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WHITE PAPER

Biogas from animal manure in Switzerland

Energy potential, technology development and resource mobilization

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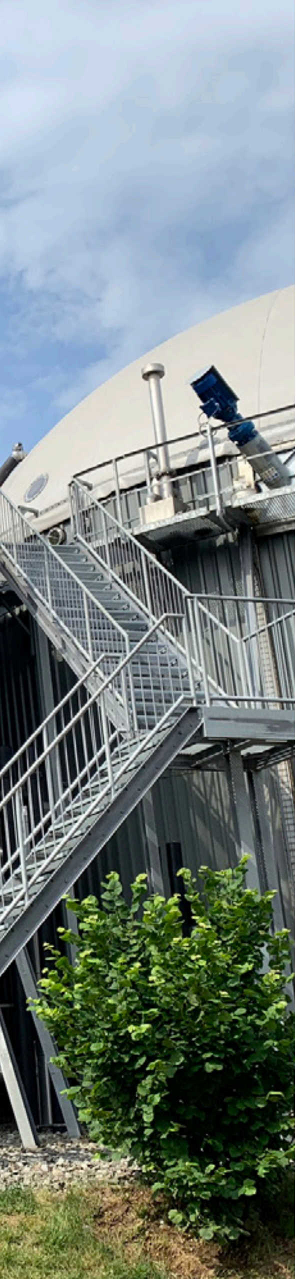

Impressum

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Suggested citation
Burg, V.; Bowman, G.; Thees, O.; Baier, U.; Biollaz, S.; Damartzis, T.; Hersener, J.-L.; Luterbacher, J.; Madi, H.; Maréchal, F.; Moioli, E.; Rüsch, F.; Studer, M.; Van herle, J.; Vogel, F.; Kröcher, O., 2021: White Paper: Biogas from animal manure in Switzerland: energy potential, technology development and resource mobilization. SCCER-BIOSWEET; Birmensdorf, Swiss Federal Research Institute WSL. 20 pp.

https://www.doi.org/10.16904/envidat.255

Aim of the white paper

Aim of this white paper is to provide decision-makers, administrations and stakeholders with the most current research findings in order to promote the optimal use of bioenergy from manure in the Swiss energy transition. For this purpose, the results of the Swiss competence center for bioenergy research – SCCER BIOSWEET – are summarized and presented in a broader context. If nothing else is mentioned, the results refer to Switzerland and in case of the feedstock to the domestic biomass potentials.

Photos cover: Florian Rüsch (ZHAW), Vanessa Burg (WSL) and Vivienne Schnorf (WSL)

Layout: Sandra Gurzeler, WSL

Editor
Swiss Federal Institute for Forest Snow and Landscape Research WSL, Birmensdorf, 13.12.2021

Summary

Switzerland is facing a far-reaching transformation of its energy system. To identify solutions to the technical, social, and political challenges linked to the energy transition, the Federal Council and Parliament launched eight Swiss Competence Centers for Energy Research (SCCERs) in 2014 in support of the Swiss Government's Energy Strategy 2050. In the SCCER BIOSWEET (BIOmass for SWiss EnErgy fuTure), the focus is on biomass and biomass conversion.

Even though biogas technology is a highly developed and ready-to-use technology, the use of manure as an energy source is still very limited in Switzerland. Anaerobic digestion (AD) is a promising technology to generate renewable bioenergy in the form of heat, electricity, and fuel from manure. Furthermore, AD improves fertilizer quality and reduces mineral fertilizer use. Thus, manure should be recognized as a crucial local resource to be used for soil fertilization, nutrient recovery, and energy supply, leading to reduced greenhouse gas (GHG) emissions.

In this white paper, we assess the situation regarding manure in Switzerland to identify the reasons for its low utilization as energy source.

The complexity and varying nature of manure makes this feedstock difficult to use for other sustainable products, and as such, its use for energy does not compete with other pathways. Today, manure conversion is characterized by small-scale converters, which suffer from low efficiency of the electricity conversion from gas. The efficiency of the energy provision from manure could be improved by introducing more efficient techniques throughout the AD process chain. This includes separation of manure into solid and liquid fractions, and technologies linked to better pre-treatment of manure (microbial pre-digestion, thermochemical pretreatment) as well as methanation, gas cleaning and fuel cells. Besides AD, hydrothermal gasification and biochar production are interesting emerging technologies with great potential for quantitative manure conversion. The overall modeling of the energy system points to the high relevance of the use of manure as energy source.

To summarize, the use of manure for energy purposes in Switzerland could be much greater than it is today. However, this would require an expansion of the biogas infrastructure and the current incentives. In addition to having potential environmental benefits (particularly reducing CO_2 emissions), providing energy from manure helps to stabilize the energy system, in combination with other renewables, and makes it possible to achieve greater energy independence from traditional fossil fuel sources.

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1 Introduction

Switzerland is facing a gradual and far-reaching transformation of its energy system. To identify solutions to the technical, social, and political challenges linked to the energy transition, the Federal Council and Parliament launched the action plan “Swiss Coordinated Energy Research”, under which the Swiss Commission for Technology and Innovation (CTI; now Innosuisse), the Swiss National Science Foundation (SNSF), and the Swiss Federal Office of Energy (SFOE) have been mandated to develop and manage interdisciplinary research networks between higher education institutions. Eight Swiss Competence Centers for Energy Research (SCCERs) were established in 2014 in support of the Swiss Government’s Energy Strategy 2050. In the SCCER BIOSWEET (BIOmass for SWiss EnErgy fuTure; www.sccer-biosweet.ch), the focus is on biomass and particularly on the research and implementation of biomass conversion processes with a high level of technological readiness. This program has led to many new insights into the domain of bioenergy, and the synthesis here presents its main findings in the context of the energy transition in Switzerland.

Despite the considerable amount of manure produced and although biogas technology is highly developed and ready for use, the use of manure as an energy source is still very limited in Switzerland. About 110 agricultural biogas units provide 1440 terajoules (TJ) per year, a considerable part of which is due to co-substrate fermentation. Thus, today only a fraction of the available manure is utilized for energy. Anaerobic digestion (AD) is a promising technology for the conversion of manure to renewable bioenergy in the form of heat, electricity, and fuel whilst mitigating greenhouse gas (GHG) emissions from conventional manure management. In Switzerland, agriculture represents 12.7 % of the country’s total GHG emissions, of which 19 % is due to manure management. Hence, manure AD offers opportunities to help Switzerland reach the goals of the Energy Strategy 2050 and to support the country’s commitment to the Paris Agreement. Furthermore, AD increases nutrient availability for plants when the digestate is used as fertilizer and reduces mineral fertilizer use. Thus, manure should be recognized as a crucial local resource that can be used for nutrient recovery (co-substrate), and as well as energy supply, leading to reduced greenhouse gas (GHG) emissions.

In this white paper, we assess the situation regarding manure in Switzerland to identify the reasons for its low utilization for energy application. More specifically, we first present manure characteristics as a feedstock with regard to its primary energy content, spatial distribution, and hotspots (section 2). We then describe the recent technological developments analyzed within the framework of the SCCER BIOSWEET program and other projects (section 3). Moreover, we examine the opportunities and barriers of manure-based bioenergy considering various aspects: GHG mitigation, farmers’ points of view and incentives, supply chains, and other possible manure valorization (section 4). We further analyze the role of manure within the energy system through a modeling approach (section 5) and provide recommendations to promote the use of manure for energy (section 6).

2 Manure feedstock

The total theoretical potential of Swiss biomass is 209 petajoules (PJ) of primary energy per year (fig. 1) – about half from forest wood (108 PJ) and a quarter from manure (49 PJ). Primary energy is the total energy contained within the resource before any transformation losses into secondary energy (1 PJ = 10^{15} Joule). This theoretical potential represents the total amount of biomass that is produced in a year. About 27 PJ of the manure could be mobilized for energy generation in a sustainable way (Burg *et al.* 2018a; Thees *et al.* 2017). This sustainable potential considers losses when the animals are in pastures and the techno-economical constraints linked to the spatial distribution of manure (as a minimum amount of locally produced manure is necessary). Currently, manure is barely used for energy, mostly due to

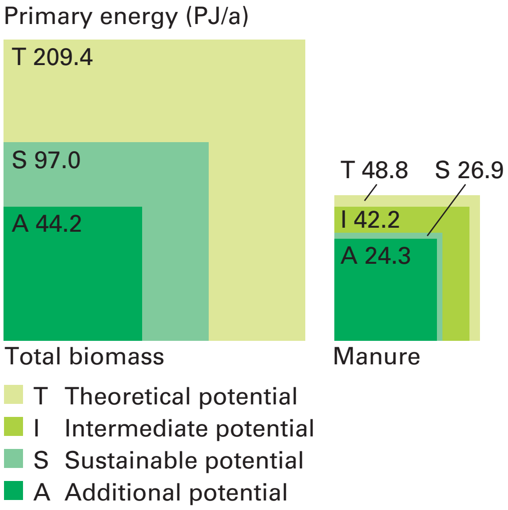

Figure 1: Manure potentials in Switzerland.

economic constraints. Hence, manure has a large additional potential (24 PJ), which corresponds to the energy content of 0.57 Mt of oil equivalent or around 2.2% of Switzerland's total gross energy consumption (1103 PJ in 2019 [SFOE 2020]).

The estimated manure potentials are widely distributed across the country (fig. 2). This spread, in addition to the relatively small-scale nature of Swiss farms (27 livestock units on average), complicates manure collection and exploitation for energy purposes. The highest manure availability can be found in the Central Plateau (in the canton of Berne, followed by Lucerne and St. Gallen), where most animal farming takes place.

In order to promote an effective deployment of biomass utilization for energy, it is important to identify and prioritize regions where both the bioenergy resource availability and the socio-economic context are suitable for bioenergy innovation. Hence, Mohr *et al.* (2019) used spatially explicit potential data to identify municipal hotspots and coldspots of biomass potentials, which they then compared with socio-economic characteristics of these regions (fig. 3). They found that manure hotspots lie in intensively farmed areas of the Central Plateau, while the coldspots are located in the Alps and densely populated areas. Their statistical analysis showed that socio-economic properties, such as household income, political orientation, and population density, differ strongly between hotspots and coldspots. For example, the attitude towards energy transition is on average better in the coldspots than in the hotspots. While the comparison shows correlation rather than causality, it may help us to find and use synergies between areas and to apply the knowledge gained to other projects in similar areas. For example, project developers with successful biomass projects in one municipality could reach out to similar municipalities in terms of bio-resource availability and population mindset towards renewable energies.

In 2050 the amount of manure available for energy is expected to be similar to the current values (Burg *et al.* 2019). Indeed, the theoretical potential is estimated to be 49 PJ, while the sustainable potential will slightly decrease by less than 2 PJ (down to 25 PJ), due to animals spending more time in the pasture where manure cannot be collected. These projections consider different possible drivers (e.g. population growth, general consumption) but no disruptive events, which are unpredictable. For example, a sudden diminution of meat consumption could drastically reduce future manure availability. The long-term estimation of the manure resource potential confirms that there will be enough feedstock available in the future to run a much larger number of (especially agricultural) biogas facilities than are operated today.

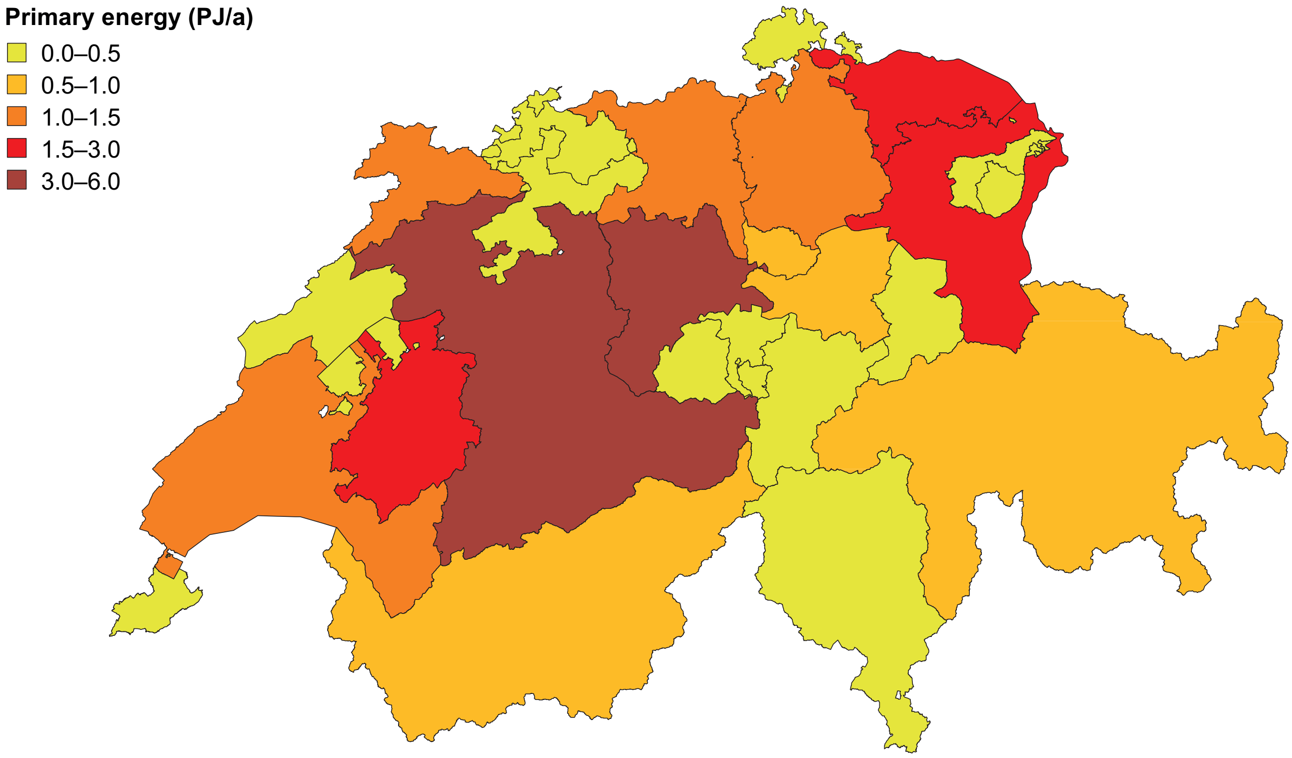

Figure 2: Cantonal distribution of the sustainable potential.

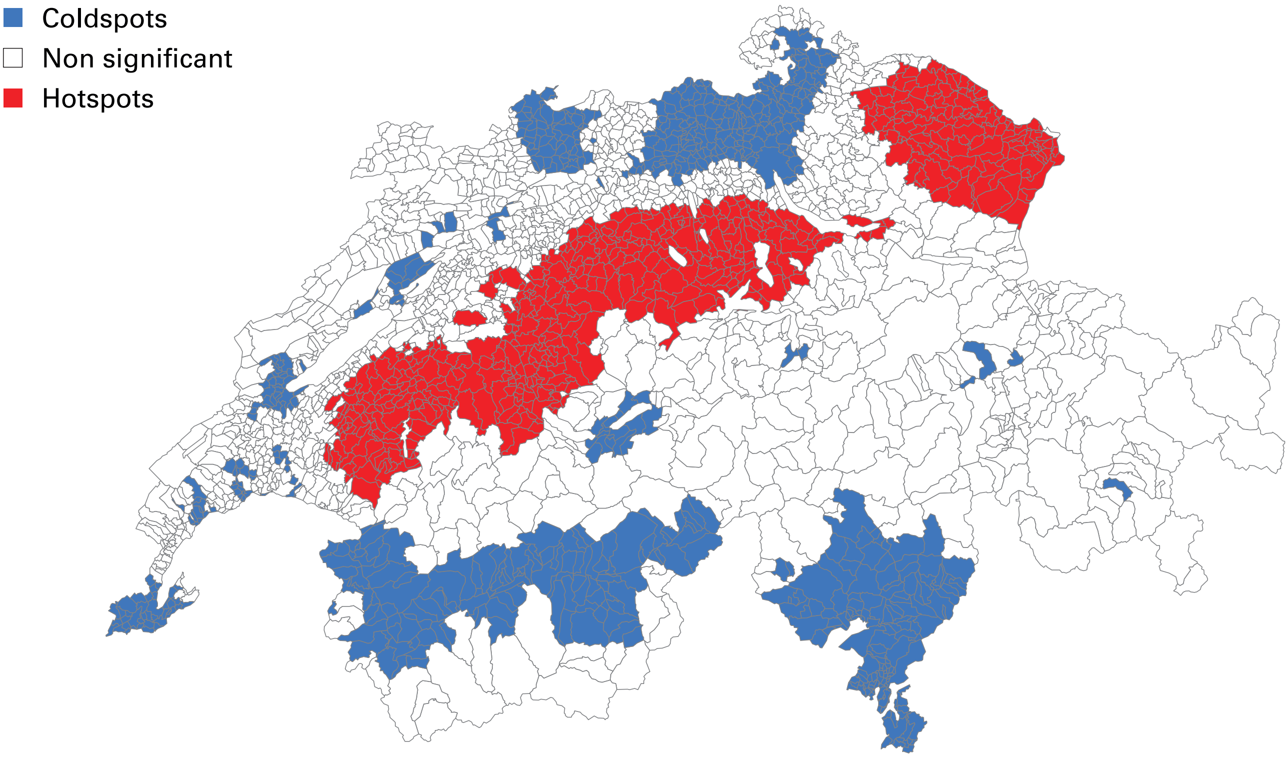

Figure 3: Hotspots and coldspots of the sustainable potential of animal manure per area (TJ / km^2) in Switzerland.

3 Recent technological developments

The large quantity of manure feedstock can be exploited using many technologies. According to current practice, the energy recovery of manure in Switzerland is mainly accomplished through AD. During AD, biogas is produced along with digestate. The digestate includes the non-fermented carbon (C) and the nutrients (N, P, K) and is used as fertilizer. The major components of biogas are methane (CH_4), which is useful as an energy carrier, and carbon dioxide (CO_2). Although AD is a well-established method to extract energy from manure, optimization of the whole process is still needed to improve the energy efficiency and economic feasibility, and hence a larger diffusion of manure-based AD in Switzerland. One strength of the program BIOSWEET was that it enabled the development of various technologies, AD and others, to a higher level of maturity (TRL, Technological Readiness Level). The corresponding technologies and processes are shown in Figure 4 and are described below.

First, we present how separation of manure into solid and liquid fractions can promote the use of manure for energy (section 3.1). Second, we describe the technologies linked to better pre-treatment of manure before AD (microbial pre-digestion [section 3.2], steam pretreatment [section 3.3]). Additionally, we present alternative technologies to AD (hydrothermal gasification [section 3.4], carbonization [section 3.5]), which can be applied either directly to manure or to the digestate from the AD process. We then present gas cleaning (section 3.6) and we describe catalytic (section 3.7) and biological methanation (section 3.8), as well as fuel cells (section 3.9).

3.1 Solid–liquid separation

A simple technology to facilitate the transport and further handling of liquid manure (slurry) consists of separating the slurry into two fractions (one solid and one liquid) and treating them separately. According to the study RAUS REIN, the separated solid fraction of slurry contains more usable energy per weight unit than untreated cattle slurry (Meier *et al.* 2018).

The liquid fraction contains less fermentable carbon than the solid fraction, but is easier to use in terms of process technology and can be efficiently digested in high-performance reactors. However, such small-scale reactors are not yet commercially available for the fermentation of the liquid fraction. The spreading of the liquid fraction with drag slurry spreaders is unproblematic, as it does not provoke blockage the way raw slurry does. In addition, the liquid fraction infiltrates better into the soil, reduces feed contamination, and develops fewer odor emissions.

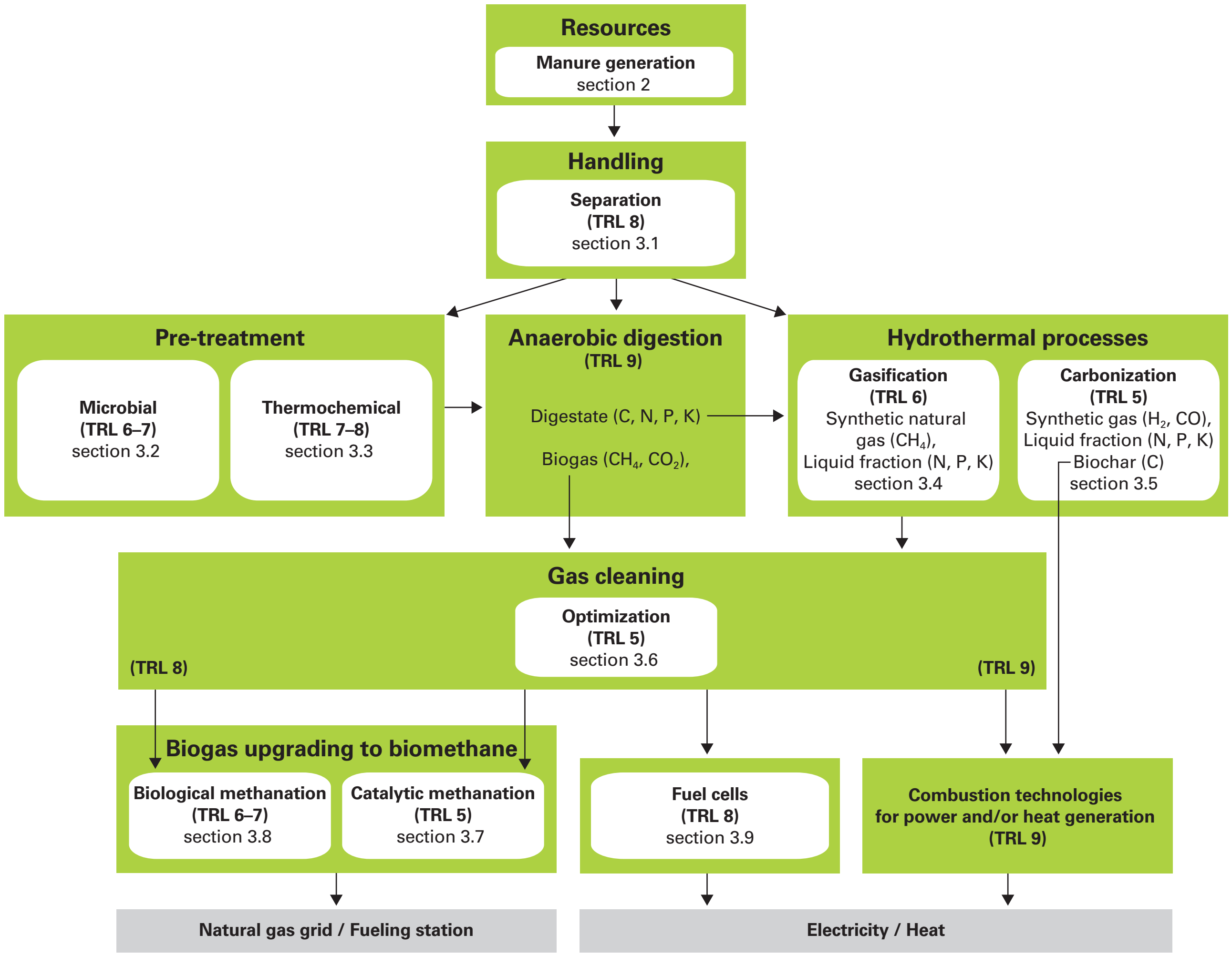

Figure 4: Overview of the technologies for energy generation from manure. The one investigated within the SCCER-BIOSWEET program are in the white boxes with their technology readiness level (TRL). The arrows represent the possible pathways.

Compared with unseparated slurry, the solid fraction contains up to four times more energy per weight unit. Hence, the ratio of energy density to required transport energy improves and the solid fraction can be transported longer distances. The solid fraction is little disruptive in stirred tank reactors and can thus replace co-substrates that are more problematic for the AD.

Separation is a proven technology in view of its feasibility. Overall, taking into account the total costs, the separation concept is not profitable at this stage, and although the separation process is operational (TRL 9), the small-scale high-performing fermenters required to use the liquid fraction are not yet available (TRL 4–5). Also, processes to increase significantly the biogas yield of the separated solids, which would increase the economic feasibility, are currently lacking on an industrial scale (see 3.2 and 3.3). However, separation reduces transport costs because less water and a biomass with a higher energy content are transported. Hence, it facilitates the pooling of the slurry into larger biogas plants (economies of scale). Optimal logistics would lead to a higher cost efficiency. This is being developed further within a project NETZ (Nägele *et al.* 2020) started in 2020, where the combination of small liquid digesters at the local level with large solid digestate at the regional level could make the system more profitable.

3.2 Microbial pre-digestion

Separate pre-treatment of manure and agricultural residues enables biomass to be digested much more quickly and completely compared with conventional AD. As a result, a 20–30 % greater biomass amount, which is digested to a limited extent only, can be used for biogas production. This increases the energy utilization potential and improves the efficiency of the entire plant by 20–30 % accordingly. Due to the physical separation of AD steps, a more efficient hydrolysis stage, and a more stable, resilient plant operation can be achieved. This is due to optimized process conditions in this two-stage fermentation process, compared with the conventional, single-stage process. Biological processes, such as microbial pre-digestion, also have the advantage of comparatively lower investment and energy costs, since they take place at moderate pressure and temperature conditions.

Microbial pre-digestion was investigated and developed in several projects from ZHAW at various technological readiness levels (TRLs). As part of the HYDROFIB project (Baier *et al.* 2019, the additional usable, Switzerland-wide energy potential of pre-digested, fiber-rich biomass was identified, including straw and solids from digestate separation. In addition, optimal substrate-specific process conditions for the microaerobic hydrolysis were determined on a laboratory scale, a pilot plant was built for more detailled investigations, and a case study was carried out on a technical-scale two-stage AD plant (Baier *et al.* 2019). As part of the MOSTCH4 project, a two-stage biogas plant with microaerobic pre-digestion of manure will demonstrate the economic advantages of small, agricultural plants as a prototype (Warthmann *et al.* 2021). In the HYKOM project, a separation of the anaerobic hydrolyzing and methane-forming degradation steps was implemented on a technical scale at an agricultural biogas plant. The process is being scientifically monitored and optimized through several measurement campaigns. Here, the aim of anaerobic, microbial pre-fermentation is primarily to achieve a more stable fermentation process (Rüsch *et al.* 2021).

Microbial pre-treatment processes are best suited for substrates, such as lignocellulosic fibers, that are difficult and slow to degrade. They offer a limited increase of energy efficiency for AD plants, of 20–30 %, without creating additional by-product streams. High conceptual flexibility and a TRL of 6–7 enable immediate pilot integration into existing farming structures, an easy operation, and broad-scale application.

3.3 Steam pre-treatment

Manure contains the indigestible components of animal feed, such as lignocellulosic fibers, and thus is difficult to degrade through anaerobic digestion, i.e. only approximately 20–50 % of the organic material is converted to biogas (Nasir *et al.* 2012). Together with the low dry matter and high ash content of many manure types, the economic operation of anaerobic digestion plants without co-substrates is difficult. To increase the biogas yield from manure, a variety of biological, mechanical, chemical, and thermal pre-treatment methods have been proposed (Li *et al.* 2021). In the framework of the SCCER BIOSWEET program and with additional funding from the Swiss Federal Office of Energy (SFOE; project ManuMax), the steam explosion pre-treatment of liquid cow manure was investigated. Steam explosion pre-treatment involves the heating of the manure to elevated temperatures (160 to 230 °C) by direct steam injection, which solubilizes part of the biomass, and an explosive pressure release after the chosen reaction time (5 to 45 minutes), which reduces strongly the particle size of the remaining matter in an energy efficient way. An elaborate laboratory-scale pre-treatment study von Li *et al.* showed that only the manure solids benefitted from a steam explosion pre-treatment and that the methane yields could be increased by up to 50 %. The yield could be further increased if a two-stage pre-treatment was performed, where the first pre-treatment stage was run at a lower temperature than the second stage. The separation of the condensate containing solubilized heat-labile compounds, such as hemicellulosic sugars, in between the stages made it possible to avoid the undesired thermal degradation of these compounds at higher temperatures. Pre-treatment of the liquid phase of manure resulted in reduced biogas yields even under very mild conditions. Economic calculations indicated that the inclusion of a steam pre-treatment made it possible to run a biogas plant operated exclusively with cow manure more economically. Based on the overall promising results, a pilot facility is being developed by the BFH with funding from the Swiss Federal Office of Energy (SFOE, ManuMax II project, TRL 6) and will be installed and tested at the Institut agricole de Grangeneuve. Here, the pre-treatment will be performed in a continuous steam explosion plant that will also be heat-integrated, and thus requires no more heat energy than if the cattle slurry were fermented in a standard plant. Steam pre-treatment therefore has great potential to largely increase the biogas yield of cattle manure and slurry in particular – the most difficult to degrade anaerobically, but also most frequently available manure. Hereby it increases the chance of actually operating biogas plants economically with only manure and without co-substrates in the future.

3.4 Hydrothermal gasification

Hydrothermal gasification (HTG) can promote a more complete energy utilization of the biomass, along with a minimization of residues, while recovering a maximum amount of nutrients. Being a thermo-chemical, i.e. non-biological, technology, it can convert wet biomass almost fully to a methane-rich biogas. Wet biomass slurries are pumped to high pressure and heated to high temperatures, keeping the water liquid. Such pressurized

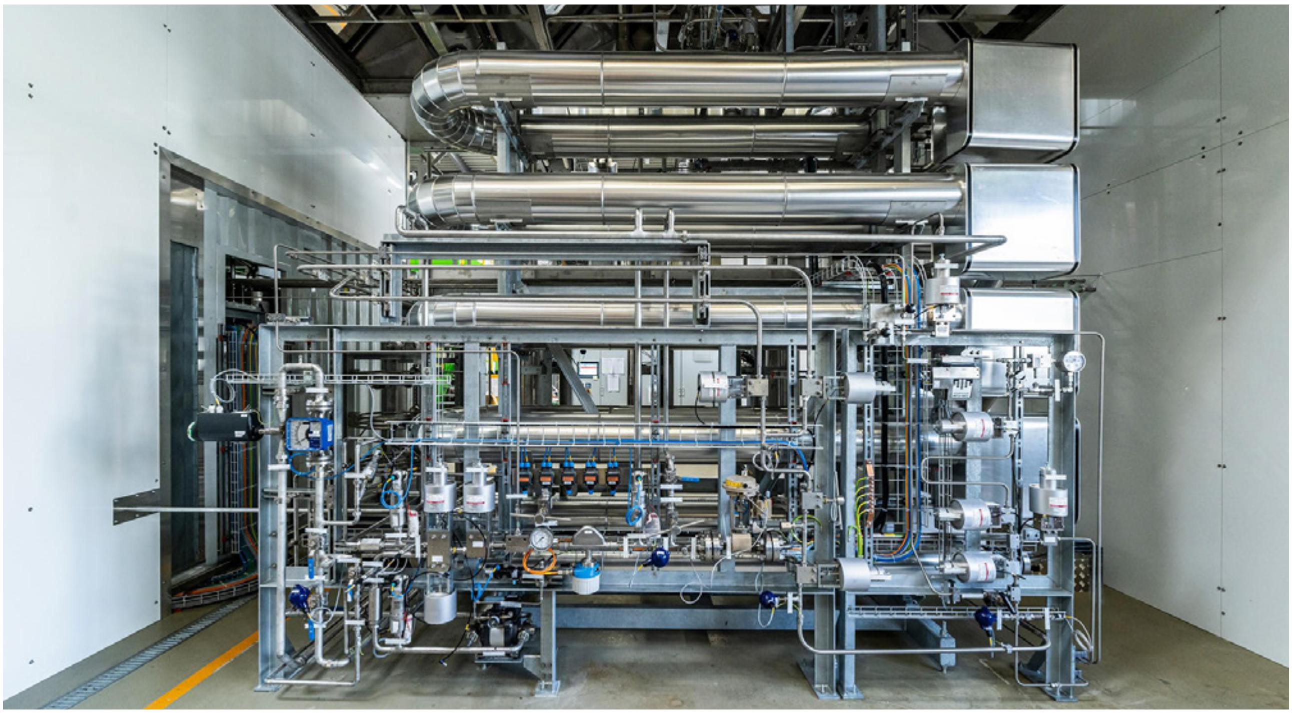

Figure 5: Pilot plant located at PSI for the hydrothermal gasification of wet biomass (Photo M. Fischer, PSI).

hot water decomposes the biomass into an oily liquid phase, which is mixed with the water and the inorganic components (minerals) from the biomass. This organic phase can be converted to a mixture of methane, hydrogen, and carbon dioxide very efficiently using a catalyst. The inorganic components are recovered and can be further processed into a fertilizer. The final products from the biomass are a methane-rich biogas and a process water stream low in organics and minerals but high in ammonium, another important nutrient.

The hydrothermal gasification process was further developed and optimized within SCCER BIOSWEET to reach a higher technological readiness level. As an important milestone, a pilot plant was built at PSI (fig. 5), together with the industrial partners and with the support of the SFOE (project HydroPilot). This semi-industrial plant has a capacity of 110 kg/h of wet biomass and can produce up to 100 kW of biogas. Around 60 % of the energy contained in the wet biomass can be transformed into biogas. This gas is obtained under high pressure and requires only minimal cleaning. The stream with the minerals is used to extract nutrients such as phosphorus. The mineral residue left after extraction can be further valorized in a cement plant. Combining hydrothermal gasification with a high-temperature fuel cell or a gas engine increases the overall system efficiency, as the heat streams from both the fuel cell and the gas engine can be used to heat the hydrothermal gasification process. For such a combined process, an electrical efficiency of up to 43 % was calculated (Vogel 2016).

The HTG technology can be applied to most pumpable sludges that contain around 10 % by weight organic matter or more. Mechanically dewatered manure is one example. Restrictions must be made for corrosive feedstock, e.g. with a high halide content, or feedstock with an extremely high sulfur content. To assess the suitability of a particular feedstock, a feed decision matrix was developed within SCCER BIOSWEET. This expert decision tool includes both hydrothermal gasification and anaerobic digestion. An important advantage of HTG is its ability to also process matter that cannot be digested anaerobically, such as woody parts. This offers the possibility to treat many waste streams at a regional level, not only manure but also e.g. green waste contaminated with plastics. Since nutrients, including volatile species such as NH_3, are fully recovered within an HTG plant, the emissions of this technology are very low. Its overall life cycle performance was shown to be very beneficial. Converting manure and replacing it, as a fertilizer, with the process's mineral byproduct leads to reduced N_2O emissions and an improved environmental performance expressed in terms such as the global warming potential: -0.6 kg CO_2eq./MJ_{SNG} (Luterbacher *et al.* 2009). Due to the versatility of the HTG process, it has the potential to convert a large fraction of the total sustainable manure potential (and other types of waste biomass) in Switzerland with a high efficiency and low environmental impact. The technology was brought to TRL 6 within SCCER BIOSWEET, and thus a market entry within the next few years is foreseeable.

3.5 Carbon recovery through biochar

When considering the use of manure and agricultural residues for energy, the aim is often to achieve maximum energy efficiency. This is synonymous with the most complete possible conversion of organically bound carbon to CO_2 and thus a removal of carbon from the system. AD of manure, for example, achieves a carbon-efficiency of 40–50 %. This ignores the fact that organic carbon cycles should not be disrupted completely because agricultural soils depend on the input and enrichment of stable carbon compounds in the form of humus to retain their fertility and storage capacity of water and nutrients. In addition to compost production from solid manure and agricultural residues, biochar from carbonization lends itself here for the material use of carbon in treating soil.

Hydrothermal carbonization (HTC) of manure or liquid digestate offers a way to generate biochar that can be used as a soil conditioner. Based on the high carbon-efficiency of the HTC process, 80–90 % of digestate carbon can be reintroduced in a stable form into the soil carbon cycle, compared with 40–50 % with direct application of raw or composted digestate. During the carbonization of digestate biochar can even be recirculated into the digester, opening possibilities of synergistic effects and elevated methane production (Sunyoto *et al.* 2016) without sacrificing the beneficial use in soil amendment.

In the BIOSWEET project HTC Rheinmühle, researchers tackled the development of an HTC reactor for liquid substrates (Mehli *et al.* 2020). Production of biochar with a consistent quality for use as a soil additive, as well as the treatment of the generated highly concentrated process waters, proved to be a major challenge. Within the Innosuisse projects CarbonVALUE from ZHAW and CarboPHOS, possibilities to recover phosphorus and other value-added products through hydrothermal carbonization are being investigated (FFA 2020; Merkle *et al.* 2021). Both projects combine material valorization through P-recovery with energy valorization through provision of exothermal reaction heat and energy savings because of massively improved product dewaterability.

During the project, it was shown that reaction conditions are harsh and process complexity is high. Combined with unsolved challenges of biochar quality and process water treatment, this technology still faces considerable hurdles that must be overcome before successful implementation in a farming environment can take place.

3.6 Gas cleaning

The major components of biogas are methane and carbon dioxide, where the methane fraction represents the useful energy resource. In addition to these, biogas can contain minor amounts (0–10 %, volume levels) of nitrogen and oxygen, as well as trace amounts (ppbv–ppmv levels) of sulfur compounds (e.g. H_2S, mercaptans, sulfides), silicon compounds (siloxanes, silanes), ammonia, halogenated compounds, and other volatile organic compounds. The proportion to which trace compounds exist in the biogas depends on a variety of factors. The biomass composition can vary, even when the primary component is manure: the manure can originate from different livestock raised under different conditions, and it can differ in availability depending on the season (i.e. whether the livestock are kept in stalls or not). Further, co-substrates from different origins, depending on availability, may also be added. The digester conditions (operating temperature, digester type, retention time) also have an effect. Additionally, in-digester desulfurization methods (by micro-aeration or addition of iron compounds) can be used to reduce H_2S levels in the biogas.

The trace compounds existing in biogas can present a significant challenge to its use for energy. In particular, sulfur compounds in concentrations of a few ppmv (or even ppbv) can significantly degrade any catalytic process that involves biogas. This includes novel, highly efficient processes such as high-temperature solid oxide fuel cells (SOFCs) or catalytic fuel upgrading units. Sulfur in the range of 0.5–2 ppmv has been demonstrated to degrade the performance of SOFCs (Lanzini *et al.* 2017) and to deactivate nickel-based methanation catalysts. At small scales, i.e. installations below 150 kWe, there is no economically viable biogas-cleaning technology available yet for such novel technologies. As most Swiss farms or plant are in this category of scale, there is a need for robust and inexpensive gas-cleaning solutions for SOFCs (explained in section 2.9). Otherwise, there will be no economic advantage of this end use.

In the framework of SCCER BIOSWEET, a gas-cleaning and gas-processing test rig (COSYMA, TRL 5) was built at PSI, which can be moved to different biogas plants for field-testing. The system can be operated at ambient temperature and pressure, or at elevated temperatures up to 400 °C and pressures up to 7 bars. These features help the researchers to find an optimal gas-cleaning solution for each biogas plant. COSYMA is now (2021) connected to the biogas plant at Inwil (fig. 6). The biogas is taken from the digesters and passed through the gas cleaning system in COSYMA, where slipstreams are sent to the diagnostics container to monitor impurities. The COSYMA and diagnostic tools have already been used in several projects at various technological readiness levels and have been continuously improved in the process. For instance, in one project (Calbry-Muzika *et al.* 2019), the analytical tools were used for the biogas composition analysis of five agricultural sites. As part of the EU project Waste2Watts (https://waste2watts-project.net), the COSYMA and diagnostic containers were used to evaluate various sorbent materials for the removal of H_2S, organic sulfur compounds, and terpenes. Solutions have been found for some impurities, such as H_2S, siloxanes, and terpenes, but further evaluations are required for organic sulfur compounds, such as dimethyl sulfides (DMS).

3.7 Catalytic methanation

Biogas can be used as a source of methane, which can be injected directly into the natural gas grid. To this end, the gas product must contain more that 96 % vol. methane. Therefore, cleaned biogas (i.e. free of impurities such as S-containing compounds and siloxanes) must be additionally treated to remove CO_2 and obtain a methane-rich stream. Several technologies are available on the market for this purpose. The most commonly employed are: water scrubbing, chemical absorption, pressure swing adsorption, and membranes (Kapoor *et al.* 2019).

In water scrubbing, water is used to selectively remove CO_2 (and H_2S) from biogas. This operation leads to high methane recovery (>98 %) with acceptable purity (above 97 % vol. methane in the product). The main drawback of this technology is the large amount of water required, which means considerable water regeneration costs. This results in the need for large capital costs (2500–5000 €/Nm$^3_{\text{Biogas}}$/h). However, this technology is the most widely used in biogas upgrading, with a market share of 40 % of the installed plants. The operation can be improved by using chemicals instead of water for the absorption step (e.g. amines). In this way, lower volumes are required, thus decreasing the capital cost of the system (1500–3000 €/Nm$^3_{\text{Biogas}}$/h) and achieving higher product purity. However, the operation of these plants is more challenging, due to the need for higher temperature in the absorption step and in the regeneration of the sorbent. The market share of chemical scrubbers in biogas upgrading is ca. 22 %.

Pressure swing adsorption (PSA) involves the selective adsorption of CO_2 on a solid material. The methane recovery rate for PSA is lower, because a considerably amount of CH_4 is lost in the off-gas. This corresponds, in the best cases, to a CH_4 recovery of 96 %. For this reason and owing to the complexity of its construction, the market share of PSA is about 20 % and the capital cost of a PSA unit is 1500–3000 €/Nm$^3_{\text{Biogas}}$/h.

Membranes are materials that selectively separate the gas flow into a CH_4-rich and a CO_2-rich stream. The main advantages of membranes are the direct application in the gas stream (without the need for additional units for regeneration) and the modularity (easy adaptation to the plant size). Accordingly, the smallest biogas purification plants commercially available today are membrane plants with a flow rate of 10 Nm$^3_{\text{Biogas}}$/h or more. However, membrane materials are expensive and the substantial amount of methane remaining in the CO_2-rich stream requires further purification.

A new technology for biogas upgrading that is currently being developed is CO_2 methanation. In this case, instead of removing CO_2 from the gas

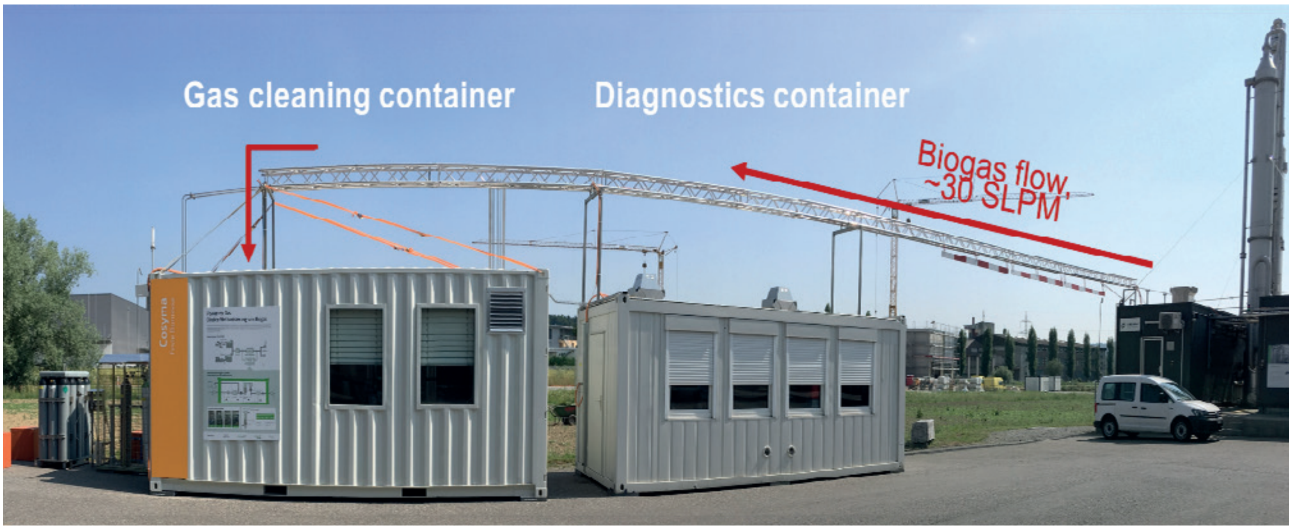

Figure 6: COSYMA gas-cleaning and gas-processing test rig (SLPM: standard liter per minute; Photo S. Biollaz, PSI).

stream, CO_2 is selectively converted into methane through the addition of H_2. This reaction is operated in catalytic reactors (usually on Ni-based catalysts) at ca. 300 °C and 5–10 bar. The main advantage of this methodology is offset by high capital and operating costs the cost of H_2 (especially if produced from electrolysis). This technology is expected to gain importance in the future, as it makes it possible to store excess renewable energy in natural gas network.

In the framework of SCCER BIOSWEET, the feasibility of the technology was proven in the field, by installing the gas-cleaning and gas-processing test rig COSYMA (TRL 5, 20 kW_{SNG}) in the wastewater treatment plant of Werdhölzli (Canton Zurich). The tests showed a stable operation of the methanation reaction for the upgrading of biogas for more than 1000 h, with an average methane yield of 96 % (Witte *et al.* 2018, 2019). Therefore, CO_2 methanation is a feasible technology for biogas upgrading, but the possibility of commercialization is limited by the development of an inexpensive solution for H_2 production. The project carried out in Werdhölzli was awarded the 2018 Watt d'Or from the SFOE.

3.8 Biological methanation

Another opportunity to increase the efficiency of manure anaerobic digestion lies in the possibility to generate additional methane through the use of renewable carbon dioxide from biogas, which is converted in the presence of hydrogen by means of microbiological methanation. Adding this process step theoretically results in 40–50 % higher energy yield with unchanged amounts of biomass and fermenter size. Furthermore, it allows the production of feed-in quality biomethane without further upgrading steps, which saves 4–6 % of raw biogas energy.

In the binational eranet project CarbonATE, the Swiss partners are developing, characterizing, and evaluating a microbiological process on the laboratory scale to convert raw biogas from anaerobic digesters, CO_2-rich lean gas from biomethane upgrading, or CO_2-rich streams from other sources to CH_4 through the addition of H_2 (Baier *et al.* 2020). The aim is to produce a gas product with a CH_4 content of >96 % that can be fed directly into the gas grid. The focus of the project is on ex-situ methanation, in which the microbiological process takes place independently of the anaerobic fermentation in a separate reactor under controlled conditions. This leads to an optimal reactor configuration with high H_2 transfer rates, increased gas conversion rates, and a small carbon footprint. Due to the availability of small- to medium-scale electrolyzers, this technology provides opportunities for the additional use of CO_2 from manure fermentation for energy generation. Accounting for the process energy requirements for electrolysis and methanation, the theoretical surplus bioenergy generation to 20–30 %. In addition to the efficient provision of renewable electricity for electrolysis, the development of highly efficient H_2 input and transfer components is one of the technical challenges of process development. Addressing this challenge would pave the way for innovative solutions for upgrading biogas plants through the use of in-situ methanation within the existing fermenter.

Ex-situ microbial methanation is suitable as an add-on to all types and ranges of agricultural AD installations, offering a considerable surplus in biomethane production of up to 50 %. Under mild process conditions, negative environmental impacts are low. A rather high process complexity and a considerable dependence on renewable electricity input currently hinder widespread implementation within farming environments.

3.9 Fuel cells

The development of solid oxide fuel cells (SOFC) to produce electricity is making continuous progress, with several developers proposing products on the market, from residential micro-scale installations (1 kW_e) to multi-100 kW_e systems. In the last few years, worldwide SOFC shipment has been 25,000 units/yr, totaling >140 MW_e/yr (E4Tech 2020). They mostly convert natural gas, but owing to their fuel flexibility they also convert biogas without major added complexity. Their key advantages, compared with engines, lie in: (i) higher electrical efficiency, (ii) much lower polluting emissions (no SO_x, no NO_x, no methane slip), (iii) lower maintenance costs, and (iv) less noise generation. This is especially true for lower-power applications (<100 kW_e), which are typical of the dispersed local nature of manure availability. The expected electrical efficiency here is 50 %. In lab tests, SOFC stacks achieve 60 % direct current efficiency on biogas mixtures (Madi *et al.* 2018). In real systems, even 1–2 kW_e SOFCs achieve a 63 % net – alternative current efficiency. In the EU project DEMOSOFC, SOFCs of 58 kW_e achieved 52–56 % net alternative current efficiency on waste-water biogas (www.demosofc.eu). Estimates show that the total amount of manure currently collected in Switzerland (intermediate potential, fig. 1 and 2) could be used in more than 5000 SOFC units of 50 kW_e.

There are three main challenges to deploying small-scale SOFCs on farms: (i) the gas cleaning cost is considerably higher than in other biogas systems, (ii) the SOFC cost is considerable, and (iii) the AD cost themselves. With respect to cleaning, thresholds for the various relevant contaminants have been established (section 2.6) which are currently being further refined not only for the SOFC fuel catalyst, but also for the biogas pre-reforming catalyst (https://waste2watts-project.net). The critical contaminant in manure biogas is total sulfur, more specifically organic sulfur (few ppm), as its compounds are more difficult to remove by classical sorbents than H_2S. The SOFC cost is coming down as the manufacturing volume increases. For the 50 MW_e/yr SOFC manufacturing plant that SOLIDpower (www.solidpower.com, Italy, Switzerland) brought into operation in 2020, the system cost is expected to come down to 2000 €/kW_e. Cost calculations for SOFC systems on farms compared with engines have been performed for different cases and countries including Switzerland (Majerus *et al.* 2017, 2018). In terms of AD cost, several small-scale manufacturers are on the European market with competitive solutions, such as Biolectric who are selling 100 systems/yr for manure biogas production systems between 11 and 73 kW_e. The Swiss partners EPFL, SOLIDpower, PSI, and EREP SA are preparing a pilot installation to run a 6 kW_e SOFC system on an agricultural biogas production site (mainly using cow manure). This is a stepping stone towards 25 kW_e and 50 kW_e systems, the 6 kW_e stack being a subunit of the 25 kW_e module that has already been validated by SOLIDpower on this scale.

Lastly, solid oxide technology has the advantage that it can be run fully reversibly, i.e. also as an electrolyzer of steam (and CO_2) to generate H_2 (and CO). Interesting integration opportunities are possible here as well for the upgrading of biogas (Jeanmonod *et al.* 2019; Wang *et al.* 2018).

4 Opportunities and barriers of manure-based bioenergy

Many non-technological aspects should be considered that can either favor or hinder the generation of bioenergy from manure. In addition to energy aspects, manure-based bioenergy can have many positive externalities.

Regarding the potential for mitigating climate change, 3 % of the agricultural GHG emissions from Switzerland could be prevented if sustainably available manure were digested (fig. 7; Burg *et al.* 2018b). Today the agriculture contributes up to 12.7 % of the total anthropogenic GHG emissions in Switzerland. Several technologies described here could reduce these GHGs. For example, AD of the estimated sustainable manure quantity could contribute 0.8 % to the reduction of GHG emissions in Switzerland to fulfill the Paris agreement goal of limiting global warming to below 2 C°. These emissions mitigations could be even higher when considering that manure-based biogas can replace high-emission fuels (e.g. fuel

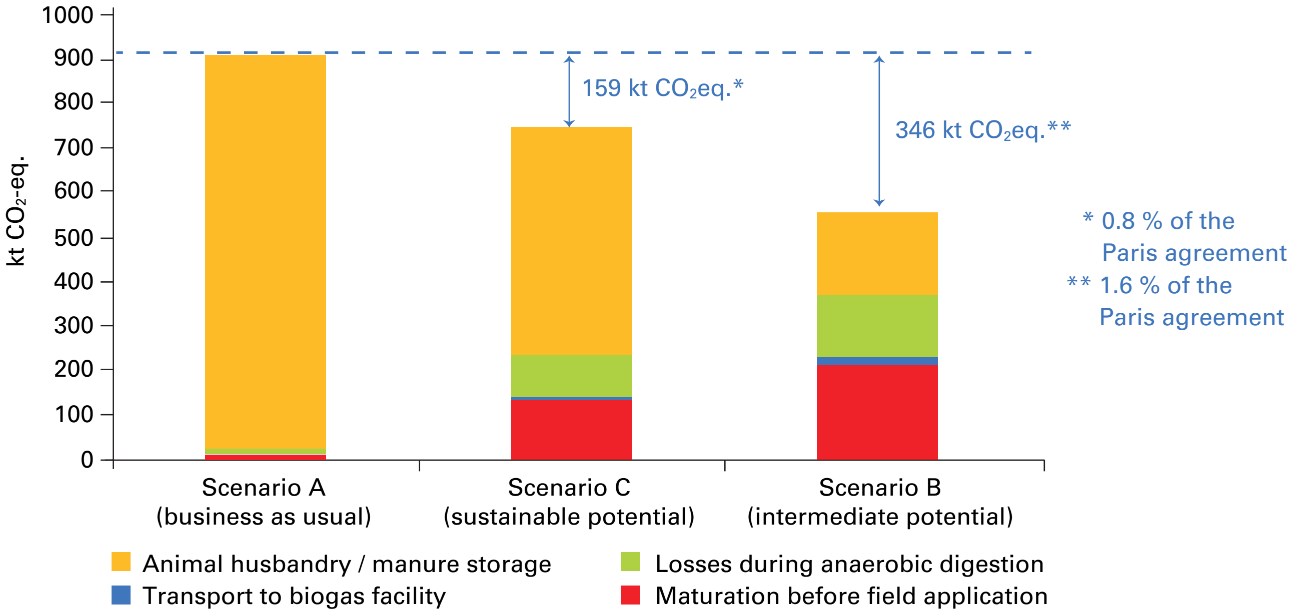

Figure 7: Total direct emissions from manure management (CO_2+CH_4+N_2O) in kt/yr CO_2eq. in Switzerland, depending on the percentage of manure fermented in a biogas plant (A: business as usual with 6 % digested, C: realistically feasible with 65 % digested, B: maximal exploitation with 100 % digested).

oil) in the energy sector and mineral fertilizers in the agricultural sector, especially when combined with co-substrates.

However, there are many barriers that currently limit the efficient use of manure for energy.

Based on a comprehensive survey including a choice experiment, the attitude of Swiss farmers towards (individual and collaborative) AD was investigated at different levels (Burg *et al.* 2021). Around 190 farmers from all over Switzerland took part in the survey. The answers confirmed that manure represents a valuable resource to the farmers for natural fertilization of their fields and that manure AD is seen as positive in principle by more than 80 %. However, many comments (e.g. regarding profitability, digestate quality, the use of co-substrates) also reflected a certain hesitation, and a high-quality digestate (without contaminants such as plastic, heavy metals, germs) would be an asset for acceptance by the farmers. Moreover, AD can contribute to farmers' self-sufficiency in Switzerland, which is viewed as highly important. Moreover, farmers generally prefer to build biogas facilities with as few co-owners as possible. Using the results of the survey, an agent-based model (ABM) has been designed and used to simulate the development of biogas facilities under different framework conditions. The agents' (farmers') properties were derived from the farmers' survey. Simulations showed that the revenue for generated energy is the main driver but not the only one. An increase of 0.10 CHF/kWh$_e$ energy revenues (added to compensation of 0.45 CHF/kWh$_e$ today including agricultural bonus for the electricity fed into the grid) would enable the establishment of only ten additional biogas facilities in the whole of Switzerland (10 % more than today). The influence of a one-time remuneration grant appeared to have much less impact on the decision to build a biogas plant. To fully harness the energy and GHG mitigation potential of converting manure to biogas, other strategies need to be developed at different levels, and policymakers should look at all the different aspects that influence the deployment of bioenergy technologies. At the organizational level, the initiative to build larger plants (with many suppliers) cannot be expected to come (only) from the farmers (e.g. dairy cooperatives, municipalities). Incentives to support collaboration between farmers and eventually other stakeholders to overcome the small-scale production structures could also be investigated. At the technical-economic level, measures are needed that lead to plants becoming cheaper and easier to run for the farmers. For example, policymakers should consider reducing administrative work linked to the building and running of agricultural biogas facilities. It is also necessary to examine the effect of remuneration rates that exceed the maximum of CHF 0.55/kWh$_e$ tested to date. At the legal level, anaerobic digestion could be made obligatory as part of manure management to avoid GHG emissions, with the corresponding subsidies or measures.

Biomass transport represents additional GHG emissions and a significant share of the final price of biomass for energy. A techno-economic analysis of biomass transport for solid and liquid manure identified the five most common transport chains from the supplier to the final consumer in Switzerland (Schnorf *et al.* 2021). Manure can be either liquid or solid and, therefore, its transport requires different types of technical solutions. Generally, farmers or professionals (with higher load capacity) bring slurry to biogas plants , avoiding empty runs when possible. Average distances range from 5 to 9 km for manure transport by road. Finally, where the infrastructure allows it, slurry can be pumped directly from the suppliers' farm to the fermenter of the plant by means of underground pipelines. This study found that the length of such pipes in Switzerland is approximately 1.5 to 4.5 km and maximal 8.5 km.

The land requirements for the use of manure for energy is small. In Switzerland, a surface of 14.5 km^2 would be needed to process the entire sustainably available amount of manure, 80 % of which would be the area required for the biogas facilities (Bowman *et al.* 2021).

To promote the use of manure for energy, further added values need to be explored. This applies, for example, to the insufficiently used heat from the AD plants: currently only 65 % of the gross heat production of biogas plants is used on average in Switzerland. When no heat consumers, such as neighboring housing or industries, are close by, the unused heat could be used to supply the heating demand of small greenhouses. This way, using the domestic potential, a total maximum greenhouse area of 104 ha could be sustained with manure-based biogas heat, producing this way 20,800 tonnes/yr of tomatoes (11 % of the total domestic tomato demand; Burg *et al.* 2020), thus strengthening local, low-carbon food production with a shorter supply chain. These greenhouses would need to be built in parallel to new biogas facilities in order to optimize the use of heat. During summer time the surplus heat could still be used for other processes such as wood drying. Further, the value of the digestate itself should not be underestimated and could contribute to reaching economic profitably for the biogas plants.

5 Bioenergy from manure in the energy system

Manure is both an energy and a carbon carrier. Taking into consideration the largely unexploited potential of animal manure, its role as an energy source is important within the Swiss energy system. This role can be modeled within the entire national energy system in order to assess the significance of manure exploitation. The full considered conversion scheme indicates the order of magnitude of the energy and CO_2 flows (fig. 8). It should be noted that, following the parameterization of each individual process within the energy system, different sub-systems may appear in the different modeling solutions. As shown, manure is mainly converted to biogas through AD and subsequently upgraded to biomethane or directly upgraded to biomethane through hydrothermal gasification (HTG). Undigested residues from AD can also be hydrothermally treated to produce additional methane. The released CO_2 from these processes can then be used with renewable H_2 to form synthetic natural gas using the Power to Gas concept, thus exploiting the full carbon potential of manure.

Multiple scenarios were generated and analyzed, using the Energyscope model, an open source model for analyzing regional energy systems (www.energyscope.ch) that consider the full decarbonization of the energy system for 2050 (Li *et al.* 2020). Model results reveal that using a variable input of manure feedstock between 18 and 30 PJ/yr to simulate the input uncertainty, its conversion through AD and HTG can cover up to 17 % of the total biomethane production. This is equivalent to around 10–11.5 % of the total biofuel production in the Swiss energy system for 2050 and also represents 2–3 % of the total energy delivered by the energy system. The simulations show a very limited contribution from the power-to-gas options and direct transformation to biomethane is preferred. During the conversion process of the available manure potential to biomethane, 2.5–4 Mt/yr CO_2 is released, which eventually requires the use of suitable capture technologies for CO_2 utilization and/or sequestration for the target of decarbonization to be achieved. Finally, the investment costs for manure conversion appear to be negligible compared with the large contributors within the energy system, such as hydro dams and PV, and comprise almost 1 % of the total capital cost of the energy conversion processes.

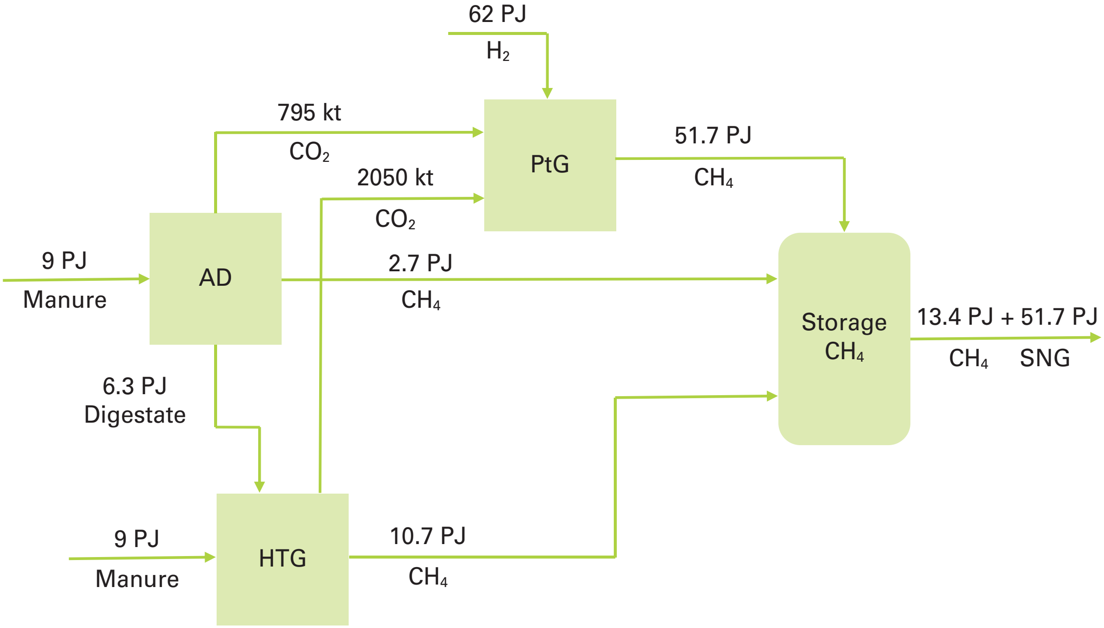

Figure 8: Pathways of manure conversion used in the modeling studies (AD: anaerobic digestion; HTG: hydrothermal gasification; PtG: Power to Gas; SNG: synthetic natural gas) and the quantification of the energy and CO_2 flows based on 18 PJ/yr feedstock input in Switzerland.

6 Promotion of biogas from manure and recommendations

In the Swiss energy perspective 2050+ (SFOE *et al.* 2020), it was determined that reaching net-zero GHG emissions by 2050, while ensuring secure energy provision, would require the use of all of the domestic sustainable biomass potential for all scenarios analyzed. Furthermore, depending on the scenario, an additional bioenergy import of maximum 60 PJ would be needed. Bioenergy will also play a role in achieving the Swiss renewable energy targets for 2050 and beyond. While biomass currently represents less than 5% of the gross energy consumption, this share is expected to reach almost 20% in the net-zero scenarios by 2050 (SFOE *et al.* 2020). Use of this sustainable resource would help the country to reduce GHG emissions as specified and secure its energy supply. To reach this, the use of biomass must be gradually increased. In this context, biogas production represents a very promising technology.

The gas sector aims to ensure a 30% share of renewable bio-methane for residential heating by 2030 (Gazenergie.ch 2020). Assuming that demand will continue to increase slightly until then, this corresponds to a total amount of around 5000 GWh (18 PJ). Based on WSL data, it has been estimated that, in principle, there would be enough wet biomass in Switzerland to produce this amount of biogas by 2030 (Gazenergie.ch 2020). For economic reasons, however, the utilization of this potential is limited. The domestic share to cover the demand is therefore likely to settle at 30–50% and the additional biogas will need to be imported to reach the objective of the sector. Concerning the additional biogas imports, it remains an open question as to where they will come from and whether this quantity can be produced sustainably and the supply guaranteed in the long term.

In Switzerland, agricultural biogas is currently mostly used for electricity generation. Due to its high share of nuclear and hydropower, Swiss electricity is already CO_2-poor. Hence, the mitigation of anthropogenic GHG emissions can be further enhanced by specifically substituting fossil fuels such as natural gas. Furthermore, along with its impact on the climate, bio-methane use as a substitute for diesel is expected to improve air quality because emission factors of methane are up to 10 times lower than those of liquid fuels when considering particle matter during their combustion. As nuclear power electricity is being phased out and electricity consumption is expected to increase 11% until 2050 (SFOE *et al.* 2020), biogas may represent an interesting complementary source to partly balance the fluctuations of solar and wind power production. Generating electricity is especially important in winter, during which time Switzerland depends on imports, which will worsen when the nuclear plants are decommissioned, and which will hardly be fully compensated by energy from photovoltaic sources. Electricity generation from manure biogas in winter could make a valuable contribution and would be a reliable source because animals are kept in stables and higher manure quantities are available. To maximize electricity, fuel cells are a promising option.

As shown in section 3 and looking at the results of SCCER BIOSWEET, a great diversity of promising approaches exist to improve its efficiency and profitability and to increase the energy generation from manure and agricultural residues. Further development of existing biogas plants and technologies will benefit from valuable pre-treatment processes, such as solid–liquid separation and microbial as well as thermo-chemical pre-treatment leading to more efficient biogas processing, which could be a major contributor to this increase. These technologies will be available on the short- to mid-term (TRL 6–8). New, innovative technologies for converting biomass into renewable energy (e.g. hydrothermal gasification, TRL 6, or the utilization of fuel cells, TRL 8), but also differentiated potential analyses and holistic concepts for exploiting manure and agricultural residues, could promote better utilization of the considerable sustainable energy potential of agricultural biomass mid-to long-term.

In order to fully harness the energy and GHG mitigation potential of converting manure into biogas, as well as a possible increase in Switzerland's energy sufficiency, strategies need to be developed at different levels. At the organizational level, the initiative to build larger biogas plants (with many suppliers) cannot be expected to arise from farmers only and is rather also seen as a benefit from municipalities or energy companies becoming active in this domain. The limited availability of valuable co-substrates (e.g. from industry or gastronomy) point to the relevance of making efficient and coordinated use of them for energy rather than simply using them in composting plants as done until now. Indeed, to increase the profitability of biogas facilities, bio-wastes are often added to agricultural biogas facilities, which is called co-fermentation. The higher biogas yields and the possible revenue of disposal fees make these agricultural biogas facilities more economical. In addition, further measures should be developed and introduced. These approaches could be coordination offers that support the cooperation of farmers to overcome the small-scale production structures, or financial incentives such as significantly higher remuneration rates for the provision of renewable energy.

Finally, improvement at the technical-economic level can lead to plants being operated more efficiently and profitably for farmers. Indeed, financial constraints are often mentioned as reasons for low stakeholder involvement: high investment costs, a lack of heat customers, a lack of gate fees, and the expiration of subsidies. Furthermore, financial compensation for the GHG mitigation effect (CO_2 compensation) could be further developed to increase the economic feasibility of agricultural biogas facilities.

7 Conclusion

Manure in Switzerland could be used for energy and climate purposes to a much greater extent than it is today. The fermentation of manure could provide significant amounts of renewable energy while avoiding greenhouse gas emissions. However, this would require an expansion of the biogas infrastructure and changes within the current framework conditions for energy generation.

The efficiency of energy generation from manure could be improved by introducing new technology for manure separation into liquid and solid phases. Anaerobic digestion processes could be improved with various pre-treatments of the feedstock that increase overall efficiency, and with post-treatments that improve biogas quality. Additionally, small-scale converters for converting gas to electricity low efficiency can still be improved. Finally, the use of waste heat should be strived for.

Hydrothermal gasification is a new technology that is potentially capable of converting even more efficiently the available manure potential into biogas while additionally extracting the nutrients in a pure form such as phosphorus. The upgrading of biogas to synthetic gas is an interesting option for Switzerland's greenhouse gas balance in the short term, especially as an environmentally friendly fuel. A parallel utilization track is the targeted generation of base-load electricity in winter via efficient solid oxide fuel cells. The modeling of the overall system demonstrates the high relevance of the use of manure with regards to energy provision and CO_2 balance. When considering the potential use of manure as a feedstock for other sustainable products, such as chemicals or materials, the characteristics of manure here militates against the replacement of fossil material products. Therefore, the use of manure for energy seems particularly advantageous. Thus, energy generation from manure can also help to a relevant extent the country to stabilize its energy system, in combination with other renewables, and achieve greater energy independence, particularly from fossil fuel imports. Furthermore, it reduces harmful effects on the climate and the consumption of resources.

Acknowledgments

This research project was financially supported by the Swiss Innovation Agency Innosuisse and is part of the Swiss Competence Center for Energy Research SCCER program BIOSWEET. We wish to thank further organizations for their financial support: Ernst Göhner Stiftung, SFOE, SFOE P&D program, and WSL, as well as the industrial partners Afry AG, ExerGo sàrl, KASAG Swiss AG und Treatech sàrl, and finally the Fuel Cells & Hydrogen Joint Undertaking (project Waste2Watts, grant 826243). Furthermore, we want to thank Prof. Dr. Karl Keilen (keilenANALYTICS) for the helpful comments on the document, Martin Moritzi (WSL) for proofreading the german version and Sandra Gurzeler (WSL) for the layout.

References

Baier, U.; Antalfy, I.; Burg, V.; Hölzel, B.; Krautwald, J.; Moser, Y.; Rüsch, F.; Schmid Lüdi, K.; Treichler, A.; Warthmann, R., 2019: Projekt Mikroaerobe Hydrolyse faserreicher Biomasse zur Steigerung der Biogasproduktion (HYDROFIB), Swisspower AG, FBI First Biogas Int'l, Allmig, WSL, SVGW FOGA, BFE. https://www.zhaw.ch/de/forschung/forschungsdatenbank/projektdetail/projektid/1422.

Baier, U.; Corbin, A.; Merkle, W., 2020: Projekt CarbonATE – Entwicklung einer enzymatischen CO_2-Abtrennungsstrategie für eine optimierte mikrobiologische Methanisierung. Intermediate Report ZHAW, Wädenswil (unpublished data).

Bowman, G.; Burg, V.; Erni, M.; Lemm, R.; Thee, O.; Björnsen Gurung, A., 2021: How much land does bioenergy require? An assessment for land-scarce Switzerland. Glob. Chang. Biol. Bioenergy, 00: 1–15. http://doi.org/10.1111/gcbb.12869.

Burg, V.; Bowman, G.; Erni, M.; Lemm, R.; Thees, O., 2018a: Analyzing the potential of domestic biomass resources for the energy transition in Switzerland. Biom. 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. Res. Cons. Recycl. 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. http://doi.org/10.3390/en12183585.

Burg, V.; Golzar, F.; Bowman, G.; Hellweg, S.; Roshandel, R., 2020: Symbiosis opportunities between food and energy system: The potential of manure-based biogas as heating source for greenhouse production. J. Ind. Ecol. http://doi.org/10.1111/jiec.13078.

Burg, V.; Troitzsch, K.G.; Akyol, D.; Baier, U.; Hellweg, S.; Thees, O., 2021: Farmer's willingness to adopt private and collective biogas facilities: an agent-based modeling approach. Res. Cons.Recycl. 167: 105400. http://doi.org/10.1016/j.resconrec.2021.105400.

Calbry-Muzyka, A.; Madi, H.; Biollaz, S., 2019: Cleaning agricultural biogas for high temperature fuel cells at pilot scale, SFOE. https://www.aramis.admin.ch/Texte/?ProjectID=40684.

E4Tech, 2020: The Fuel Cell Industry Review 2020 edition. www.FuelCellIndustryReview.com.

FFA Forschungsfonds Aargau 20200331_10 CarbonVALUE, 2020: Nutzbarmachung des energetischen und des stofflichen Potenzials von Prozesswässern aus der hydrothermalen Karbonisierung.

Jeanmonod, G.; Wang, L.; Diethelm, S.; Maréchal, F.; Van herle, J., 2019: Trade-off designs of power-to-methane systems via solid-oxide electrolyzer and the application to biogas upgrading. Appl. Energy 247: 57–581.

Kapoor, R.; Ghosh, P.; Kumar, M.; Vijay, V.K., 2019: Evaluation of biogas upgrading technologies and future perspectives: a review. Env. Sci. Pollut. Res. 26: 11631–11661.

Lanzini, A.; Madi, H.; Chiodo, V.; Papurello, D.; Maisano, S.; Santarelli, M.; Van herle, J., 2017: Dealing with fuel contaminants in biogas-fed solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) plants: Degradation of catalytic and electro-catalytic active surfaces and related gas purification methods. Prog. Energy Combust. Sci. 61. https://doi.org/10.1016/j.pecs.2017.04.002.

Li, X.; Damartzis, T.; Stadler, Z.; Moret, S.; Meier, B.; Friedl, M.; Maréchal, F., 2020: Decarbonization in complex energy systems: A study on the feasibility of carbon neutrality for Switzerland in 2050. Front. Energy Res. 8, 274. http://doi.org/10.3389/fenrg.2020.549615.

Li, Y.; Zhao, J.; Krooneman, J.; Euverink, G.; Jan, W., 2021: Strategies to boost anaerobic digestion performance of cow manure: Laboratory achievements and their full-scale application potential. Sc. Total Env. 755 (Pt 1), S. 142940.

Luterbacher, J.S.; Fröling, M.; Vogel, F.; Maréchal, F.; Tester, J.W., 2009: Hydrothermal gasification of waste biomass: process design and life cycle assessment. Environ. Sci. Technol. 43, 5: 1578–1583. https://doi.org/10.1021/es801532f.

Madi, H.; Diethelm, S.; Constantin, D.; Van herle, J., 2018: Biogas-fed SOFC: Performance investigation with variable CH_4/CO_2 composition, 13th European Solid Oxide Fuel Cell & Electrolyser Forum, Lucerne (CH), Paper A1110, 67–74.

Majerus, S.; Lauinger, D.; Van herle, J., 2017: Cost requirements for a small-scale SOFC fed from agricultural-derived biogas. J. Electrochem. Energy Conv. Stor. 14, 1: 011002.

Majerus, S.; Lauinger, D.; Van herle, J., 2018: Taking advantage of the vastly underused European biogas potential:break-even conditions for a fuel Cell and an engine as biogas converters J. Electrochem. Energy Conv. Stor.15, 3: 031006.

Mehli, A.D.; Winkler, D.; Griffin, G.; Gerner, B.; Kulli, U.; Baier, M.; Kühni, A.; Treichler, S.; Garcia, A., 2020: Pilotanlage zur Hydrothermalen Karbonisierung. Prozessoptimierung & Verfahrenserkenntnisse. Final Report SFOE Project SI/501670-01. Bern.

Meier, U.; Hersener, J.-L.; Bolli, S.; Anspach, V., 2018: "RAUS – REIN": Feststoffe "RAUS" aus der Gülle und "REIN" in die Vergärung, Neuartiges Konzept zur Verbreitung der Vergärung von Hofdünger in der Schweiz, Schlussbericht, im Auftrag von Bundesamt für Energie und Bundesamt für Landwirtschaft, Bern.

Merkle, W.; Keller, R.; Treichler, A.; Ebert, J.; Edelmann, M.; Hüsch, S.; Kühni, M.; Stucki, M., 2021: Projekt CarboPHOS – Phosphorous recovery through hydrothermal carbonisation of sewage sludge Antaco AG, Ostschweizer Fachhochschule OST, Abwasserverband Aarau und Umgebung. AVA https://www.zhaw.ch/en/research/research-database/project-detailview/projektid/4682.

Mohr, L.; Burg, V.; Thees, O.; Trutnevyte, E., 2019: Spatial hot spots and clusters of bioenergy combined with socio-economic analysis in Switzerland. Renew. Energy 140: 840–851.

Nasir, I.M.; Mohd Ghazi, T.I.; Omar, R., 2012: Anaerobic digestion technology in livestock manure treatment for biogas production: A review. Eng. Life Sci. 12, 3: 258–269. https://doi.org/10.1002/elsc.201100150.

Nägele, H.-J.; Rüsch, F.; Baier, U., 2020: Projekt Vorprojekt Netz: Nährstoff- und Energietechnik-Zentrum Ingenieurbüro HERSENER GmbH, LAVEBA Genossenschaft, GRegio Energie AG, Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL. https://www.zhaw.ch/de/forschung/forschungsdatenbank/projektdetail/projektid/3778.

Rüsch, F.; Huber, S.; Baier, U.; Nägele, H.-J.; Merkle, W.; Senn, M.N.; Wittwer, K., 2021: Projekt HYKOM – Energieoptimierte Kombination von Hygienisierung und Hydrolyse zur Vorbehandlung von Flüssigsubstraten vor der Vergärung, ZHAW, Gebr. Klaus und Urs Wittwer/wigako. https://www.zhaw.ch/de/forschung/forschungsdatenbank/projektdetail/projektid/3838.

Schnorf, V.; Trutnevyte, E.; Bowman, G.; Burg, V., 2021: Biomass transport for energy: cost, energy and CO_2 performance of forest wood and manure transport chains in Switzerland. J. Cleaner Prod. 293: 125971. https://doi.org/10.1016/j.jclepro.2021.125971.

SFOE, 2020: Schweizerische Gesamtenergiestatistik 2019. Retrieved from https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.html.

SFOE Prognos AG; INFRAS AG; TEP Energy Gmbh; Ecoplan AG, 2020: Energieperspektiven 2050+. Retrieved 14 January 2021 from https://www.bfe.admin.ch/bfe/fr/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZnIvcHVibGljYX/Rpb24vZG93bmxvYWQvMTAzMjM=.html. Kurzbericht, Bern. 112 p.

Sunyoto, N.M.S.; Zhu, M.; Zhang, Z.; Zhang, D., 2016: Effect of biochar addition on hydrogen and methane production in two-phase anaerobic digestion of aqueous carbohydrates food waste. Bioresour. Technol. 219: 29–36.

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 Ber. 57, 299 p.

Vogel, F., 2016: Hydrothermal production of SNG from wet biomass, In: Synthetic Natural Gas from Coal, Dry Biomass, and Power-to-Gas Applications. In: Schildhauer, T.J.; Biollaz, S.M.A. (eds). John Wiley & Sons, Inc.

Wang, L.; Jeanmonod, G.; Pérez-Fortes, M.; Diethelm, S.; Van herle, J.; Maréchal, F., 2018: Technical evaluation of sustainable biogas upgrading via solid-oxide electrolysis. 13th European Solid Oxide Fuel Cell & Electrolyser Forum, Lucerne (CH). Paper A0910: 70–80.

Warthmann, R.; Arioli, G.; Principi, P.; Baier, U.; König, R.; Treichler, A., 2021: Projekt MOSTCH4: Mini Onsite System To valorize manure in methane, ZHAW, Scuola universitaria professionale della Svizzera italiana SUPSI, Laborex SA. https://www.zhaw.ch/de/forschung/forschungsdatenbank/projektdetail/projektid/3541/.

Witte, J.; Kunz, A.; Biollaz SMA; Schildhauer, T.J., 2018: Direct catalytic methanation of biogas – Part II: Techno-economic process assessment and feasibility reflections. Energy Convers. Manag. 178: 26–43.

Witte, J.; Calbry-Muzyka, A.; Wieseler, T.; Hottinger, P.; Biollaz, S.M.A.; Schildhauer, T.J., 2019: Demonstrating direct methanation of real biogas in a fluidised bed reactor. Appl. Energy 240: 359–71.