processes or to make additional efforts to increase the quality of their digestate products, they were asked for their ideas in this regard (see Figure 21). The most common answer was also the most obvious, namely to separate the digestate to obtain two products: liquid separated digestate and solid separated, digestate. For an estimated 50% of the agricultural biogas plants, this option is already commonplace and for some, it would be a good extension of their activities but still too expensive in terms of purchase or cost-benefit ratio. Other answers also contained ideas that also fall into the category of "post-treatment of digestate". There is not only separation, but it is also suggested to compost the solid digestate with regional green waste. The advantage of this could be that the product compost is much better known in the private or hobby gardening sector in terms of handling and possible uses than the digestate itself and can therefore be commercialized more easily. Another idea for post-treatment is the installation of screening systems to remove foreign matter such as plastic from the digestate. This is certainly a good way to point out when marketing that the digestate product has been freed from foreign matter. Thus, in addition to the nutrients and the humus effect, one has another sales argument, the "purity". Other ideas fall under the category of "use of additives", i.e., optimizing the digestate properties by mixing in, for example, algae, EM (effective microorganisms), or charcoal, which can bind the nitrogen and reduce the risk of ammonia emissions. So there are a number of different ideas that are already in the minds of biogas plant operators and accordingly have the potential to be implemented.

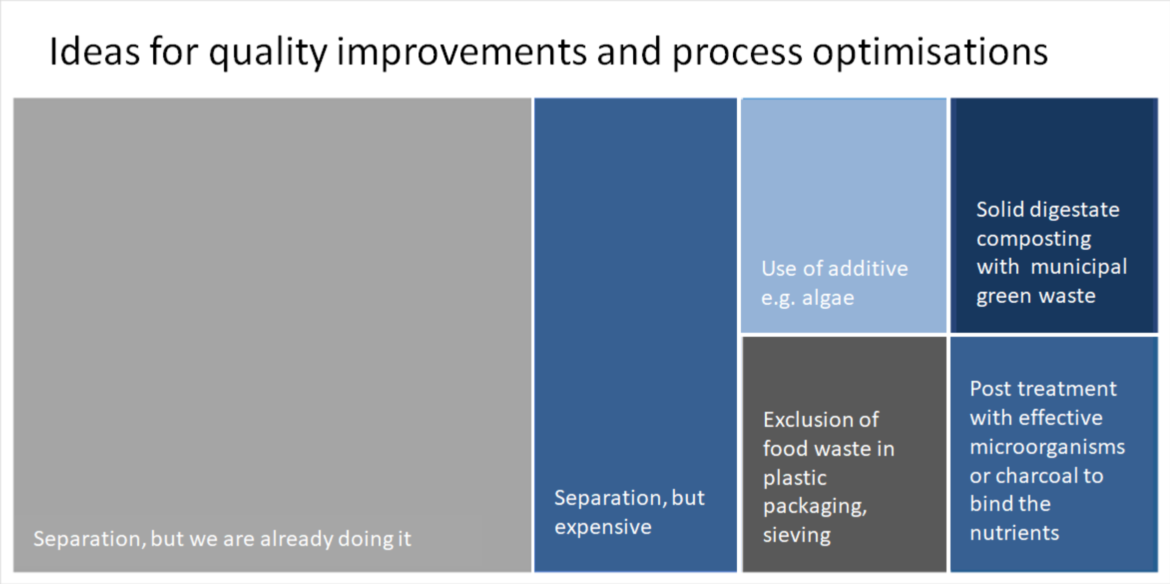


Figure 21: Treemap with answers of the surveyed biogas plant operators to the question "Do you have ideas for quality improvements and process optimizations for the future? The most frequent answers are on the left. The frequency of the answers decreases towards the right.

In the survey, biogas plant operators were also asked for ideas on achieving improved value creation (Figure 22). The most frequent answer concerned the topic of marketing, which should receive more attention. From the view of the association Ökostrom Schweiz, this gap was acknowledged a few years ago. Therefore, a brochure and a flyer on the properties of digestates were designed for operators, which they can also use for their customers and their marketing activities (Ökostrom, 2020). Nevertheless, the topic of marketing, acceptance, and know-how on digestate products is still a "field that needs to be cultivated". The second most frequent answer also shows this: wish for improved education on the properties "humus effect, hygienization of weed seeds, etc.". Our professional association can certainly provide the basics here and communicate them in a wide variety of channels. In addition, plant operators can achieve improved acceptance among the local population with guided tours or events at biogas plants. Further ideas for more added value concern "quality improvement" and "services". While the topic of quality enhancement has already been dealt with above, the topic of services has newly emerged. The ideas for service offers range from an offer for spreading the digestate on the fields to refining the digestate by adding further nutrients or trace elements to make it more attractive or more suitable for the needs. These two ideas are, in fact, already in use. Some biogas plant operators offer their customers the spreading as a service. This was also evident in the survey with regard to revenue. Some operators can only charge for the transport or spreading of the digestate. And the addition of nutrients or trace elements is already being used successfully by at least one operator. It is unclear whether this idea is possible for other plant operators to improve the added value of their digestate products. This activity of "fertilizer production" presumably requires good chemical know-how to ultimately create a digestate product that is harmless or beneficial in terms of pH value, nutrient availability, and other aspects.

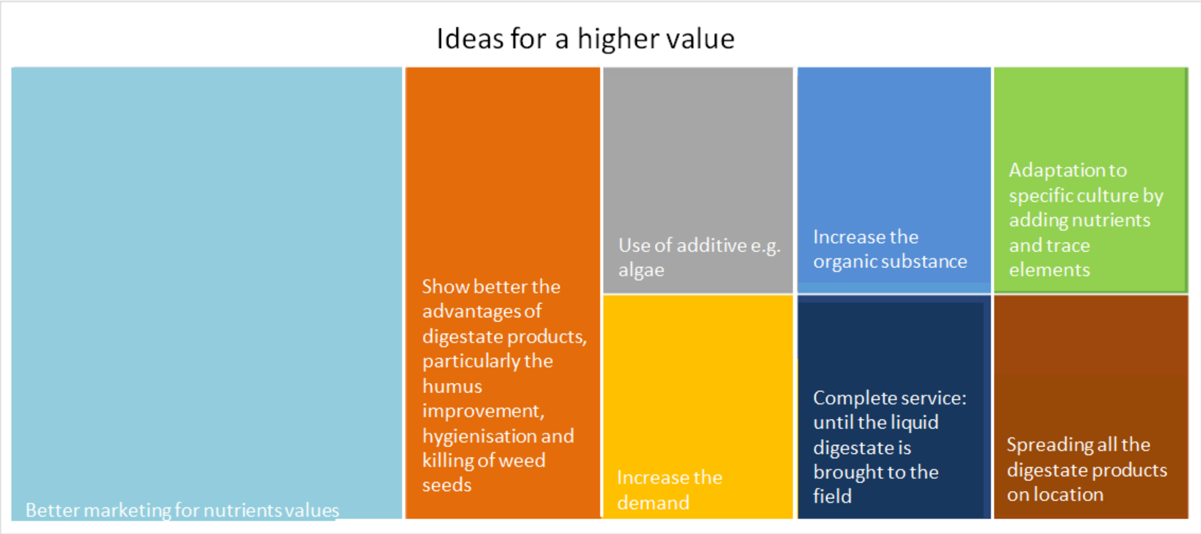


Figure 22: Treemap with answers of the interviewed biogas plant operators to the question "Do you have ideas on how to increase the added value of the digestate products? The most frequent answers are on the left. The frequency of the answers decreases towards the right.

Another idea in terms of "increasing value creation" is that in this regard, demand would have to be increased first and foremost. But how can this be achieved? Perhaps it is not only positive customer reports or the aforementioned educational work on the qualities of the digestate products that are needed here. The political framework conditions can also play a role here. The legally stipulated goal of reducing the nutrient surplus described in chapter 3.6 could help here. Should farmers be "forced" to reduce mineral fertilizers, either due to the political objective or sharply increased mineral fertilizer prices, the demand for organic fertilizers with rapidly available nitrogen properties, such as liquid digestate, could increase abruptly.

What is striking about the answers of the biogas plant operators surveyed is that apparently, the customer segment outside agriculture is not being considered yet. This means that the nutrient surpluses can still be compensated regionally (or even supra-regionally), or customers outside agriculture are not yet "needed". Or it means that commercialization in non-agricultural circles has not yet been tried, either because of uncertainty, lack of know-how or contacts, or other reasons.

So far, there is only one example known to us of Swiss biogas plants with specific marketing of digestate products as garden or hobby fertilizer, under the name "florganic", to be found at www.florganic.ch. This granulated solid digestate from the GBAC énergies SA biogas plant in Rances (VD) has been on sale for three years. Their website states that the current purchase price is CHF 13 per kg. This is a higher revenue than what is achieved for the untreated liquid or also solid digestate. At the moment, the FOEN is still clarifying whether the product can be included in FiBL's fertilizer list so that it can be used in organic agriculture or horticulture. According to the biogas plant operator, user feedback has been positive. There is no unpleasant smell when applied, and two municipalities use it on green areas.

Based on the calculated fertilization values and the survey of biogas plant operators, the most promising value creation strategies for digestate products in Switzerland are compiled below:

1. **Improve marketing** → Make the qualitative value, i.e., the properties and possible uses of the digestate, better known and thus increase acceptance. A price can be charged for the digestate if it is known what it "can" do. This aspect includes labeling the digestate products with nutrients, fertilizer, and possibly humus values, and, for example, farm tours or "open days" to get to know the farm and the products better.
2. **Include the storage costs in the price** → For many animal manure suppliers, temporal storage of their animal manure in the biogas plant is a favorable storage option. They may not

need to build a new, covered animal manure storage facility to cover the winter season. The storage costs could be an indirect approach to valorize the digestate products.

3. **Increase quality** → Improve added value by upgrading the quality. The customer does not only get liquid digestate but treated liquid digestate. This can be different treatments (e.g., separation, e.g., with nutrient additives, e.g., acidified, e.g., with plant charcoal/EM).
4. **Increase the number of products** → If there is the possibility of producing several products, a more extensive clientele can be reached. Some users need liquid separated digestate, others need solid separated digestate, others need pellets, others prefer granules, etc.. -> more added value can be created through a product range versus individual product
5. **Expand the range of services** → If the digestate products can not only be delivered but also spread, this is convenient for the customer and brings him added value.
6. **Cooperative networks** → The digestate products can be valued monetarily or in exchange for other services or in kind, e.g., hay/grain. Cooperation in the form of machine loans or work assignments can also be worth a lot.
7. **Discovering original customers** → There are always opportunities to provide digestate products to original customers. Golf courses, for example, are sometimes happy to receive cheap fertilizer, especially solid digestate.

In **Error! Reference source not found.**, these strategies are exemplarily embedded in the initial situation of the plant operation. In the case of a value creation strategy, it naturally also depends on how the individual framework conditions of a biogas plant are in relation to the sales conditions. This includes, for example, the location, the personnel resources and plant size.

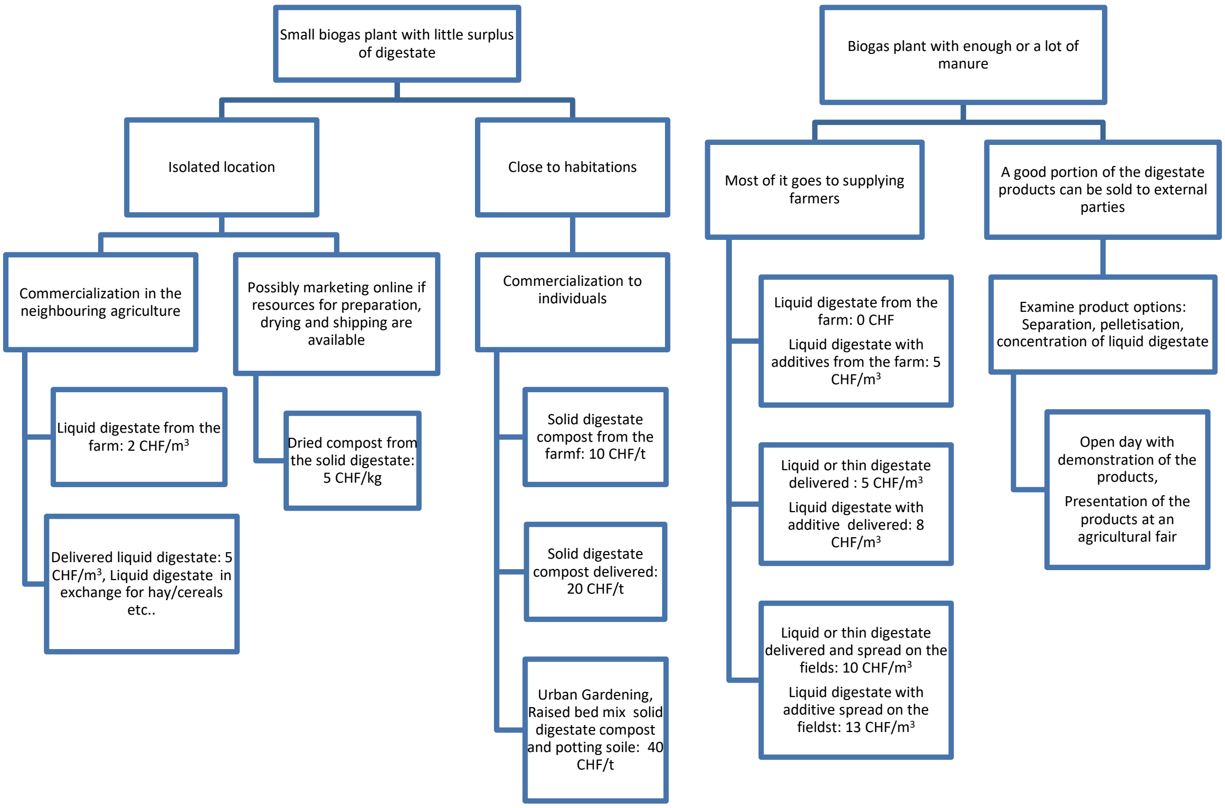


Figure 23: Exemplary decision paths and prices for value creation strategies of digestate products.

6.3.6 Relevant political developments

The parliamentary initiative 19.475 (Pa.Iv. 19.475) was primarily concerned with reducing the use of pesticides in agriculture. In March 2021, the initiative was accepted, and the Federal Act on the Reduction of Risks from the Use of Pesticides was passed (2021), after which the Agriculture Act was amended (among other things) to include targets for the reduction of nutrient losses and pesticide risks. By 2030, nutrient surpluses in nitrogen and phosphorus must be reduced by 20%. The new legal provision stipulates that the Federal Council is to be guided in this by the goal of replacing imported artificial fertilizers with domestic animal manure and biomass. At the same time, farms and traders are now obliged to disclose artificial fertilizer shifts so that nutrient balances can be balanced more accurately at the national and regional levels. The current nitrogen surplus from agriculture, according to OSPAR, amounts to around 100,000 tonnes of nitrogen (Blw, 2021).

The agricultural sector and producer organizations are explicitly called upon to take or propose various measures to reduce the nutrient surplus in agriculture and to regularly report to the Confederation on the nature and effect of their actions. With the new reduction targets, the community benefits of animal manure digestate also gain additional relevance.. Lacking manure storage capacity is a problem that will be exacerbated in particular by the new requirements in connection with the reduction path (e.g., deletion of the Suisse Balance tolerance range). While nutrient surpluses have to be addressed without doubt, agricultural biogas plants can partly counteract the problem of regional animal manure surpluses by providing large digestate and storage capacities.For green electricity in Switzerland, this means that the digestate of animal manure and the substitution of mineral fertilizer through digestate products will gain importance, which could open up better marketing opportunities.

6.4 Discussion of monetary aspects

As part of the BioCircle project, the economic value of digestate products was investigated, as well as the question of promising value creation ideas for digestate products. One of the main findings of the actual analysis of the monetary aspects of digestate products through a survey of agricultural biogas producers is that 70% of the plant operators are currently able to distribute their digestate products without any problems but do not generate any revenue for the products. This situation is partly because most animal manure suppliers also receive their animal manure back after digestion. They lend their animal manure to the biogas plant. At first glance, it seems unfair to demand money for the animal manure when it is returned while the biogas producer earns money with the produced electricity or fuel. On closer inspection, however, the digestate is a different product, an “improved fertilizer” compared to the original animal manure, and the biogas producers have high investment costs to amortize as well as operating costs to tackle with the revenues from the produced energy. And this is where marketing comes in. The value of the digestate products must be known and recognizable. Based on the calculations of the fertilizer values for digestate products following current mineral fertilizer prices, a theoretical economic value of 5-6 CHF for the cubic meter of liquid digestate and 10 CHF for the tonne of solid digestate was determined. These theoretical prices corresponded surprisingly well with the prices achieved in practice (at the biogas plants which were able to sell their products) and the desired prices. Therefore, the ideas about the financial value of the digestate products also seem to reflect the nutritional value for agricultural practice. For commercialization, a system similar to Germany’s RAL seal of quality could be helpful here. The nutrient properties and the corresponding fertilizer value are explicitly shown on the digestate products through the RAL seal of quality. This is not yet commercialization but merely labeling. However, this can help to promote the product better, as the product has a declaration.

Other studies have also looked at the economic value of digestion products. An interesting study from Estonia investigated in a field trial the monetary value of liquid digestate and untreated slurry in terms of nutrient value and the yield of the crop that is fertilized with it (Kall et al., 2016). For untreated cattle slurry, a fertilizer value of 3.23 € per tonne was determined, and for liquid digestate, a fertilizer value of 3.78 € per tonne. Considering grassland’s yield and effective nutrient uptake by fertilizing with these two fertilizer variants, a fertilizer value of 2.58 € for cattle slurry and 2.87 € for liquid digestate was calculated. This study concluded that even if the fertilizer value, taking into account the nutrient uptake of the crops, is not relatively as high as the "gross fertilizer value", the organic fertilizers can, in any case, be assigned an economic value. And due to the higher ammonium-N content, higher potassium values, and associated lower application rates per area, a higher economic value could be assigned to the liquid digestate than cattle slurry.

Since there are currently also efforts at the political level to reduce mineral fertilizers and nutrient surpluses from mineral fertilizers, the question arises as to the ability of digestate products to replace mineral fertilizers. A rough calculation was done to estimate a replacement potential. Digestate products can replace mineral fertilizer because co-substrates supplement the nutrient content of animal manure and, above all, because nitrogen availability is increased by digestate. As in the “Swissbilanz”, a 5% increase in N availability was used compared to undigested manure. Based on the 2019 data on animal manure inputs and co-substrate quantities used in agricultural biogas plants (internal survey at Ökostrom Schweiz, as well as the 5% of the nitrogen in the produced digestate and the liquid separated digestate, the replacement calculation resulted in the equivalent quantity of 423,236 kg of urea. This amount would replace single fertilization with urea on 2116 ha, assuming that, for example, 1 hectare of maize is fertilized with 200 kg of urea. The calculated amount of urea that can be replaced with digestate today corresponds to a share of the annual urea consumption in Switzerland of 2.5% (see **Error! Reference source not found.**). Converted into an economic value, a saving of around CHF 221,000 could have been achieved by replacing just under 500 tonnes of urea. The additional replacement of mineral fertilizers with P and K by digestate products from co-digestion is an exciting topic. Still, quantification is much more complicated than for nitrogen, even though they have the same chemical form in mineral fertilizer and digestate (P_2O_5 and K_2O), leading to 100% availability. No calculation was done for P and K fertilizer replacement estimates.

In a current project to assess the positive externalities of biogas plants, the replacement of mineral nitrogen fertilizer with digestate products was also estimated as an example. It was calculated that a biogas plant with a digestate of 20,000 tonnes of biomass (animal manure and co-substrates) could generate an N mineral fertilizer replacement value of CHF 42,000 (Montpart et al., 2021). This is about ten times higher replacement value than our estimates. The most important difference between the two calculation methods seems to be that in the study by Montpart et al. (2021), the additional nitrogen made available by digestate was taken into account at +20% for the input materials liquid digestate and +34% for solid digestate, whereas in our calculations +5% was used for liquid and solid digestate. Therefore, it can be said that our estimate is conservative.

During the project, considerable changes were happening in the mineral fertilizer market, and prices increased massively, especially towards the end of 2021. A cascade of sharply increased gas prices, which in turn made the production of mineral fertilizers more expensive, whereupon production was curtailed and led to reduced availability of mineral fertilizers. So while thinking of possible value-adding opportunities, animal manure suddenly became interesting for agriculture because mineral fertilizers now cost three times as much. This changes the initial situation and gives the digestate products a suddenly greatly improved marketing opportunity. Thus, the value of the theoretically saved costs for urea based on values of 2020 is suddenly no longer at 221,000 CHF but 662,000 CHF. Accordingly, 2022 seems to be a good moment for agricultural biogas plants to start their plans for pricing their digestate products.

7 Discussion

According to the present study, the Switzerland's agricultural and industrial biogas plants process 1.9 Mt of biomass per year (62% agricultural and 38 % industrial), leading to a yearly biogas production of 2,579 TJ. This biogas quantity corresponds to about 0.2% of the Swiss total gross energy consumption (1,096PJ) and 2% of the total gas consumption in Switzerland (119PJ) (BFE, 2019b). Also, it is similar to the values of official federal statistics, which recorded about 1,400 TJ of gross biogas production for agricultural facilities and 1,300 TJ for industrial biogas facilities in 2018 (BFE, 2019a). This corresponds to about 0.2% of the Swiss total gross energy consumption (1096PJ) and 2% of the total gas consumption in Switzerland (119PJ) (BFE, 2019b)

Together with the biogas, agricultural and industrial biogas produced 1,6 Mt of fertilizer, containing more than 22,000 tonnes of nutrients. Regarding nutrient flows, a high transfer (>75%) was found from input material into biofertilizer, both in industrial and agricultural facilities. Nutrients and carbon are already well recycled in agriculture as manure is applied to the fields even without AD.

However, the nutrients and carbon added by the co-substrates are far from negligible. Indeed, about 11,000 tonnes of nutrients originated from non-agricultural substrates: whereby N (~5000 t), P_2O_5 (~2000 t), and K_2O (~4000 t). This corresponds to a saving of 40,000 tonnes CO_2-eq and 510 TJ of energy compared to the equivalent mineral fertilizers' production. In Switzerland, mineral fertilizers come from abroad and represent 23% of the nitrogen used in agriculture (BLW, 2022). During the fertilization year 2019-2020 a total of 210,099 tonnes of mineral fertilizers were applied in Switzerland (Agricura Platform, Activity Report 2019/2020), of which 43,000 tonnes of nitrogen, 16,500 tonnes of potassium (K_2O), and 9,500 tonnes of phosphorus. Thus, the nutrient quantities provided by the co-substrates represent 12% of N, 24% of K, and 21% of P of applied mineral fertilizer per growing season. These quantities are already being used in today's agricultural system, but as much could be additionally provided if the entire sustainable potential was used.

Looking specifically at the nitrogen from existing agricultural biogas plants (including all agricultural and non-agricultural substrates), just by assuming 5% increased N availability, a urea quantity of 500 tonnes can be substituted by the digestate. This calculated urea amount corresponds to 2.5% of Switzerland's annual urea consumption, and if converted into an economic value to a saving of around CHF 221,000. Moreover, urea is bought abroad, whereas the equivalent quantities of nutrients from the biogas plant would keep the monetary value within Swiss agriculture. Similar high values are expected for P_2O_5 and K_2O.

The quality of biofertilizers is more variable coming out from biogas plants than standardized chemical fertilizer, in line with Switzerland's highly heterogeneous specific biomass characteristics. The digestate and compost characteristics may vary even at the same biogas plant throughout the year. Thus, there is a need for better data regarding the feedstock input and outputs characteristics and precise measurements of emissionsl. As the scenarios examined here showed, the proportion of the different input types also plays a role in the final composition of the digestate and could be adapted to influence the digestate characteristics.

Regarding the possible contaminants, the quality control for plastic is already high, as it is sorted first when it arrives, manually or mechanically, and then in the compost afterward. This is very important for the buyers, and the environment, as visible pieces of plastics, in addition to their chemical pollution, are detrimental to the general landscape and the price of the fertilizers. Microplastic was not considered in detail here but causes further concerns and should be studied further. However, a high potential for biodegradation of microplastic in conventional AD reactors has been shown (Nielsen et al., 2019). Moreover, the pathogenic properties of fermentation products demonstrated a killing effect of dangerous human, veterinary, and plant pathogens during fermentation (Fuchs et al., 2014). Inputs and outputs testing indicated low heavy metal contents in Switzerland (Baier et al., 2016). Therefore, in a circular economy, where the same material is recirculated many times, the possibility of accumulating unwanted substances in the loop needs to be considered and addressed, but the conditions for digestate products are promising.

Some decades ago, anaerobic digestion and composting were considered competitive methods, one excluding the other. Today, anaerobic digestion 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 the circular bioeconomy, the integration of the two processes brings two main advantages: (i) the generation of renewable energy and (ii) the production of organic fertilizer to be used for food production, leading to important environmental and economic gains. Investing in treating waste and residual biomass through anaerobic digestion will lead to less dependence on fossil fuels, higher agricultural self-sufficiency, and cleaner energy. With increasing prices of mineral fertilizers and recognition of the many opportunities they represent, there is today a strong incentive to increase the commercialization of digestate products. Moreover, while the biogas plants need to ensure that the quality of their output biofertilizers is good, the composting installation should keep good practices to limit the losses and emissions that occur during the maturation process. Indeed, the most detrimental greenhouse gas emissions (CH_4, NH_3…) can be limited through management, such as manual aeration of the compost.

Thus AD can be considered a central pillar of resource recovery and the circular economy. Therefore, policymakers need to develop a biogas plant support program that is as comprehensive as possible and goes further than the current support measures, including promoting of energy and material until the market can maintain its economic viability alone. Although limited, the contribution of domestic biogas has a role to play in the energy transition. To achieve the climate goals of the Paris Agreement, Switzerland must fully exploit the potential of all renewable energies by 2050, including sustainable biomass (SFOE, 2020). Indeed, today's quantified advantages could be increased more than twofold, if the entire sustainable potential was used.

8 Conclusions

The study investigated the current industrial and agricultural biogas system in Switzerland and analyzed the effects of potential changes that may occur in the future. The production of biogas, as a renewable energy source, and digestate, as an organic fertilizer, were quantified. Both aspects were assessed from the circular economy perspective. The use of biomass for biogas production impacts 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). After fermentation, the digestate is easier to spread on the fields, 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.

Regarding the monetary aspects, the value of agricultural digestate products depends on how they are valued in terms of quality and quantity. While there is not yet a sales and overproduction problem in this country, there have already been negative prices for digestate products in neighboring Germany. To counteract this development, there are already some market-ready technologies for the post-treatment of liquid digestate. In Switzerland, however, there seems to be primarily a lack of appreciation in marketing for digestate products. The current development of sharply rising mineral fertilizer prices and the political goal of reducing the nitrogen surplus in agriculture comes at a good time to change this. This could even partly compensate for the reduction in support for biogas installation. However, more detailed analysis would be needed on the subject, and it is very dependent on the world market.

Promoting the digestion of residual biomass in an agricultural and industrial setting is one aspect that should be tackled to promote energy autonomy and agricultural self-sufficiency while reducing greenhouse gas emissions. Our first quantification of the biomass available and its potential for fertilization and climate mitigation can provide guidance to decision-makers. An effort should be put into measuring with more precision inputs, outputs, and emissions of biogas plants. Finally, a thorough understanding of material and energy flows in biogas plants offers great potential for optimizing the system, leading to reduced energy demand, more economical operation, and better ecological performance.

9 Outlook and next steps

A next step would be to approach the problem at the business scale to identify the best management methods for the practical operation of biogas plants. Future studies are also needed to investigate how new business models could become profitable and how to integrate circular economy principles in the planning stage. The current increase both in energy and biofertilizer prices may indicate that the market itself could soon better support the difficult economic situation of agricultural biogas plants .

Additionally, the full national biomass system could be included. Regarding industrial biogas plants, this is already done in another study. However, to gain a complete view, it would be necessary to include other biomass types and uses, such as other bioenergy (e.g., municipal waste or wood incinerators) or material usages. The assessment could go up to a detailed national carbon cycle analysis.

Considering wider environmental impacts, Tonini et al. (2014) further notified that MFAs, SFAs, and EFAs can also serve as a basis for life-cycle assessments and are, therefore, complementary tools for environmental management strategies. Indeed, manure management can have many other impacts, e.g., on water pollution and soil fertility. An LCA approach at the country level could show other possibilities to improve the environment in a more holistic way.

10 National and international cooperation

The transdisciplinary approach enabled the establishment of dialogue and exchange of knowledge with the relevant stakeholders. The project supported disseminating the SCCER Biosweet results and the continuing informal cooperation with ZHAW, especially with the project NETZ.

Experts from the Federal Office for Agriculture (FOAG) and Ökostrom Schweiz have accompanied the project and enriched it with their knowledge. Exchanges occurred regularly with experts from universities and other projects (NETZ, EDGE, former BIOSWEET).

Moreover, interactions with other stakeholders have taken place: Agroscope, Biogas plants, Biomasse Suisse.

11 Communication

Through our transdisciplinary approach, we had regular exchanges with relevant stakeholders and experts (e.g., interviews), who will all be informed of the results. This also allowed for the continuation of a dialog between research and practicians.

The open-access scientific publications are an important part of communicating the results (see list in Section 7). These publications and the present report will additionally be sent, once published, to the relevant stakeholders.

WSL webpage:

https://www.wsl.ch/de/projekte/bioenergy-and-circular-economy-the-biogas-plant-as-a-hub.html

Bioénergie et économie circulaire: l'installation de biogaz comme plaque tournante, Journée de la recherche sur la bioénergie en Suisse - Office fédéral de l'énergie 25.05.2021

Master Presentation: Ayed Lana, Material flows of fermentable biomass in the Swiss bioenergy system: Industrial biogas plants, Master thesis, ETH Zürich, 23.04.2021

Poster session for ETH masters: Ayed Lana, Material flows of fermentable biomass in the Swiss bioenergy system: Industrial biogas plants, Master thesis, ETH Zürich, 2022.

Bachelor Presentation: Rolli Christian, Zukunftsszenarien für Biogasanlagen in der Schweiz: Energie-, Stoff- und Massenflussanalyse für die Verwertung von organischer Substanz in landwirtschaftlichen Biogasanlagen, Bachelor thesis, ETH Zürich, 16.08.2021

Nurtured by the expertise built up at WSL through several projects, including Biocircle, several articles regarding the use of manure in biogas plants in Switzerland also appeared in the general press (NZZ, Tagesanzeiger, LeTemps …).

Bioenergy research at WSL, Sustainable bio-resources management and strategies for the transition towards a low fossil carbon economy, Vanessa Burg, Gillianne Bowman - WSL conference, 27 January 2022

Oekostrom Schweiz has issued a member information letter in Spring 2021 with the observed developments in the mineral fertilizer price market, mentioning the theoretical monetary value of the digestates calculated in the BioCircle project and pointing out the currently improved opportunities for digestate marketing.

Oekostrom Schweiz plans to hand out the report on the monetary aspects to its members after the final project report has been accepted, in German and French language.

12 Publications

Ayed Lana, Material flows of fermentable biomass in the Swiss bioenergy system: Industrial biogas plants, Master thesis, ETH Zürich, April 2021

Rolli Christian, Zukunftsszenarien für Biogasanlagen in der Schweiz: Energie-, Stoff- und Massenflussanalyse für die Verwertung von organischer Substanz in landwirtschaftlichen Biogasanlagen, Bachelor thesis, ETH Zürich, September 2021

Bowman, G., Ayed, L., Burg, V., The role of anaerobic digestion in the circular economy: Material and energy flows of industrial biogas plants in Switzerland, challenges and future perspectives, Bioresource Technology Reports, submitted.

Burg, V., Rolli, C., Schnorf, V., Scharfy, D., Ansprach, V., Bowman, G., Agricultural biogas plants as a hub to foster circular economy and bioenergy: An assessment using material and energy flow analysis, Resources, Conservation & Recycling, submitted.

Scharfy, D. and A. Victor (2022). Projekt BioCircle «Bioenergie und zirkuläre Ökonomie» - Arbeitspaket Monetarisierung. Ö. Schweiz. Winterthur.

13 References

2019a. Verordnung (EU) 2019/1009 des Europäischen Parlaments und des Rates mit Vorschriften für die Bereitstellung von EU-Düngeprodukten auf dem Markt. pp. 1-114.

2019b. Verordnung des WBF über das Inverkehrbringen von Düngern. pp. 1-94.

2020. Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung DüV) vom 26.MAi 2017 (BGBl. I S.1305), zuletzt geändert durch Art. 97 G vom 10. August 2021 (BGBl. I S.3436, 3477).

2021. Bundesgesetz über die Verminderung der Risiken durch den Einsatz von Pestiziden (Änderung des Chemikaliengesetzes, des Gewässerschutzgesetzes und des Landwirtschaftsgesetzes).

AGRIDEA, 2020. REFLEX 2020. Betriebswirtschaftliche Datensammlung.

Arnaudruz, M., Weyermann, I., Scheidiger, M., Hunkeler, J., Nyffenegger, L., Ofner, M., 2020. Wegleitung Suisse-Bilanz. Bundesamt für Landwirtschaft und AGRIDEA, Bern, Lindau und Lausanne. Schweiz.

BAFU, 2015. Standardmethode für Kompensationsprojekte des Typs „Landwirtschaftliche Biogasanlagen". p. 24.

BAFU, 2016. Kompostier- und Vergärungsanlagen, Erhebung in der Schweiz und im Liechtenstein.

Baier, U., 2021. Interview Szenarienentwicklung, Pers. Com.

Baier, U., 2022. Vapor emissions from biogas plants and composts, Pers. Com.

Baier, U., Vollmert, B., Wanner, R., Schär, G., Fehr, M., 2016. Schlussbericht Schwermetalle in schweizer Grüungut, in: Report, T. (Ed.).

Barber, M., 2006. Wildcards - Signals from a Future Near You. Journal of Futures Studies.

BFE, 2015. Richtlinie kostendeckende Einspeisevergütung (KEV), Art. 7a EnG, Biomasse Anhang 1.5 EnV.

BFE, 2019a. Schweizerische Statistik der erneuerbaren Energien 2018. https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/teilstatistiken.exturl.html, p. 75.

BFE, 2019b. Schweizerische Gesamtenergiestatistik 2018: 72 p. https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.html/

BGK, 2013. Humus- und Düngewert von Kompost und Gärprodukten. Bundesgütegemeinschaft Kompost e.V., Köln-Gremberghoven, Deutschland.

BGK, 2021. Ablauf der Gütesicherung. Bundesgütegmeinschaft Kompost e.V. https://www.kompost.de/guetesicherung/guetesicherung-gaerprodukt/ablauf-der-guetesicherung.

Binder, C., De Baan, L., Wittmer, D., 2009. Phosphorflüsse in der Schweiz: Stand, Risiken und Handlungsoptionen. Abschlussbericht. Umwelt-Wissen(0928).

Biomasse Schweiz, 2012. QM Biogas. Qualitätsmanagement für Biogasanlagen.

BLW, 2016. Wegleitung Düngerrecht: Kennzeichnung von Düngern. Bundesamt für Landwirtschaft, Bern, Schweiz.

BLW, 2019. Daten aus dem zentralen Informationssystem zu Nährstoffverschiebungen HODUFLU.

BLW, 2021. Stickstoff.

BLW, 2022. Versorgung - Dünger. https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/produktionssicherheit/versorgung.html

Bowman, G., Ayed, L., Burg, V., Submitted. The role of anaerobic digestion in the circular economy: Material and energy flows of industrial biogas plants in Switzerland, challenges and future perspectives. Bioresource Technology Reports, Submitted.

Brunner, P.H., Rechberger, H., 2016. Handbook of material flow analysis: For environmental, resource, and waste engineers. CRC press.

Burg, V., Bowman, G., Erni, M., Lemm, R., Thees, O., 2018a. Analyzing the potential of domestic biomass resources for the energy transition in Switzerland. Biomass Bioenerg 111, 60-69.

Burg, V., Bowman, G., Haubensak, M., Baier, U., Thees, O., 2018b. Valorization of an untapped resource: Energy and greenhouse gas emissions benefits of converting manure to biogas through anaerobic digestion. Resources Conservation and Recycling 136, 53-62.

Burg, V., Bowman, G., Hellweg, S., Thees, O., 2019. Long-term wet bioenergy resources in Switzerland: drivers and projections until 2050. Energies 12(18), 3585.

Burg, V., Bowman, G., Thees, O., Baier, U., Biollaz, S., Damartzis, T., Hersener, J.-L., Luterbacher, J., Madi, H., Maréchal, F., 2021a. Biogas from animal manure in Switzerland.

Burg, V., Rolli, C., Schnorf, V., Scharfy, D., Ansprach, V., Bowman, G., Submitted. Agricultural biogas plants as a hub to foster circular economy and bioenergy: An assessment using material and energy flow analysis. Resources, Conservation & Recycling, Submitted.

Burg, V., Troitzsch, K.G., Akyol, D., Baier, U., Hellweg, S., Thees, O., 2021b. Farmer's willingness to adopt private and collective biogas facilities: an agent-based modeling approach. Resources, Conservation and Recycling 167, 105400.

Calbry-Muzyka, A., Madi, H., Rüsch-Pfund, F., Gandiglio, M., Biollaz, S., 2022. Biogas composition from agricultural sources and organic fraction of municipal solid waste. Renewable Energy 181, 1000-1007.

Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN, EnviroInfo. pp. 440-447.

Chojnacka, K., Gorazda, K., Witek-Krowiak, A., Moustakas, K., 2019. Recovery of fertilizer nutrients from materials - Contradictions, mistakes and future trends. Renewable and Sustainable Energy Reviews 110, 485-498.

Coppens, J., Meers, E., Boon, N., Buysse, J., Vlaeminck, S.E., 2016. Follow the N and P road: high-resolution nutrient flow analysis of the Flanders region as precursor for sustainable resource management. Resources, Conservation and Recycling 115, 9-21.

CVIS, 2020. Biogas installations in Switzerland: Processes, inputs and outputs, in Inspektorat der Kompostier- und Vergärbranche der Schweiz.

Dahlin, J., Herbes, C., Nelles, M., 2015. Biogas digestate marketing: Qualitative insights into the supply side. Resources, Conservation and Recycling 104, 152-161.

Der Schweizerische Bundesrat, 1990. Technische Verordnung über Abfälle (TVA), 10.12.1990 (Stand 2011).

Der Schweizerische Bundesrat, 2001. Verordnung über das Inverkehrbringen von Düngern (Dünger-Verordnung, DüV), 10. Januar 2001 (Stand am 1. Januar 2016).

Der Schweizerische Bundesrat, 2015. Verordnung über die Vermeidung und die Entsorgung von Abfällen (Abfallverordnung, VVEA), 4.12.2015 (Stand 1.2019).

Dinkel, F., Zschokke, M., Schleiss, K., 2012. Ökobilanzen zur Biomasseverwertung. Autragnehmer: Carbotech AG. Publikation 290577.

Enea Consulting, 2019. Revue des externalités positives de la filière biométhane. https://www.afgaz.fr/sites/default/files/u200/annexe_enea_externalites_de_la_filiere_biomethane_22032019.pdf.

European Biogas Association, 2015. Digestate Factsheet: the value of organic fertilisers for Europe's economy, society and environment. http://europeanbiogas.eu/wp-content/uploads/2015/07/Digestate-paper-final-08072015.pdf: 4.

European Biomass Industry Association, 2022. Anaerobic digestion. https://www.eubia.org/cms/wiki-biomass/anaerobic-digestion/European Commission, 2015. Closing the loop - An EU action plan for the Circular Economy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

European Parliament, 2022. "Circular economy: definition, importance and benefits." News, https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

Fagerström, A., Al Seadi, T., Rasi, S., Briseid, T., 2018. The role of anaerobic digestion and biogas in the circular economy. IEA Bioenergy.

Fantner, G., 2013. A brief introduction to error analysis and propagation. EPFL, p. 12.

FOEN, 2020. Circular economy in Switzerland. Dec. 07, 2020.

Fuchs, J., 2015. Hygienische Qualität von schweizerischem flüssigem Gärgut und daraus abgeleitete Anwendungsempfehlungen, compostmagazine.

Fuchs, J., Baier, U., Berner, A., Philipp, W., Schleiss, K., 2014. Abschätzung des hygienischen Risikos im Zusammenhang mit der Anwendung von flüssigem Gärgut in der Schweiz. FiBL, Frick, Schweiz.

Gisler, S., 2021. Interview Szenarienentwicklung, Pers. Com.

GRUD, 2017. Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD) |, in: Spezialpublikation. Agroscope, https://www.agroscope.admin.ch/agroscope/de/home/themen/umwelt-ressourcen/boden-gewaesser-naehrstoffe/projekte-zur-verbesserung-der-naehrstoffeffizienz/grud.html.

GRUDAF, 2009. Principles of fertiliser application in arable and forage cultivation.

Hersener, J.-L., 2021. Interview Szenarienentwicklung, Pers. Com.

Hüsch, S., Baier, U., Breitenmoser, L., Gross, T., Rüsch, F., 2018. Lebensmittelabfälle in Schweizer Grüngut.

Jarosch, K., Richner, W., Mayer, J., 2018. Stickstoffausnutzungseffizienz von Biogasgülle. Agrarforschung Schweiz 9(3), 76-81.

Jensen, M.B., Møller, J., Scheutz, C., 2017. Assessment of a combined dry anaerobic digestion and post-composting treatment facility for source-separated organic household waste, using material and substance flow analysis and life cycle inventory. Waste Management 66, 23-35.

Kall, K., Roosmaa, Ü., Viiralt, R., 2016. Assessment of the economic value of cattle slurry and biogas digestate used on grassland. Agronomy Research 14(1), 54–66.

Kawecki, D., Goldberg, L., Nowack, B., 2021. Material flow analysis of plastic in organic waste in Switzerland. Soil Use and Management 37(2), 277-288.

Kröger, R., Reckermann, M., Schaper, C., Theuvsen, L., 2016. Gärreste als Gartendünger vermarkten?, Zeitschrift für Agrarpolitik und Landwirtschaft. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV), Bonn, Deutschland.

KTBL, 2013. Faustzahlen Biogas.

Meier, A., 2021. Interview Szenarienentwicklung, Pers. Com.

Meier, U., Hersener, J.-L., Bolli, S., Anspach, V., 2016. „RAUS – REIN": Feststoffe „RAUS" aus der Gülle und „REIN" in die Vergärung, Neuartiges Konzept zur Verbreitung der Vergärung von Hofdünger in der Schweiz. p. 50.

Montpart, N., Husser, T., Stephan, H., 2021. Evaluation et monétarisation des externalités positives de la méthanisation en Suisse. Office fédéral de l'énergie OFEN, Bern, Schweiz.

Müller, A., 2021. Interview Szenarienentwicklung, Pers. Com.

Nägele, H.-J., 2021. Interview Szenarienentwicklung, Pers. Com.

Nägele, H.-J., Baier, U., Rüsch, F., 2021. Vorprojekt Netz: Nährstoff- und Energietechnik-Zentrum.

Nielsen, J.L., Pedersen, N.K., Peydaei, A., Baudu, E., Gurevich, L., Fojan, P., Wimmer, R., de Jonge, N., Fernando, E., 2019. Potential for biodegradation of microplastics in thermophilic anaerobic digesters, Anaerobic Digestion Conference AD16. Delft, The Netherlands.

Ökostrom, S., 2020. Vergärungsprodukte aus landwirtschaftlichen Biogasanlagen. Effizient und nachhaltig düngen mit Gärgülle und Gärmist. Fachverband landwirtschaftliches Biogas, Winterthur, Schweiz.

Ow, v., 2021. Interview Szenarienentwicklung, Pers. Com.

Reinhold, J., 2008. Bestimmung und Entwicklung des Wertes organischer Substanz in Kompost, Humustag. Potsdam, Deutschand.

Scharfy, D., 2021. Interview Szenarienentwicklung, Pers. Com.

Scharfy, D., Anspach, V., 2021. EvEmBi - Evaluation und Reduktion von Methanemissionen verschiedener Biogasanlagenkonzepte in Europa: Fokus Schweiz. Genossenschaft Ökostrom Schweiz, Winterthur, Schweiz.

Scharfy, D., Victor, A., 2022. Projekt BioCircle «Bioenergie und zirkuläre Ökonomie» - Arbeitspaket Monetarisierung, in: Ökostrom Schweiz. Winterthur.

Schievano, A., D'Imporzano, G., Salati, S., Adani, F., 2011. On-field study of anaerobic digestion full-scale plants (Part I): An on-field methodology to determine mass, carbon and nutrients balance. Bioresource technology 102(17), 7737-7744.

Schievano, A D'Imporzano, G., Salati, S., Adani, F., Scaglia, B., Genevini, P. L. 2009. "What is the digestate?" https://www.researchgate.net/publication/237805800_WHAT_IS_THE_DIGESTATE: 13.

Schleiss, K., 2020. Abschlussbericht: Erhebung Schweizer Daten zu Mengen in der Kompostierung. Bundesamt für Umwelt (BAFU).

Schnorf, V., Trutnevyte, E., Bowman, G., Burg, V., 2021. Biomass transport for energy: Cost, energy and CO2 performance of forest wood and manure transport chains in Switzerland. Journal of Cleaner Production, 125971.

SFOE, 2020. Energieperspektiven 2050+, Retrieved January 14 2021, from https://www.bfe.admin.ch/bfe/fr/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZnIvcHVibGljYX/Rpb24vZG93bmxvYWQvMTAzMjM=.html, p. 112.

Stürmer, B., Leiers, D., Anspach, V., Brügging, E., Scharfy, D., Wissel, T., 2021. Agricultural biogas production: A regional comparison of technical parameters. Renewable Energy 164, 171-182.

Tanzer, J., Rechberger, H., 2019. Setting the common ground: a generic framework for material flow analysis of complex systems. Recycling 4(2), 23.

The Swiss Federal Council, 2000. Legal ordinance on spatial planning - Raumplanungsverordnung (RPV), 28. Juni 2000 in: Der Schweizerische Bundesrat 700.1, (Stand am 1. Januar 2021) ed.

Thees, O., Burg, V., Erni, M., Bowman, G., Lemm, R., 2017. Biomassepotenziale der Schweiz für die energetische Nutzung, Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER Biosweet., WSL Bericht. WSL, SCCER, p. 299.

Tonini, D., Dorini, G., Astrup, T.F., 2014. Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process. Applied Energy 121, 64-78.

Treichler, A., Warthmann, R., Baier, U., Hersener, J.-L., Meier, U., Büeler, E., Hommes, G., 2016. LEVER, Leistungssteigerung der Vergärung von Rindergülle zu Biogas durch innovative Vorbehandlung und neuartige Reaktorsysteme, in: BFE. p. 100.

VDLUFA, 2014. Humusbilanzierung. Eine Methode zur Analyse und Bewertung der Humusversorgung von Ackerland, in: Forschungsanstalten. https://www.humusbilanz.ch/download/VDLUFA_2014_Humusbilanzierung.pdf.

Virtanen, M., Manskinen, K., Uusitalo, V., Syvänne, J., Cura, K., 2019. Regional material flow tools to promote circular economy. Journal of Cleaner Production 235, 1020-1025.

Webb, J., Sorensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Reid, J., 2013. An Assessment of the Variation of Manure Nitrogen Efficiency throughout Europe and an Appraisal of Means to Increase Manure-N Efficiency. Advances in Agronomy 119, 371-442.

Wilken, D., 2020. Digestate as Fertiliser. Application, upgrading and marketing, Biogas Convention International.

Zabaleta, I., Rodic, L., 2015. Recovery of essential nutrients from municipal solid waste–Impact of waste management infrastructure and governance aspects. Waste Management 44, 178-187.

Zimmermann, A., Nemecek, T., Waldvogel, T., 2017. Umwelt- und ressourcenschonende Ernährung: Detaillierte Analyse für die Schweiz, in: Agroscope (Ed.). Bildung und Forschung WBF Eidgenössisches Departement für Wirtschaft.

14 Appendix

14.1 Method and modell

Wild Card Method and interview design

In order to bring the interviewees to a different thinking - from today's perspective to one in the future - the task of coming up with one or more “wild cards” was given as an introduction to each interview (Breit 2021). Wild cards are events or changes in the future which have a low probability of occurrence but a high impact (Barber 2006). Through these wild cards, a picture of possible changes in the system can be depicted and possible influencing factors can be identified. These changes could be, for example, in the area of political framework conditions, consumption and nutritional behavior, or in the technical area. The discussion of these wild cards provided a basis to formulate the scenarios. Subsequently, we moved from the wild cards to more realistic changes in order to obtain a holistic picture of the possible and relevant futures from which four main scenarios were derived.

To develop the scenarios, the interviews were divided into three categories with different main objective. In a first category of basic interviews, the main objective was defining scenarios. The secondary objective was to concretize these. For this first group of interviews, experts with broad knowledge and a good overview of the overall system were chosen and first versions of scenarios were formulated. Then, in a second category, the focus was on concretizing the formulated scenarios. The experts were also asked to provide topic-specific information on the scenarios that had already been roughly defined. The last category of interviews was primarily used to discuss unresolved issues or to obtain experts' opinions on the assumptions made to validate them.

Scenario 1: Favorable conditions

The first scenario was defined to provide a reference scenario for the year 2050, which is realistic to achieve in the next 30 years. The time horizon 2050 was chosen based on the Energy Perspective 2050+ (SFOE 2020). Through the interviews (Gisler 2021; Meier 2021; Scharfy 2021), we estimated how many additional plants could realistically be built in the coming years. Since it is hardly possible to predict the development of the political framework conditions, which have a very strong influence on the construction of new plants (Meier 2021; Scharfy 2021), assumptions were made about further development. Through initiatives such as the CO_2 Act, which was rejected in June 2021 (Federal Chancellery, 2021), or the parliamentary initiative 20.3485 in the Council of States (Fässler 2021), which was accepted, attempts are being made at the political level to improve the framework conditions for biogas plants. Therefore, for this scenario, we assumed that Swiss policy will promote biogas plants similarly to today’s situation. Ökostrom Schweiz calculates that a doubling of plants in 10 years is realistic under improved conditions such as simplified permit procedure and cost-covering operation in the longer term (Meier 2021). Based on the 2018 flows model and the development until 2050, this doubling was converted into a new construction rate:

$$\frac{+100\%}{10\,a} = +10\%\,per\ Year \rightarrow 2050 - 2018 = 32a \rightarrow 32a * 0.1 = 3.2 = \underline{+320\%}$$

This increase corresponds to a system with about 458 agricultural biogas plants. All input flows were increased by this factor, similar to the extrapolation for the already existing plants in the base model.

Scenario 2: Utilization of the sustainable potential

This scenario is based on the complete utilization of the sustainable potential of manure for energy according to Thees et al. (2017). For the STAN model, all import flows were divided into three categories: Manure, Agricultural by-products, and Other substrates. Within each category, changes were calculated in the same way and under the same assumptions. The amounts of energy, carbon, and nutrients per tonne of fresh matter (FM) were held constant for all flows since it is primarily their amounts that change, not their composition.

Scenario 3: Sustainable food system

Nutrition in Switzerland will develop in the future, which could have a direct influence on agricultural production (Müller 2021; Ow 2021) and thus also on the availability of substrates for agricultural biogas plants. Already today, a slight trend towards less meat consumption can be observed. This influences the amounts of manure produced, which make up a large part of the input. A previous study (Zimmermann et al. 2017) analyzed and compared four nutrition scenarios under different framework conditions, where environmental impacts were reduced by running a model with an objective function for minimized environmental factors. No time horizons were given for these scenarios. We modelled the Sustainable food system scenario using the "FoodWaste" nutrition scenario from Zimmermann et al. (2017) as it has the lowest environmental impact and, together with the maximum possible reduction in food waste, is closest to a closed-loop system.

The changes under the "FoodWaste" scenario were compared to the STAN Sustainable potential scenario to calculate a new potential with a sustainable food system where all sustainably available resources are used for energy. For the calculations, the input flows were again divided into three categories but all food waste was excluded from the category "Other substrates" and treated separately.

The calculations of manure quantities are based on the assumption that these correlate directly with the animal population and were therefore derived from animal population trends.

$$\text{Example for cows} \qquad 475'000\ LSU\ /\ 916'634\ LSU\ = 0.52$$

This factor was then multiplied by the fresh mass value of the scenario Sustainable potential to calculate the new quantities. We did not consider changes in the ratio between theoretical and sustainable potential due to e.g. extensification of livestock production or longer grazing time.

The agricultural by-products considered in this scenario were cereal waste and grass. In the "FoodWaste" nutrition scenario, the cultivated area for each crop was calculated by Zimmermann et al. (2017). Using additional data from Thees et al. (2017) on reference yields of by-products and their sustainably usable portions, the factor by which agricultural by-products will increase or decrease was calculated. Since it was difficult to distinguish between crop by-products, intercrops, and grass, the average was used for the factor of change. In addition, it was assumed that the input flow grass "Grass" is not only grass, but also other intercrops.

$$\text{Faktor} = \frac{\sum(A_{i\,FoodWaste} * N_i * x_i)}{\sum(A_{i\,Ref} * N_i * x_i)} = 1.118$$

A = Area [ha]	(Zimmermann et al. 2017)
N = By-products [t/a pro ha]	(Thees et al. 2017)
x = Sustainable usable part	(Thees et al. 2017)

Food processing losses are on average 22.3%, of which 19.5% could be avoided and thus would lead to a reduction of 87.4% of food waste (Zimmermann et al. 2017). Accordingly, all food waste in this scenario was reduced by 87.4% compared to the sustainable potential. The input "Milk" was assumed to be directly correlated with the cow population. For the input flows such as "Animal remainings", "Blood" and "Silage", a direct correlation with the total livestock was assumed. All remaining organic substrates account for 0.94% of the total fresh matter input, respectively 4.08% of the total dry matter in the scenario Sustainable potential. Due to their small contribution to the total input and the lack of data, the assumption was made that the remaining organic substrates will remain constant.

Scenario 4: Technical changes in the system

The focus of technical changes was placed on separation before fermentation (Nägele 2021; Hersener 2021) in accordance with the ongoing project NETZ. The project aims to achieve higher exploitation of the biomass potential by separating raw manure into liquid and solid fractions and subsequent separate fermentation (Nägele et al. 2021; Hersener 2021).

In the modeling, all input flows remain constant compared to the status quo, to show the impact of separation on biomass, energy, carbon, and nutrient flows. The separation values of the pressing screw come from the final report LEVER (Treichler et al. 2016) but no data were collected for carbon. The ratios had to be calculated based on a European study (Webb et al. 2013) where the DM content in the liquid fraction is reduced by 40-45% and the C content by 45-50%. The 39% reduction in DM content in the liquid fraction is in a similar range for the LEVER data (Treichler et al. 2016).

Only input flows that occur directly on farms and have a dry matter content of less than 10% are fed into the separator. These criteria apply to the two flows cattle slurry and cattle manure. From these two flows, a raw slurry was calculated with the average values weighted by quantity. Subsequently, from this raw slurry, using the relative data from (Treichler et al. 2016; Webb et al. 2013), the values of separated slurry solids and thin slurry were calculated.

Storage losses were quantified as 0.1% in the 2018 model. Therefore, it was assumed that this remains unchanged and that 0.1% of all substrates are lost as storage losses during pre-treatment.

The proportions of oDM were used to calculate the biogas yields of the two digesters. For this purpose, the proportions of total oDM were calculated and the total biogas was offset with these two factors. The NETZ project also aims to reduce emissions and energy losses by using larger and more efficient regional digesters but it is not yet clear how much higher this efficiency will be (Nägele 2021). We assumed that the regional digester would have a 5% increase in gas yield and a 10% reduction in emissions. This results in the following calculation for biogas yields:

$$Biogas_{tot}(DM) * Anteil\ oDM_{tot} * Efficience_{rel\ to\ Baseline} = Biogas_{FM\ XY}\ (FS)$$

Biogas in liquid digester: 59'453 t*0.111*1 =6‘589 t

Biogas in regional digester: 59'453 t*0.889*1.05 =55'508 t

For the emissions, it was assumed that they correlate with the dry matter since all nutrient fractions are calculated via the dry matter and the water fraction is irrelevant. Furthermore, it was assumed that the dry matter fraction in the emissions remains the same, since this is also given as 85% in the Status Quo scenario, and accordingly contains only very low water fractions.

$$\frac{Emissions_{tot}(DM) * Proportion\ DM_{tot} * Efficience_{rel\ to\ Baseline}}{\%DM} = Biogas_{FM\ XY}$$

Emissions in the liquid digester: $\frac{13'879\ t * 0.137 * 1}{0.845} = 2'252\ t$

Emissions in the regional digester: $\frac{13'879\ t * 0.863 * 0.9}{0.845} = 55'508\ t$

The relative errors of 7% on the FM were taken from the status quo and the uncertainty in separation could increase it by an additional 10% (Hersener 2021).

Since there are no values yet on the energy, nutrient and carbon contents of the digestate from the liquid digester, an assumption had to be made. The raw slurry with a DM content of 4.4% corresponds most closely to the two liquid digestates “Thin Digestate” (4.7%) and “Liquid Digestate” (5.3%) from the Status Quo model. A “Thin+Liquid Digestate” was calculated from these two flows, from which the recalculated liquid digestate from the liquid digester was subtracted since this fraction no longer enters the regional digester. This apportionment is highly simplified due to the assumption’s uncertainty. By increasing the error ranges by a further 10%, STAN was given more leeway to ensure that the outputs nutrient values merge with those of the inputs to the respective digesters in the calculation.

14.2 Results

Table A1: Secondary energy according to the industrial biogas plant data

	Unit	Type 1	Type 2	Type 3	Total
Total biogas production	m^3	43,778,633	12,243,209	4,984,286	61,006,129
	TJ	942	263	107	1,313

Total electricity production	MkWh	62,849	25,277	6,573	94,700
	TJ	226	91	23	340
Biomethane sold	m^3	107,557,355	14,284,565	0	121,841,920
	TJ	387	51	0	438
Heat sold	MkWh	23,526	18,692	9,627	51,845
	TJ	84	67	34	186

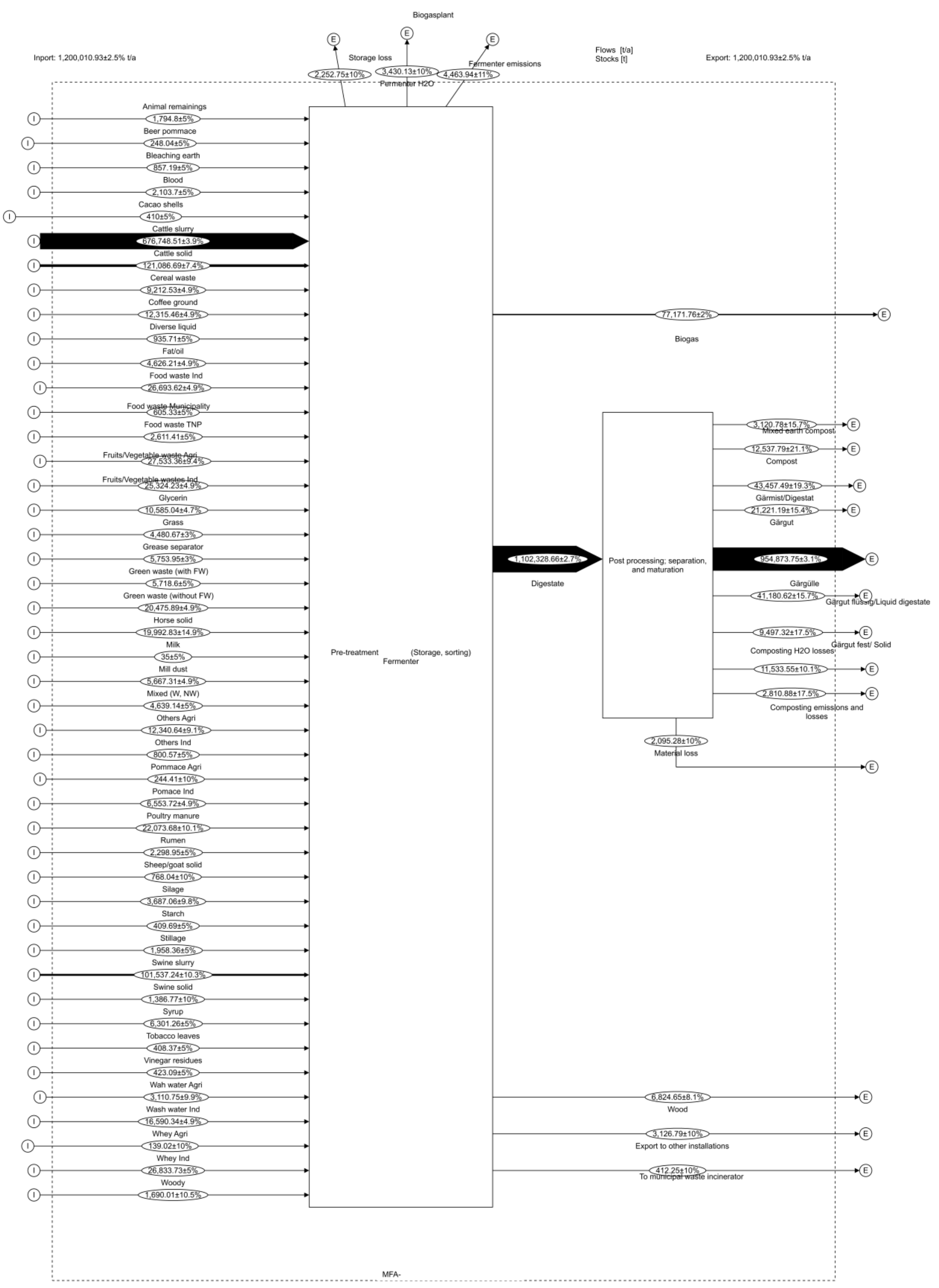


Figure A.1: Material flow analysis of the agricultural subsystem in 2018.

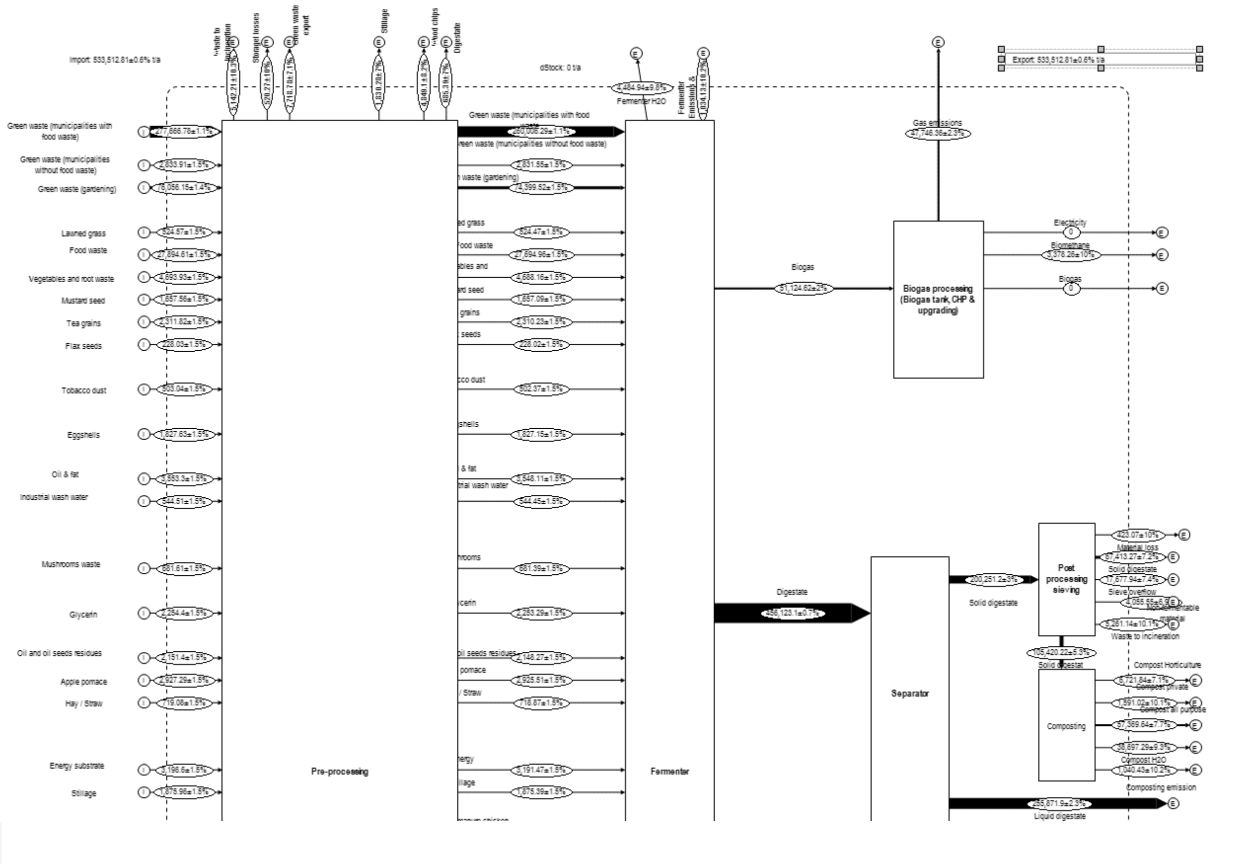


Figure A.2: Material flow analysis of the industrial subsystem Type 1 in 2018 (zoom in STAN).

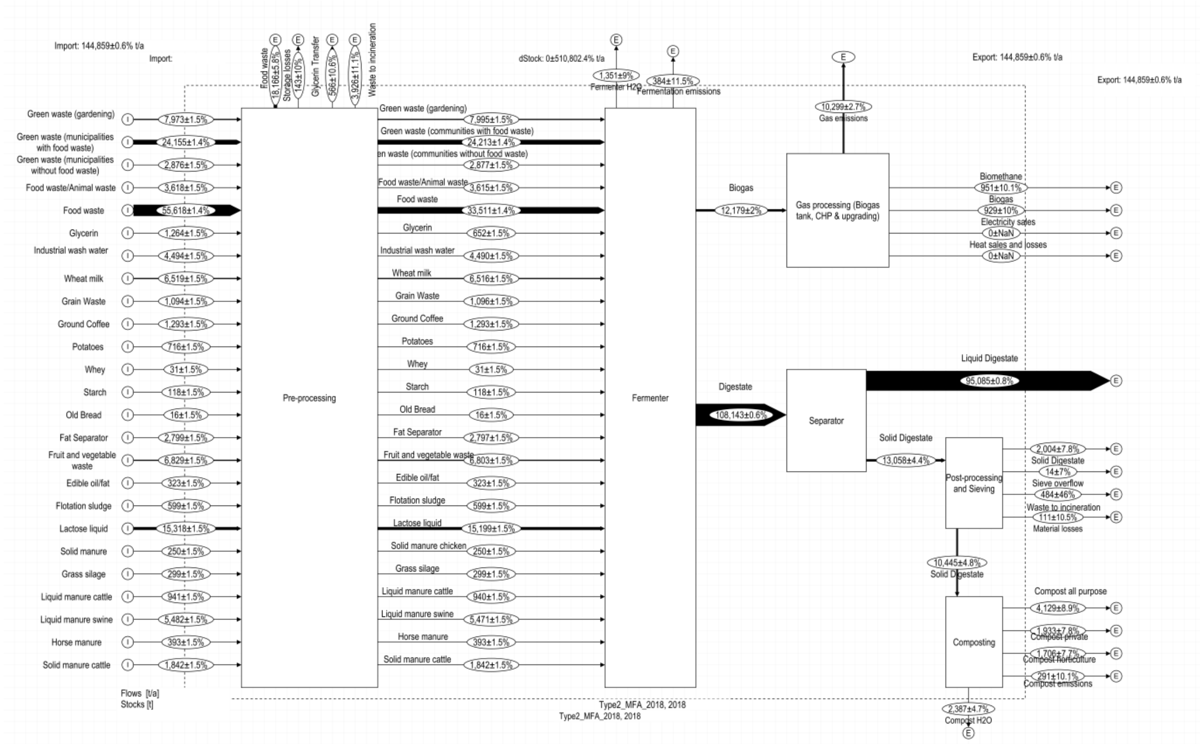


Figure A.3: Material flow analysis of the industrial subsystem Type 2 in 2018.

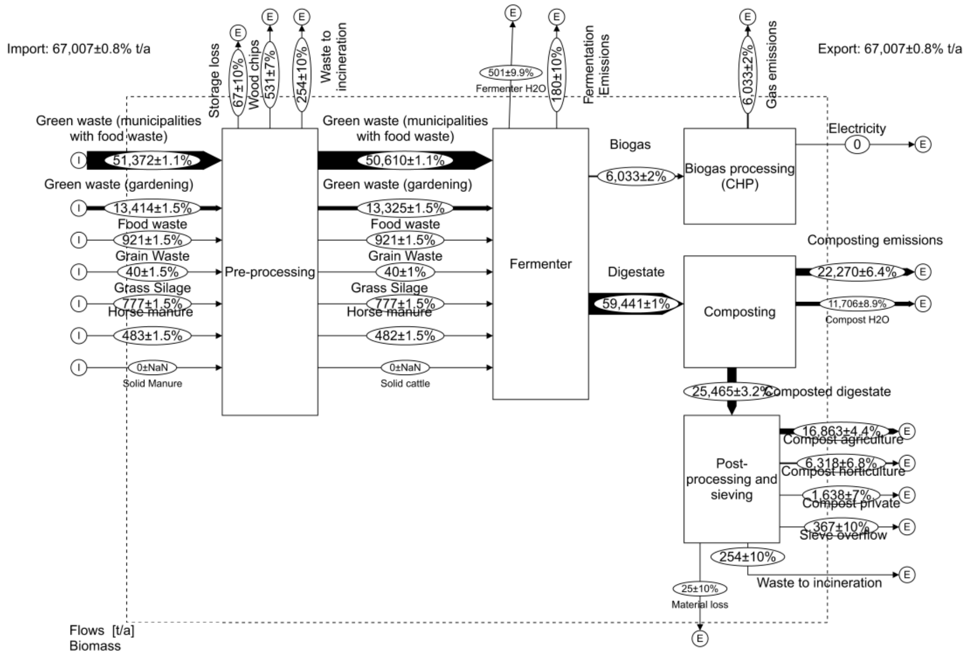


Figure A.4: Material flow analysis of the industrial subsystem Type 3 in 2018.