Schweizerische Eidgenossenschaft
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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

SWEET Call 1-2020: SWEET EDGE

Deliverable report

Deliverable n°	D2.1
Deliverable name	Report with the results on small-scale biogas systems and on combined biomass and solar energy
Authors The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.	Gillianne, Bowman, gillianne.bowman@wsl.ch Janine, Schweier, WSL, janine.schweier@wsl.ch Vanessa, Burg, WSL, vaburg@ethz.ch Hossein, Madi, PSI, hossein.madi@psi.ch Tilman, Schildhauer, PSI, tilman.schildhauer@psi.ch
Delivery date	11.2022

sweet swiss energy research for the energy transition

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Summary

This report includes three main parts.

First, existing spatial data on the Swiss biomass resources were analyzed to identify areas in the midlands and in the whole of Switzerland that are particularly suitable for different existing technologies.

Abstract: Agricultural biogas production is subject to various spatial restrictions including legislation, biomass availability, transport, and the distribution of final energy products. This study introduces a geographic information system (GIS)-based approach for a comprehensive techno-spatial assessment of the above-mentioned factors, which was tested for Switzerland. First, spatial criteria were identified based on an extensive literature review that was complemented by expert knowledge. Then, quantitative GIS-based methods were developed to identify suitable areas for biogas production. Finally, a location- allocation algorithm was used to estimate national production potentials of biogas, electricity, heat, and biomethane and to assess the relevance of greenhouse gas (GHG) emissions from biomass transport. Maximum production potentials for electricity, heat, and biomethane were found to be in the order of 6.3, 8.5, and 13.8 PJ per year, respectively. Heat utilization and biomethane injection are often limited to areas in proximity of settlements. Furthermore, biogas production potentials varied depending on in legal, economic, and technological factors. Particularly the utilization of excess heat from combined heat and power (CHP) plants was found to react very sensitive to altering spatial constraints due to its dependency on local demand. Resulting emissions from biomass transport were in the order of 0.5 - 0.8 kgCO2 equivalent per gigajoule of produced biogas, which is negligible compared to benefits from agricultural biogas production. The modeling results therefore suggest that attention should rather be concentrated on biomass utilization, plant efficiency, and optimal energy utilization when aiming to optimize GHG efficiency. Overall, the findings support the strategic planning of practitioners and authorities for the future development of agricultural biogas production. Moreover, the presented methodology can be transferred to different spatial and technological contexts.

Take-home message:

- Production potentials are strongly influenced by legal, economic and technological factors.
- Transport-based greenhouse gas emissions are negligible in this context.

Second, we assessed the possibilities to combine solar and biomass technologies. A spatial and temporal analysis was performed to identify areas and conditions, where such systems could be considered.

Abstract: Today, the energy transition is underway to tackle the problems of climate change and energy sufficiency in a changing world. For this transition to succeed, it is essential to use all available renewable energy resources most efficiently. However, renewable energies often bring high volatility that needs to be balanced. One solution could be combining the use of different renewable sources to increase the overall energy output or reduce its environmental impact. Here, we estimate the agricultural solar and biomass resources at the local level in Switzerland, considering their spatial and temporal variability using Geographic Information Systems. We then identify the technologies that could allow synergies or complementarities to develop. Overall, the technical agricultural resources potential is ~15PJ/a biogas yield from residual biomass and ~10TWh/a electricity from solar installed on roofs (equivalent to ~36PJ/a). Several technologies could be used to foster complementarity in the system, such as power-to-X. Temporal complementarity at the farm scale can only lead to partial autarchy. Overall, larger scales are more relevant for complementarities between solar and biomass resources.

Take-home message:

- Agricultural potential ~15PJ/a biogas yield and ~10TWh/a (36PJ) solar electricity.
- Several technologies have been identified as possibilities for local complementarities.
- Temporal complementarity at the farm scale can only lead to partial autarchy.
- Larger scales are more relevant for complementarities between solar and biomass resources.

Third, we conducted a systematic review of woody and agricultural biomass technologies as well as their technical and economic characteristics, especially for technologies that are applicable to the midlands setting for electricity, heat and transport. The review methodology was harmonized with Task 1.1. and Task 2.2.

A consistent database is necessary to describe important performance parameters of biomass related technologies as input for the modelling activitie. The biomass related technologies to be considered (incl. woody/agricultural biomass and anthropogenic biomass technologies) were chosen based on the Technical readiness and applicability in Swiss cities and the midlands. The performance parameters considered offer a sufficient level of technical details for the modelling tools to be developed in the SWEET EDGE.

Following the methodology developed by the SCCER Joint activity CEDA ("Coherent Energy Demonstrator Assessment"), the technology descriptions follow a black box approach where the parameters describe everything between one of the clearly defined resources and the clearly defined energy services. Where needed, these parameters are given only for a limited range of plant size or capacity, as they often change with scale. For the availability of the biomass resources, the GIS based database of WSL was used.

Within these studies, a biomass database was developed for data from 2014 and from 2018 for agricultural biomass with a monthly temporal resolution when relevant (Manure, Greenwaste). This database is available on Envidat. Exchanges with the modeling team should ensure a good integration of this data within the wider project.

1 Energy generation potentials from agricultural residues: The influence of techno-spatial restrictions on biomethane, electricity, and heat production.

1.1 Introduction

The utilization of biomass for energy generation is a common practice worldwide. In 2019, bioenergy was responsible for almost 10 percent of the global energy supply and was thus the most important source of renewable energy [1]. Furthermore, biomass can easily be stored and transported, and its energy can be used for various applications including heating, electricity, cooking, and fuel production. Therefore, the upscaling of bioenergy is widely considered a central aspect of climate change mitigation strategies to reach the goals outlined in the Paris agreement [2]. Among the most established technologies to produce renewable energy from biomass is anaerobic digestion (AD). The storable product, biogas, has multiple applications in electricity generation, heating, and mobility, which makes it a relevant option for the decarbonization of the energy sector. At the same time, if fed with residual biomass such as biowaste or agricultural residues, AD serves as a means of waste treatment [3]. As the process is preserving key nutrients from the feedstock, the digestate can be used as a bio-fertilizer [4], which is in line with the concept of circular economy [3]. Furthermore, AD of manure is widely considered an efficient way to reduce greenhouse gas (GHG) emissions from manure management, which is responsible for a substantial share of overall agricultural emissions [5].

At the European level, animal manure alone yields an exploitable potential of up to 640 PJ primary energy per year [6]. Together with an estimated annual potential of 1530 PJ primary energy from crop residues [7] agricultural biogas production has a vast potential. This has also been recognized on a political level as most EU member states offer financial and institutional support for biogas projects [8,9]. Despite its diverse advantages and existing support, however, biogas production from agricultural residues is still at a low level in the European Union [6,7]. The same is true for non-European countries such as the USA and China [10].

Among the most prevalent explanations for the slow development is economic constraints. Depending on the region, available biomass can be distributed on multiple small farms. Consequently, individual farm-scale digesters are often too small for an economic operation [11,12]. At the same time, logistics and spatial planning can be challenging [13], biomass transport is a significant cost factor in bioenergy generation [14], and farmers are hesitant to share an installation with multiple co-owners [15]. Further, biogas plants may face legal restrictions that govern land use and spatial planning or limit their maximum capacity in certain regions [16,17]. Another challenge is the distribution of final energy products and limited energy sales revenues, particularly from heat [12]. Finally, noise and odor emissions can lead to objections from residents if the facility is located in the proximity of housing areas [18]. Thus, logistics and spatial planning are central to the success of agricultural biogas production alongside political and economic factors like subsidies and energy market prices [19].

The high relevance of spatial questions regarding biogas production from residual biomass has attracted attention of research teams worldwide. A first group of studies has focused exclusively on the spatial analysis of biomass supply in various countries, e.g. Argentina [20], Croatia [21], Italy [22], or at a European level [23]. Instead of focusing on the status quo, Hamelin et al. [24] have conducted a scenario analysis on how Danish biomass supplies for biomethane production could be increased through sustainable agricultural intensification. Other research projects have investigated the site suitability for biogas plants based on spatial land use and infrastructure data, often in combination with biomass availability [25–27]. Sliz-Szkliniarz et al. [28] additionally provided a cost-benefit analysis for selected sites in a Polish study area considering transport, processing, and energy sales. Finally, different research teams have used the above-mentioned spatial constraints in optimization algorithms to identify optimal biogas plant locations based on minimal biomass and / or digestate transport under current conditions [29–31] or potential food system transformations [13].

Building on previous research, the current study presents a GIS-based approach for a techno-spatial assessment of agricultural biogas production, which will be applied to the study area of Switzerland. The country is a suitable area of investigation for multiple reasons. With an average farm size of 21 hectares and 27 reference livestock units [32], Switzerland is representative of agricultural areas dominated by smaller farms, where implementing agricultural biogas plants is considered more challenging. Furthermore, the diverse landscape expands over intensively used plains with high cattle densities and alpine areas that only allow for extensive management practices. Regarding biomass supply, the feedstock is restricted to agricultural residues as available co-substrates are increasingly limited [33] and the cultivation of energy crops is not done due to a lack of support and subsidies [34]. Finally, the public availability of spatial data is very high.

The multi-dimensional approach focuses on biomass and digestate transport as well as the production and utilization potentials of biomethane, electricity, and heat. Additionally, it incorporates boundary conditions from legislation and land use. Particularly, the spatial assessment of heat utilization potentials addresses a relevant research gap due to its importance for the economic viability of CHP systems [12]. The study is entirely based on publicly available spatial data and was implemented in ArcGIS. Results should support the development of agricultural biogas production and yield relevant information for policymaking, research, and interest groups in Switzerland and beyond. In particular, the presented approach should provide answers to the following four research questions:

- Where are suitable locations for the production of agricultural biogas, the grid injection of biomethane, and the utilization of thermal energy in the building sector?
- What are nationwide production and utilization potentials of electricity, heat, and biomethane generated from agricultural residues?
- How sensitive are the above-mentioned outcomes to future technological and legal developments regarding site selection and energy distribution?
- How relevant are GHG emissions from biomass and digestate transport under different configurations of the agricultural biogas sector?

1.2 Material and methods

The proposed methodology is based on the analysis of publicly available spatial data (section 1.2.1) and consists of two main parts. In a first step, a newly developed workflow was used to identify areas that are fulfilling legal boundary conditions for biogas production and to estimate the availability of biomass therein (section 1.2.2). Further, suitable areas for the implementation of biogas-fueled heating networks and the upgrading and grid injection of biomethane were identified. A second step made use of the network analyst toolset in ArcGIS (section 1.2.3) together with findings from the first part to quantify nationwide production potentials of biogas, electricity, heat, and biomethane (section 1.2.4). Additionally, the approach was used to estimate potential greenhouse gas (GHG) emissions arising from agricultural biomass transport and digestate delivery (section 1.2.5). Finally, a sensitivity analysis was performed to test the robustness of the results and explore the potential impacts of developments on a technological, political or institutional level (section 1.2.6). Further information including step-by-step procedures of the performed spatial operations can be found in the supplementary information (SI).

1.2.1 Datasets

Table 1 provides an overview of the input data used. In Switzerland, the most comprehensive national representation of agricultural and residential areas was found in land use statistics from the years 2004 – 2009 [35]. They indicate the dominant land use type of every raster cell at a resolution of 100 m x 100 m. The large-scale topographic landscape model of Switzerland [36] provided vector data sets indicating the location of water bodies, railway lines, and roads. The biomass considered in this study consists of agricultural residues arising according to current practice, i.e. mainly manure and some crop by-products. Availability was calculated following the method of Burg et al. [37] based on the updated national agricultural inventory [38]. The animal manure potential represents the total annually collected amount, i.e. generated amount after subtracting losses from grazing. With regard to crop by-products, only a small percentage of the theoretical potential was considered to be available since most crop by-products cannot be readily collected today [37]. The potential biogas production used in the present study was calculated analogously as in Burg et al. [37] based on a specific biogas yield from fresh biomass. The additional potential of co-substrates from industrial or municipal organic wastes was not considered here.

Heat demand data of the Swiss building stock was obtained in form of aggregated 200 m x 200 m raster data expressed in kWh per cell and year [39]. The data is based on a statistical regression bottom-up model [40], which is built on measured heat demand data from a representative set of around 27000 buildings. In addition, the work of Streicher et al. [41,42] provided estimates at the same spatial resolution for potential energy savings resulting from techno-economically feasible retrofitting measures. A combination of both datasets yielded estimates for the future heat demand of the Swiss building stock. However, future projections on population growth are not included. The aggregated form of raster data sets posed two issues for the identification of suitable areas for the construction of heating networks. First, it is impossible to know how exactly the heat demand is distributed within each 200 x 200 m raster cell. Therefore, each cell was considered as one demand point by converting the raster data to point data. Secondly, it is unknown how many neighboring demand points will be included in a heating network, which is relevant for the estimation of a heat demand density. To address this uncertainty, two separate cases were analyzed. Once each heat demand point was considered separately and once the heat demand of all adjacent demand points was summed up (Table 2, Figure 1.1).

The location of the high-pressure gas grid was obtained in form of a vector dataset [43], based on a digital map provided by Swissgas [44]. As no information about the location of the low-pressure gas grid was available, its location was approximated. The Swiss gas industry VSG maintains a list of Swiss municipalities supplied with natural gas [45]. Based on this list, settlement areas of all municipalities have previously been extracted [43] to estimate the extent of the low-pressure gas grid in urban areas. Furthermore, a minimum spanning tree function was applied to estimate the location of low-pressure gas grid segments that are connecting municipalities with the high-pressure gas grid (Figure 1.1, SI A.2). The algorithm computes a network that connects a given set of points based on the path of least resistance. Here, elevation levels from the Swiss digital height model (DHM) [46] were used as an impedance function whereas the impedance was set close to zero along the pipelines of the high-pressure grid to include it as the core of the spanning tree.

Table 1 Overview of input data.

Dataset	Information used	Description
Land use statistics [35]	Agricultural areas without alpine pastures and residential areas	100 x 100 m raster grid, dominant land use type
TLM3D [36]	Water bodies, railway lines, road network	Vector data, topographic landscape model
Agricultural structure survey [38]	Biomass availability at every farm	Point data indicating biomass availability at >50000 farms
Heat demand model [39]	Heat demand for heating and warm water	200 x 200 m raster grid, heat demand of buildings stock
High-pressure gas grid [44]	Location of high-pressure gas grid	Digital map provided by Swiss-gas
Gas-supplied municipalities [45]	Residential areas of municipalities connected to the national gas grid	Areas extracted based on assoc. of Swiss gas providers
DHM25 [46]	Elevation of land surface	Digital height model, 25 m resolution

1.2.2 Identification of suitable areas and biomass availability

Relevant spatial criteria with general validity and their respective parameter values (Table 2) have been identified based on an extensive literature review and complementing expert interviews (see SI A.1 for more information). The criteria include legal requirements as well as technological and economic limitations. The latter can be site-specific, e.g., costs of connection pipeline between biogas facility and gas grid depending on terrain, land use, etc. Therefore, the most liberal estimates from experts and literature were selected as standard cases and more restrictive parameter values were evaluated in the sensitivity analysis (section 1.2.6). Implementing these criteria should yield two maps indicating (i) the area where biogas production is feasible with the expected amount of available biomass and (ii) suitable areas for electricity, heat, and biomethane production.

Table 2: Implemented criteria with the respective parameter values that were used as model inputs. The parameter values expressing the standard case, i.e. the most realistic depiction of today's situation, are highlighted in bold letters. The other values were used for the sensitivity analysis. Legal criteria were always implemented. Transport, heat network, and gas-to-grid criteria were added where required.

Analysis	Relevant criteria	Parameter values (Increasingly restrictive to the right)							
Legal	Location in agricultural zone	**Yes**							
	Minimum distance to residential areas in m	**100**	200	300					
Transport	Maximum biomass transport in km on road	20	**15**	10					
Heat network	Maximum distance of heat network in m	**1000**							
	Linear heat demand density in MWh/m/a	1	1.25	1.5	1.75	**2**			
	Heat demand in MWh	**Current**		Future					
	Cumulating adjacent heat demand points	**Yes**	No						
Gas-to-grid	Maximum distance from gas grid in m	**1000**	900	800	700	600	500	400	300

Legal criteria and biomass availability within permitted transport distance

Legal criteria were implemented in GIS by creating buffer zones around residential areas and their subsequent subtraction from the agricultural area. The resulting area served as a basis for all further investigations, as it indicates zones where the construction of agricultural biogas plants is generally permitted. The criterion of biomass transport was simplified at this point by translating the permitted transport of 15 km road distance into a linear distance of 12 km by means of a so-called “detour factor” [47]. In combination with the point data on biomass availability (farm coordinates), this allowed for the application of a point statistics function to estimate the maximum amount of biomass within reach from every raster cell fulfilling the legal requirements.

Identification of suitable areas for electricity, biomethane, and heat production

Electricity can be fed to the national grid from practically every established farm. Therefore, the suitable area for electricity generation corresponds to the entire area where legal criteria for biogas production are fulfilled. Regarding the construction of biogas plants that aim to feed upgraded biomethane into the low-pressure gas grid, buffer zones were generated around settlement areas of gas-supplied municipalities and the extracted low-pressure connection pipelines (Figure 1.2). Thereby, the maximum distance criteria (Table 2) was used as a radius for the buffer zones. It represents a spatial recommendation for economic project feasibility. A similar approach was taken to identify suitable areas for the construction of biogas plants aiming to supply nearby buildings with thermal energy through a heating network (Figure 1.2). Dividing the heat demand of a given demand point by the linear heat demand density that should be maintained to economically operate a heating network (Table 2) led to a maximum distance between demand point and biogas plant. This distance served as a radius for the buffer zones that were created around each demand point. If the calculated radius was exceeding the maximum of 1000 m (Table 2), it was limited to this distance.

Multiple experts have highlighted that natural and anthropogenic barriers such as water bodies, important roads, and railway lines can significantly increase the price or even prevent the construction of heat networks and gas pipelines (see SI A.1). Therefore, linear vector data of the above-mentioned barriers were used to split the previously extracted buffer polygons. Buffer segments that did not contain or intersect with heat demand points or low-pressure gas grid segments were discarded (Figure 1.3). It required too much computational power to split the buffer polygons of each individual heat demand point (> 600000) and gas grid sector separately. Thus, overlapping buffer zones were combined into one large polygon before they were split by barriers. In a few cases, this led to false-positive results in the subsequent selection process where areas are too far from the next heat demand point without a barrier in between. An example is indicated by question marks in Figure 1.3. However, these errors are small and rare and were thus considered a tolerable uncertainty.

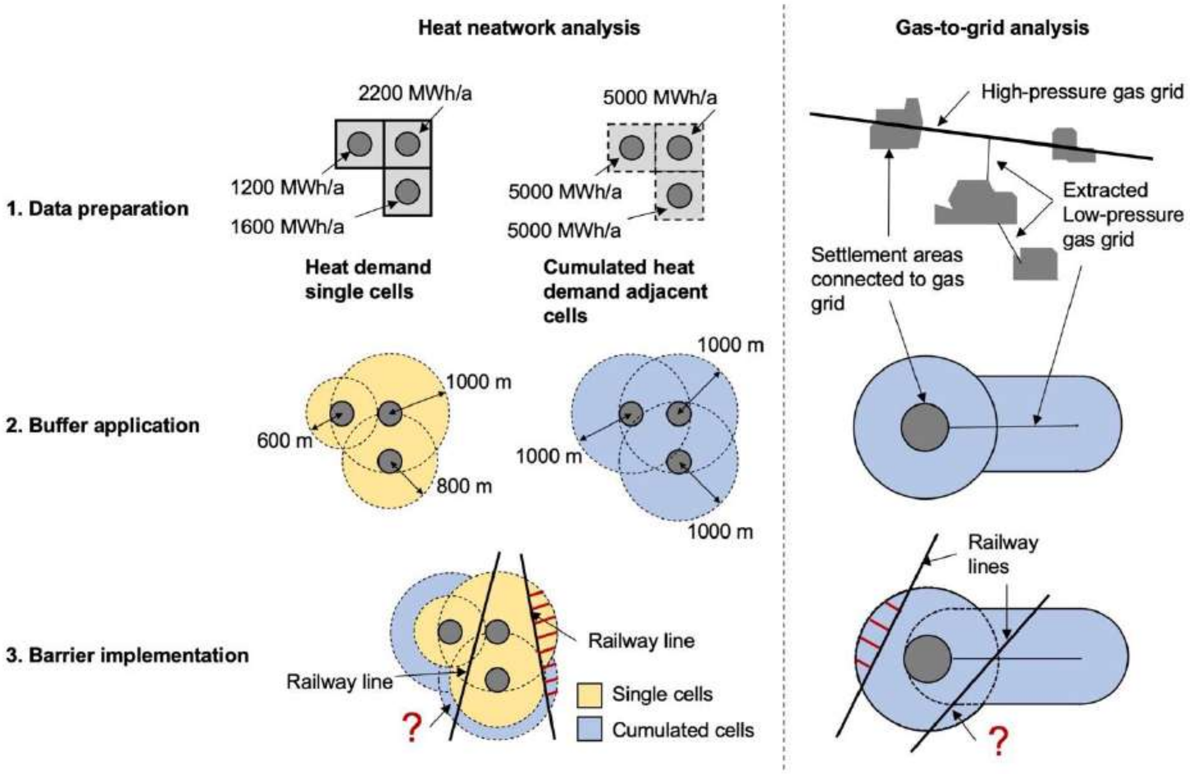

Figure 1: Illustration of the workflows being used to extract areas that potentially allow for the construction of biogas plants supplying thermal energy to nearby buildings through a heat network (left) or feeding biomethane into the low-pressure gas grid (right). The question marks indicate areas that would not have been erased according to the applied method for the implementation of barriers such as railway lines.

1.2.3 Network analysis

The location-allocation tool set [48] from the network analyst extension of ArcGIS selects optimal locations for facilities (here biogas plants) from a set of candidate locations in order to serve so-called demand points (here farms providing biomass) as efficiently as possible (Figure 2). The efficiency is thereby defined by the distance between facilities and demand points along a network data set (here the Swiss road network). In the present study, coordinates of Swiss farms served as both candidate locations and demand points. Indeed, agricultural residues are usually collected and stored on farms and agricultural biogas plants are currently built in the immediate proximity of farms for legal compliance. Thereby, it was assumed that farms require a minimum amount of feedstock to be considered as candidate locations or biomass suppliers. The limit was set to a biogas production potential of 720 GJ (lower heating value LHV) and 144 GJ (LHV) per year for candidate locations and biomass suppliers, respectively. Considering an average CHP efficiency of 40 percent and 8000 hours of operation per year, this corresponds to 10 kW and 2 kW electrical power, respectively. Finally, candidate locations had to comply with legal requirements (Table 2). However, farms lying within 100 m outside of the extracted agricultural zones were added to the pool of candidate locations. Due to the 100 x 100 m resolution of the underlying land use statistics data set, several thousand farms would have been wrongly excluded otherwise. In the present analysis, unselected candidate locations simply provided their biomass to a selected facility within the permitted transport distance (here: 15 km road distance) according to the algorithm’s solution.

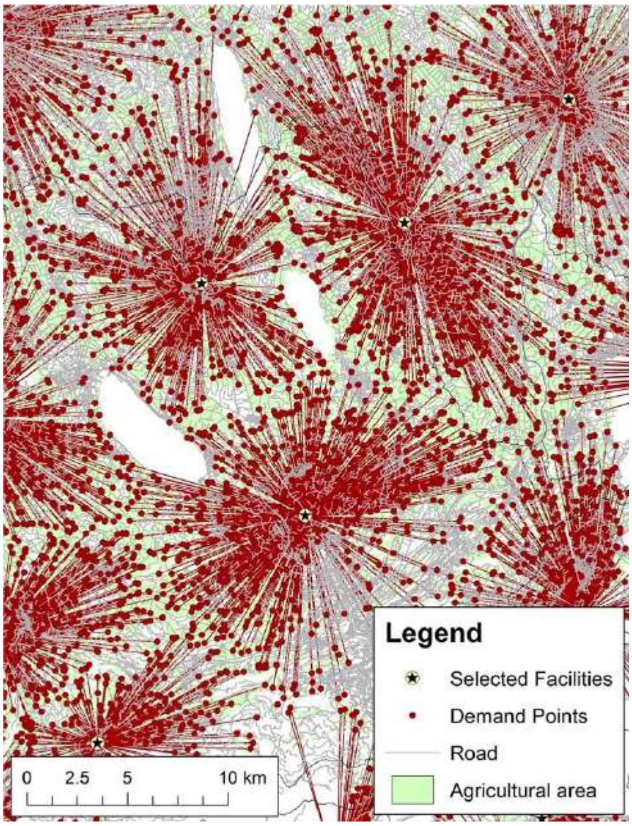

Figure 2: Example of a location-allocation algorithm solution. The straight lines are only representative. Calculations were conducted following the road network.

1.2.4 Estimation of production potentials

The focus of this assessment was not to identify optimal locations for individual plants but to estimate nation-wide production potentials of biogas and final energy products under the spatial constraints implemented according to section 1.2.2. To do so, the location-allocation algorithm was run three times to optimize biomass utilization for (i) the production of biogas and electricity, (ii) the production of biomethane, and (iii) the production and utilization of heat. For the energetic conversion, efficiencies from current state-of-the-art technologies were applied, i.e. two percent losses in biomethane upgrading and a CHP plants electrical and thermal efficiency of 40 and 55 percent, respectively. Because electricity can be fed into the national grid from practically every established farm, it was assumed that every candidate location is suitable for electricity production, too. The potential for electricity production thus corresponds to the biogas production potential times the electrical efficiency. In contrast, the production and distribution of biomethane is limited to candidate locations that fulfill the spatial gas-to-grid requirements (Table 2 & section 0). As a co-product of CHP plants, heat can also be produced at every candidate location. However, a full utilization of excess heat in neighboring buildings is limited by their demand. To investigate the maximum heat utilization potential by the Swiss building stock, candidate locations were therefore selected according to the spatial heat network criteria (Table 2 & section 0). Furthermore, the capacity of candidate locations was limited. For this purpose, the heat demand of every demand point was distributed equally among the candidate locations lying within its buffer zone. If a candidate location was lying within multiple buffer zones, the heat demands were added up.

The plant capacity was then estimated based on the following formula:

$$Cap_{GJ} = \frac{HD_{tot}}{Eff_{th} * (1 - HD_{int})} * F_{MW}^{GJ} \quad (1)$$

Cap_{GJ} = *Plant capacity in GJ biogas production*

HD_{tot} = *Total heat demand in MWh*

Eff_{th} = *Thermal efficiency of CHP module (here: 0.55)*

HD_{int} = *Share of internal heat demand (here: 0.4)*

F_{MW}^{GJ} = *Conversion factor, 3.6 GJ per MWh*

1.2.5 Investigation of biomass transport

A last analysis explored biomass transport impacts on GHG emissions. Identifying how transport distances and related emissions change under different configurations of the agricultural biogas sector was of particular interest. It was assumed that the system configuration is mainly defined by the number and capacity of individual biogas plants. Thus, multiple model runs with varying input values for both parameters were conducted to explore their effect on transport. Individual plant capacities were modeled by production limits ranging from 3 to 15 times the biogas production potential of candidate locations' on-site biomass availability (hereafter referred to as capacity factor CF). Additionally, the algorithm was reiterated to select the optimal 300, 600, 900, and 1200 locations of biogas plants for each CF. Output parameters included the location of selected facilities, amounts of effectively allocated biomass, and road distances to farms (weighted or not by the biogas production potential of the transported biomass). For the present assessment, it was assumed that farms are both provider of biomass and recipients of the corresponding amount of digestate after accounting for the volume reduction during AD. This is in line with previous research on manure transport chains in Switzerland [14]. Weighted transport distances were translated into transport-based CO_2 emissions. First, data from Burg et al. [37] was used to calculate the average volumetric contributions of solid and liquid manure and crop residues per GJ of biogas. Secondly, the volume reduction of each substrate during anaerobic digestion was calculated following a procedure described in Schnorf et al. [14]. Thirdly, empirical data of Swiss biomass transport chains from Schnorf et al. [14] was used to calculate average CO_2 emissions originating from transporting solid and liquid manure, crop residues, and digestate for one kilometer. For more information about the calculation, please refer to SI A.4.

1.2.6 Sensitivity analysis: standard and worst-case estimations

Most spatial parameters (Table 2) are subject to uncertainty or can be expected to change in the future. To better understand the consequences of parameter changes on the modeling results, each analysis of section 1.2.2 was conducted with all possible parameter combinations (Table 2), e.g., maximum tolerable distance to the gas grid of 300 m combined with 300 m minimum distance to housing zone (standard case: 1000m and 100m). Subsequently, model outputs were statistically evaluated based on the resulting area and the number of suitable candidate locations. The results from the most restrictive parameter sets were further used to visualize the effect on suitable areas for energy generation compared to the standard case. Also, they were used to select candidate locations for the estimation of production potentials of biogas and final energy products (see chapter 1.2.4). Thereby, the estimated production potentials based on standard parameter values were complemented by a worst-case perspective. Finally, it was investigated for both cases how a change of the maximum permitted biomass transport distance (15 km) by ± 5 km affects the overall production potentials.

1.3 Results

1.3.1 Biomass availability and technology-specific biogas production potentials

The spatial analysis yielded a total area of approximately 8500 km^2 that includes more than 30000 farms (i.e. 60% of all Swiss farms) where biogas plants can be built in compliance with the considered legal criteria (Table 3, standard parameter values). The area consists of the entire colored part in Figure 3. Different colors indicate the maximum annual biogas production potential at every location assuming full energetic utilization of the available biomass within a linear distance of 12 km. The values strongly correlate with cattle density and are highest in the Swiss central plateau. However, also more remote locations in alpine valleys show a potential from several thousand up to over 100000 GJ biogas production per year.

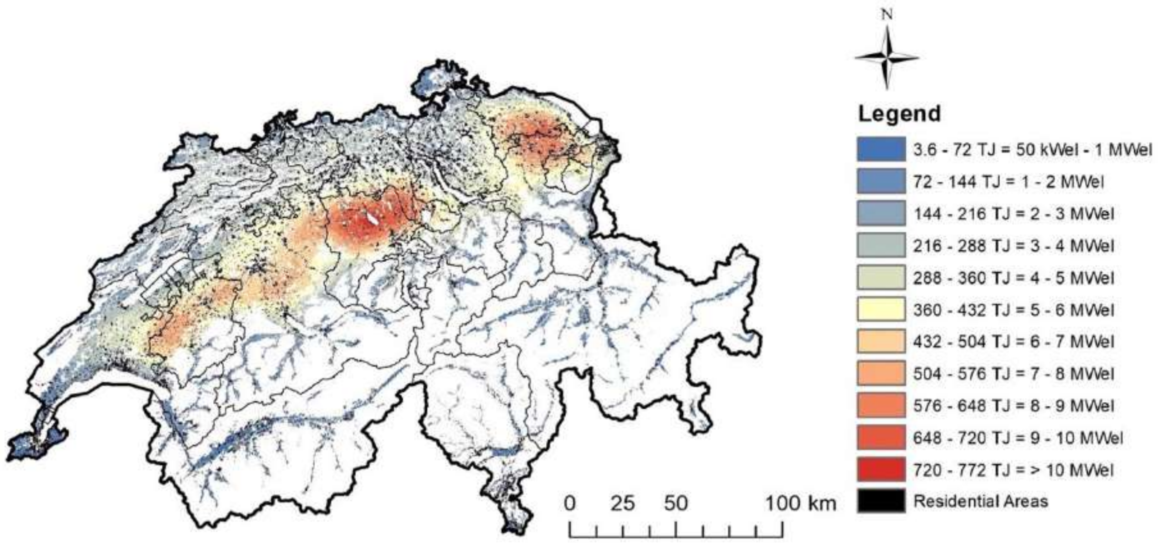

Figure 3: Maximum annual biogas production potential (LHV) at every location in Switzerland, that is fulfilling the considered legal requirements. The analysis is assuming full energetic utilization of the available biomass within a linear distance of 12 km. The values are expressed in MW electric power of a CHP unit assuming a transformation efficiency of 40 percent and 8000 operating hours per year.

Adding spatial requirements for the grid injection of biomethane and the distribution of excess heat in heating networks yielded four zones indicated by different colors in Figure 4.1. Electricity production is assumed to be feasible wherever the legal requirements are met. According to the model results, it is often the only valid option for the energetic valorization of biomass, particularly in large extents of the agrarian area. Even though excess heat of the CHP units can potentially be used for the heating of farm buildings and internal operations to a certain degree, its commercial distribution via heating networks seems unrealistic in these zones. The sustainable operation of heating networks requires a sufficiently large heat demand density, which can primarily be found in the proximity of densely populated settlement areas. Often, these zones are overlapping with suitable areas to produce biomethane as many major settlements are connected to the national gas grid. Areas that are suitable for biomethane production yet unsuitable for the operation of heating networks are sparse and limited to the vicinity of the extracted low-pressure gas pipelines.

A summary of the resulting areas and farm counts for each zone can be found in Table 3 (standard cases) together with the corresponding annual production potentials of electricity, heat, and biomethane that were obtained by the network analysis. With a focus on maximum electricity production, the annual output could reach up to 6.3 PJ of electric energy. This corresponds to an annual biogas production of almost 16 PJ and a utilization of over 93 percent of the available agricultural residues. In this case, however, it is unclear how much of the calculated 8.72 PJ of excess heat can be utilized. When aiming at a full utilization of thermal energy in heating networks, the model outputs were slightly reduced with an estimated annual production potential of 6.2 and 8.5 PJ of electricity and heat, respectively. The annual production potential of biomethane was found to be 13.8 PJ. This corresponds to 14.1 PJ of raw biogas and a biomass utilization of almost 83 percent. This is approximately ten percent lower compared to electricity and heat production in CHP plants.

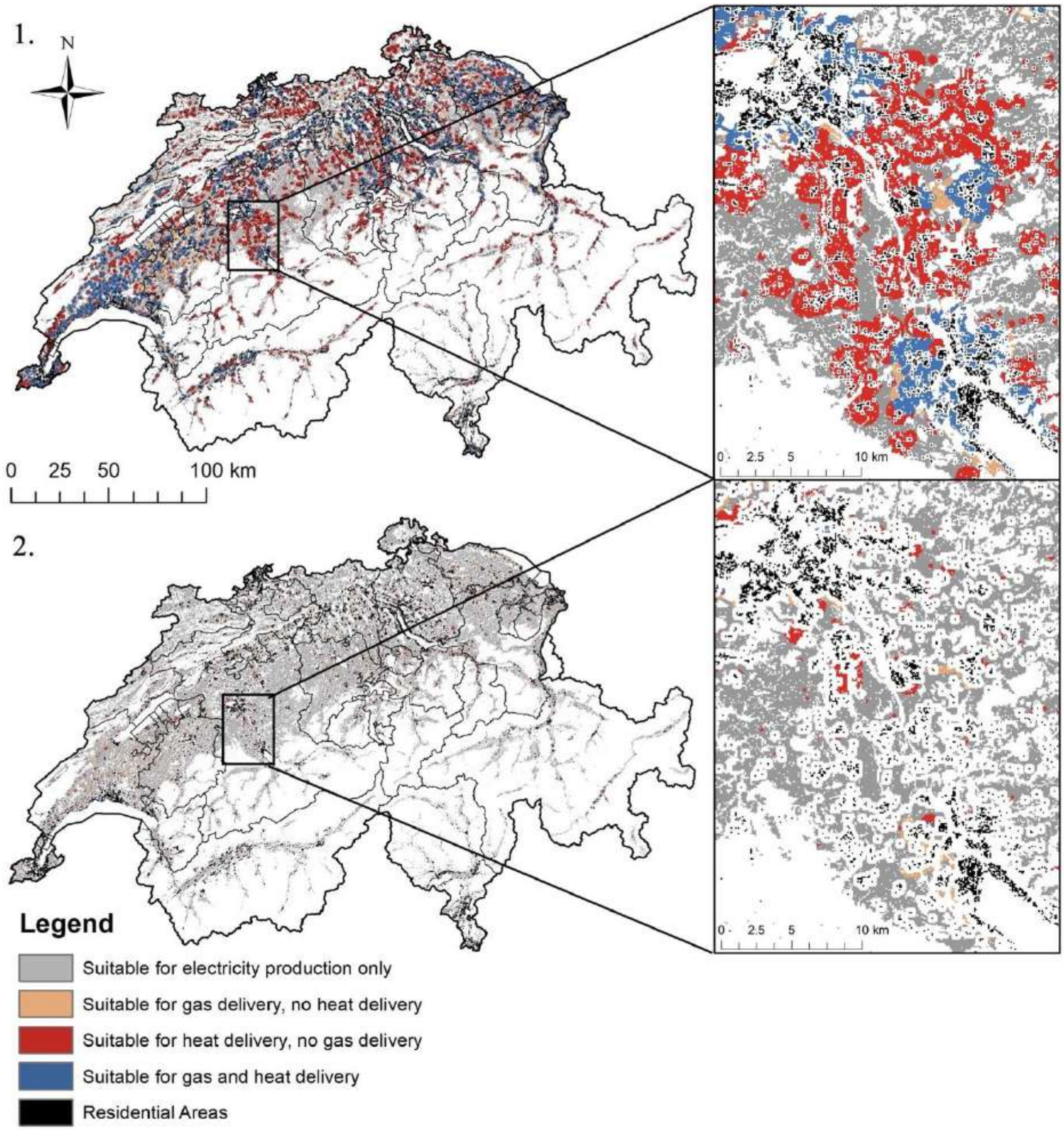

Figure 4: Suitable zones for the production and delivery of the final energy products electricity, heat, and biomethane. For better visibility, the map extracts on the right are zoomed in on the region south of the country's capital Bern. The maps were obtained using the standard (top) and most restrictive (bottom) parameter values (Table 2).

1.3.2 Sensitivity of results

The model outputs' sensitivity regarding individual parameter changes could not be determined independently due to strong parameter interactions (SI A.5). Nevertheless, some general observations are worth mentioning. First, all parameters were found to significantly influence the resulting area and number of farms therein, i.e. any individual parameter change by one step (Table 2) altered the resulting area by a minimum of 150 up to 2200 km^2.

The impact is similar for the number of farms, which is strongly correlated with the total area ($R^2 > 0.95$). Second, the more restrictive a parameter combination is chosen, the smaller the absolute and the larger the relative effect of an individual parameter change on the model outputs. Third, the choice of heat demand data and the consideration of either the individual heat demand of single demand points or the cumulated demand of neighboring demand points showed by far the largest effect on the model outputs (SI A.5).

A comparison of Figure 4.1 and Figure 4.2 highlights how drastically the model results change when the most restrictive parameters are applied instead of the standard ones. Suitable zones for heat and biomethane delivery are significantly reduced. Also, the effect of an increased minimum distance to housing zones becomes clearly visible. These observations are supported by a significantly lower resulting area as shown in Table 3. Additionally, the annual production and utilization potentials of biogas, electricity, heat, and biomethane are affected by a reduced number of available candidate locations due to the restrictive parameter values. While the maximum production potential of electricity remains practically unchanged, the limited number of available candidate locations leads to a significantly lower production potential of biomethane. By far the strongest effect observed was on the potential to utilize excess heat in heating networks, which experienced almost a six fold decrease compared to the standard case. Altering the maximum transport distance for biomass (15 km) by ± 5 km had almost no effect on the maximum production potential of electricity (Table 3). At the same time, the effects on biomethane production potentials were significant, ranging from + 16 to - 22 percent. In terms of heat utilization, the observable effects from reduction of the transport distance were in the order of 10 to 20 percent, while an increase had almost no effect.

Table 3: Overview of the modeling results of the extent of suitable production areas and the corresponding production potentials for each analysis' standard and most restrictive sets of parameters. Corresponding parameter values can be found in Table 2. Biogas and biomethane production potentials are expressed by the lower heating value. The effect of changing the maximum transport distance for biomass of 15 km by + / - 5 km is expressed by a percent change of production potentials (last column).

Applied parameter values	Area [km²]	Number of farms [-]	Biomass utilization [%]	Biogas production potential [PJ / a]	Production potential final energy product [PJ / a]	Effect transport distance [%]
Legal aspects (electricity)						
Standard parameters	8499	31632	93.1	15.86	6.34[1] / 8.72[2]	+0.9 / -2.0
Most restrictive parameters	5890	20344	91.9	15.65	6.26[1] / 8.62[2]	+1.6 / -3.2
Heat network (heat)						
Standard parameters	4071	14827	90.8	15.46	6.18[1] / 8.50[3]	+1.9 / -20.6
Most restrictive parameters	244	999	15.7	2.67	1.07[1] / 1.43[3]	+0.6 / -10.2
Gas-to-grid (biomethane)						
Standard parameters	2628	8210	82.8	14.11	13.83[4]	+5.3 / -9.7
Most restrictive parameters	463	1151	64.4	10.96	10.74[4]	+16.9 / -22.0

[1]Potential for electricity production and utilization
[2]Potential for heat production
[3]Potential for heat production and utilization
[4]Potential for biomethane production and injection

1.3.3 GHG emissions from biomass transport

A summary of the evaluated model results for biomass transport under various potential configurations of the agricultural biogas sector is shown in Figure 5. Below 10 PJ, the overall biogas production potential for a given number of facilities is linearly increasing with an incremental expansion of plant capacities (Figure 5.1). Above, the incremental gain in biogas production is decreasing, which eventually leads to converging model outputs. Independent of the number of selected facilities, this trend towards stagnating biogas production corresponds to an observable decrease in the mean capacity utilization of biogas plants (Figure 5.2).

For a given number of facilities, overall transport-based GHG emissions follow an S-shaped growth pattern when plant capacities are increased (Figure 5.3). Thereby, a higher number of selected facilities leads to larger maximum growth rates. At the same time, total GHG emissions start stagnating at lower capacity limits. As with biogas production, the stagnation corresponds well to a decrease in the mean capacity utilization of biogas plants (Figure 5.2). For the largest modeled capacity limits, this resulted in higher total emissions occurring from the supply chains of fewer selected facilities. Finally, production-specific GHG emissions (Figure 5.4) were obtained from a division of total GHG emissions (Figure 5.3) by the overall biogas production (Figure 5.1). Accordingly, the resulting emission levels are increasing at first, before stagnating or even decreasing with increasing capacity limits. While resulting GHG emissions are largest for higher numbers of selected facilities at low capacity limits, the order of emission intensity is being inverted with increasing capacity limits. Average transport distances were between 2.5 and 4.5 km for all model runs. Maps indicating the biogas plant locations for selected scenarios can be found in SI A.6.

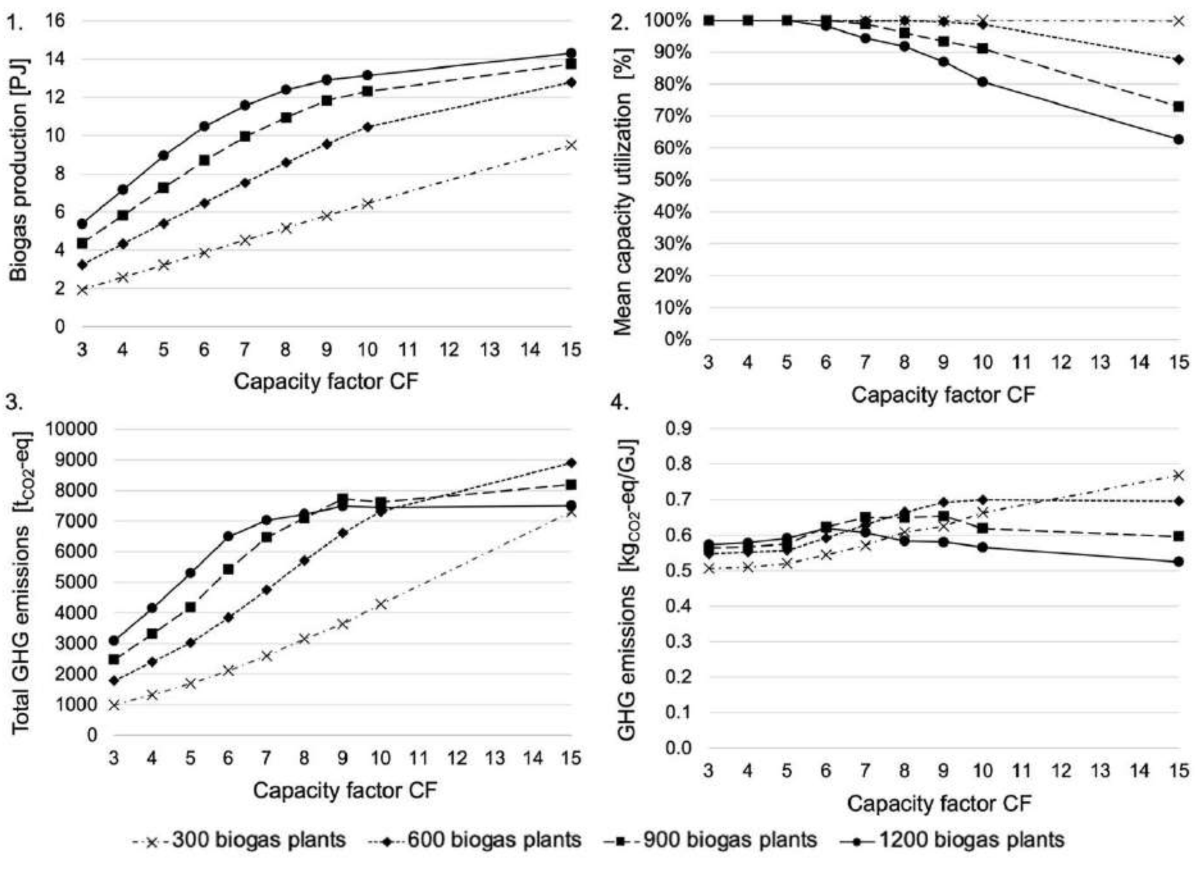

Figure 5: Distribution of model outputs regarding the number of selected biogas facilities and the applied individual capacity limits at candidate locations in multiples of the on-site biomass availability (capacity factor CF). (1.) resulting overall biogas production. (2.) Mean capacity utilization of all selected facilities. (3.) Total GHG emissions related to biomass transport. (4.) Product-specific GHG emissions from biomass transport.

1.4 Discussion

Overall, the proposed methodology proved to be suitable for investigating relevant spatial information to better understand the limits and opportunities in developing the agricultural biogas sector. This was demonstrated in a practical case for Switzerland, a diverse country with areas of both intensive and extensive agriculture dominated by small-scale farms. The methodology combines approaches presented in previous work with novel elements in its design. Metson et al. [31] and Sahoo et al. [29] have relied on similar boundary conditions regarding land use, housing zones, and existing infrastructure as well as a minimization algorithm for biomass transport in their assessment of optimal biogas plant locations in Sweden and Ohio, respectively. Similarly, Höhn et al. [49] have identified optimal locations for biomethane generation in Finland based on biomass supply and nearby road and gas network access. However, the first study primarily focused on optimal nutrient utilization, while the latter two exclusively considered the grid-injection of biomethane. In contrast, the present approach aims to identify the maximum production potentials of biogas, biomethane, electricity, and heat from agricultural residues for an entire country. Particularly, the utilization of heat from biogas plants equipped with CHP technology has not been considered in a spatial study to date. Being a crucial factor for the economic viability of CHP systems [12,19], its inclusion in the present study is an important refinement with regard to the identification of suitable plant locations and as a basis for economic assessments. It could for example be used to calculate spatially explicit revenue potentials from heat sales and thereby improve the accuracy of existing cost-benefit approaches [28].

Additionally, the extensive sensitivity analysis provides valuable insights into the relevance of individual spatial criteria and how future technological or legal developments regarding site selection and energy distribution can influence biogas production. The present study thereby complements work in prospective scenario analysis, e.g. by Hamelin et al. [24] and Metson et al. [13] who investigated the effect of sustainable agricultural intensification on biomethane production and the influence of food system transformations on biomass transport, respectively. The presented method primarily relies on high-quality spatial data and accurate agricultural statistics, both publicly available in the study area of Switzerland. However, the approach is universally applicable and can therefore be transferred to different regions or countries with similar data availability by adapting the spatial criteria to local conditions. Additionally, it can be adapted for the investigation of different technologies, biomass types, and other renewable energy sources.

Many uncertainties of the present study have already been discussed throughout this article. Among the most relevant ones is the inherent uncertainty of spatial data sets. Particularly raster data sets were a major source of uncertainty in the present study as information on land use types and heat demand was aggregated in cells covering one to several hectares. Furthermore, it can be expected that mainly inefficient heating systems would be replaced by heating networks that are supplied with excess heat from CHP systems. This aspect has been neglected in the present study for the sake of simplicity as well as diurnal and seasonal fluctuations in the heat demand and population growth. All aspects, however, may have an influence on the potential utilization of excess heat in heating networks. Additionally, the heat distribution via heating networks within raster cells has not been accounted for, which might increase the required pipe length [50] and thus costs and thereby reduce the maximum distance between demand points and biogas plants. Regarding the injection of biomethane, no information about the extent of the low-pressure gas grid in Switzerland was available. Therefore, its layout had to be fully estimated by means of a minimum spanning tree based on the high-pressure gas grid and the settlement areas of municipalities that have access to the national grid. For biomass and digestate transport modeling, we assumed that farms are both substrate providers and digestate recipients. While this is generally true for the Swiss context today [14], this assumption might need to be changed over time or in different geographic contexts. Finally, spatial parameters such as the linear heat demand density may vary depending on the local terrain and land use type among other factors. The extensive sensitivity analysis has addressed these uncertainties as thoroughly as possible..

The results obtained for the spatial distribution of agricultural residues (Figure 3) are in line with previous research [37,51,52] conducted for Switzerland. Furthermore, the applied approach allowed estimating location-specific biogas production potentials within a linear distance of 12 km. The findings indicate that the biomass availability within this distance would permit the operation of CHP units of up to 10 MW installed electric capacity in intensively used agricultural regions. These results are comparable to findings for southern Finland [30] even though the average farm size there is significantly larger compared to Switzerland [53]. At the same time, biomass availability in more remote alpine regions was found to support installations with an equivalent electric power of 50 to several hundred kW. Both observations indicate that the installation of biogas plants is not prevented by biomass availability per se, despite its scattered distribution on multiple small-scale farms. In fact, it will be important to encourage cooperation among farmers, optimize revenues e.g. from energy sales, and induce changes on an institutional level to foster agricultural biogas production as highlighted by previous research [15,54]. Also legal limitations may play a crucial role, as shown by the example of Switzerland, where legislation currently prevents installations above capacities of few MW are currently prevented by the Swiss legislation. in certain regions [17] and requires them to be subordinate to agricultural operations [19].

Compared to previous research [37], which was based on comparable input data, the present results for maximum biogas production potentials (16 PJ) are approximately 45 percent higher (Table 3). The main reason for this large difference lies in the applied spatial criteria. Burg et al. [37] relied on a minimum spatial biomass density within 1 km as a threshold for sustainable biomass utilization because cooperation among nearby farms seemed more likely. In contrast, the present approach was based on spatial boundary conditions for biogas plant locations and the subsequent allocation of biomass within the legally permitted transport distance of 15 km.

Estimated potentials for electricity, heat, and biomethane production (Table 3) could significantly contribute to the Swiss energy sector. Annual production and utilization potentials for electricity and heat correspond to 2.7 percent of the current nationwide electricity production of 65.5 TWh / a and 1.6 percent of the heat demand from the entire building stock (assuming 40 percent internal heat demand of biogas plants), respectively [55,56]. Remarkably, a focus on optimal heat utilization did not significantly alter the obtained potentials for electricity production (Table 3). Therefore, the findings suggest that careful spatial planning could significantly increase the heat utilization of biogas-fueled CHP units without compromising electricity generation, thereby improving the energy efficiency and economic sustainability of individual facilities and the entire sector. However, financial incentives for an optimized heat utilization are currently lacking in Switzerland and many other countries. Thermal energy has a significantly lower market price than electricity, which is subsidized more often [57,58]. This imbalance has led to a prioritization of electricity production in the planning process and has impeded improved heat utilization so far. Similarly, lacking financial support can prevent the installation of biogas upgrading facilities despite their large potential. For Switzerland, it was estimated that a maximum of almost 14 PJ (= 3.84 TWh) biomethane can be generated from agricultural biomass per year. This corresponds to over 15 percent of the gas-fueled heat market in Switzerland and could contribute to sustainability goals set by the gas industry [59]. In fact, considerable potentials for biomethane production have also been identified for other countries, e.g., Finland [30] and Sweden [24]. The countries' dependency on imported fossil fuels could be significantly reduced by exploiting these potentials,

It must be kept in mind, however, that the presented production potentials were calculated individually for different production systems and cannot be accumulated. The technologies of biomethane upgrading and CHP are in direct competition with each other for a limited amount of biomass, particularly in the proximity of settlements (Figure 4). Further competitors are different processing technologies, e.g., composting and biochar production. Therefore, economic, social, and institutional criteria eventually determine which technology will prevail in a specific project (e.g., SI A.1.1). Regarding CHP and biogas upgrading, the conducted sensitivity analysis could demonstrate how susceptible model outputs are to changing technological and legal limitations.

On an individual level, already small parameter changes could overturn the suitability of several hundred farms for the installation of a biogas plant or specific technology (Figure 4). In terms of overall electricity production, observable effects remained small as the high number of suitable production sites in all analyses allowed for a high spatial coverage and thus biomass utilization (Table 3). In comparison, biomethane production reacted more sensitively to parameter changes including the limitation for biomass transport, which in general has a comparatively higher effect for a lower availability of suitable production sites. The largest effect, however, was observed for heat utilization potentials which has two reasons. Firstly, the analysis for heat utilization included the most numerous and interlinked parameters such as heat demand and linear heat demand density. Consequently, technological developments may both reduce and increase the potential for heat utilization, e.g., by reducing the heat demand of the building stock and by improving the performance and the range of heat distribution systems, respectively. Secondly, capacity limits were applied for candidate locations because heat utilization requires a local demand compared to electricity and biomethane which are fed to a larger grid. Hence, under restrictive conditions, the resulting potentials were mainly limited by the local heat demand, which also explains the comparatively smaller effect of an altered biomass supply through varied transportation limits. The case of heat utilization further illustrates how limited plant capacities (by laws or other restrictions) can significantly reduce overall biomass utilization in processes that are supply- or demand-wise restricted to specific areas. Even though the criteria utilized in the present analysis were specific to Switzerland, similar findings can be expected from different regions.

Results from modelling biomass transport indicate a high accessibility of biomass up to approximately 10 PJ before incremental production gains of additional or larger plants decrease (Figure 5.1). Above, the density of facilities is instead increased. This leads to overlapping service areas, expressed by lower utilized capacities (Figure 5.2). Correspondingly, transport distances become shorter, and emissions stagnate or even decrease (Figure 5.3-4) This point can be reached by high numbers or high individual capacities of biogas plants. Thereby, findings confirm the intuitive expectation that a higher density of smaller facilities causes comparatively lower transport-based emissions for a given overall production than fewer larger installations. However, independent of the number and size of modeled biogas plants, the average production specific GHG emissions were always within 0.5 – 0.8 kg_{CO2}-eq per GJ of produced biogas.

These emissions seem negligible compared to other aspects of agricultural biogas production. According to a calculation approach by Schnorf et al. [14], anaerobic digestion of manure can prevent emissions of roughly 30 kg_{CO2}-eq per GJ of biogas compared to conventional storage. Additionally, the generated energy in the form of biomethane, electricity, and heat could save an additional two, four, and 31 kg_{CO2}-eq per GJ biogas by replacing the Swiss mix of natural gas, the average EU electricity mix, and the fossil share of the Swiss district heating mix, respectively [60–63]. Similar relations can also be found in other life cycle studies, e.g. Metson et al. [13]. Overall, this indicates that leakage prevention, efficient AD and energy transformation processes, and optimized utilization of final energy products will be much more important than aspects of biomass transport with regard to climate change. Therefore, these aspects should be prioritized over biomass transport when aiming to achieve an optimal GHG balance. Even though the minimization of transport distances should be encouraged to reduce emissions, it is questionable whether legal limits are appropriate. Previous research has shown that economic aspects already incentivize short transport distances while economies of scale favor large biogas facilities with higher electrical efficiencies [64,65].

Future improvements of the proposed methodology should aim at reducing existing uncertainties, particularly regarding heat utilization. It will be important to consider a temporally distributed heat demand and to investigate potential synergies and competition with other heating systems. Alternative utilization pathways of digestate, e.g. for nutrient regeneration [66], introduce novel aspects of spatial planning that could be considered in future assessments. When focusing on the utilization of agricultural biomass in general, further research could integrate future food system scenarios as well as other technologies such as composting and biochar production in a comprehensive spatial assessment to develop an overall strategy for improved biomass utilization. Finally, combining the current methodology with socio-economic assessments will help to refine the estimates for biogas production potentials under existing financial and social constraints.

1.5 Conclusions

Biomass can make a significant contribution to the energy transition due to its quality as a low-carbon energy source with various applications in heating, electricity production, and transport. However, the utilization of agricultural residues, which offer large sustainable bioenergy potentials, is limited by multiple spatial constraints. The presented GIS-based approach allows addressing multiple of these constraints in one comprehensive assessment. As a result, the methodology supports the identification of suitable areas for biogas production and provides estimates for maximum annual production potentials of electricity (6.3 PJ), heat (8.5 PJ), and biomethane (13.8 PJ). Findings from the study area, Switzerland, indicate that the distribution of biomass on many small farms and the difficult terrain in alpine regions do not necessarily prevent agricultural biogas development, given that cooperation and economic sustainability can be achieved. In addition, the methodology facilitates the understanding of spatial implications and mutual interaction of the considered spatial parameters. Particularly heat utilization was found to be highly sensitive to legal, economic, and technological restrictions due to its requirement for a local demand. Therefore, foresighted spatial planning encouraged, for example, by targeted financial incentives could significantly improve the utilization rate of excess heat from CHP units and thereby increase the plant’s overall efficiency.

Modelling biomass and digestate transport led to the conclusion that transport-based emissions are negligible compared to benefits from anaerobic digestion independent of future development trajectories. Thus, it is questionable whether legal limitations for biomass transport are constructive in developing the agricultural biogas sector. Future efforts should rather focus on the achievement of high plant efficiencies and utilization rates of final energy products, instead.

On the one hand, findings from the study support planning efforts through the provision of high-resolution spatial data, refine estimates on future production potentials, and identify regions for the deployment of specific technologies. On the other hand, the gained insights facilitate the prioritization of relevant factors when debating the future development of agricultural biogas production. Finally, the presented approach can be adapted to different spatial or technological contexts and serve as a starting point for economic investigations. Therefore, findings from the present study are of likewise interest to practitioners, decision-makers, and researchers.

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2 Linking solar and biomass resources to generate renewable energy: can we find local complementarities in the agricultural setting?

2.1 Introduction

Today, the energy transition is underway, and has to tackle the problems of climate change and energy sufficiency in a fast-paced, changing world. However, renewable energies often bring high volatility that needs to be balanced between the different resources [1]. Indeed, the energy system built at the moment has difficulties dealing with the fluctuating nature of many renewable resources [2]. For this transition to succeed, it is crucial to use available renewable energy resources in the most efficient way and in combination to limit the need for storage, which is costly and is often associated with losses. Moreover, matured technologies are already established in most countries, including Switzerland, and others are still being developed [3, 4]. To ensure an efficient transition, resource availability needs to be quantified, including their spatial and temporal constraints [5-7]. In Switzerland, solar and biomass resources have been estimated in detail throughout the countries [8, 9].

Today, biomass is the biggest contributor (65%) to renewable energy sources in the EU and the second after hydropower in Switzerland [10]. Bioenergy can originate from various feedstock sources, including woody (e.g., forest wood, waste wood) and non-woody (e.g., manure, green wastes) biomass. In a previous study, we identified the largest remaining domestic biomass potential in Switzerland to be, by far, animal manure, with about 40 PJ primary energy or about 15 PJ biogas yield still to be mobilized [8]. One of the main benefits of biogas is that it can provide energy for an array of applications including electricity generation, heat, and transport. With the added inputs of other agricultural by-products, such as chaff, this untapped potential represents more than three-quarters of the biomass that could be mobilized in addition to what is used today. Farmers already see manure as an essential resource for fertilization [11], and its use for energy should therefore be embedded within the agricultural system. Agricultural biogas plant numbers have shown a slightly increasing trend of roughly 10 new installations in the last ten years [12]. Yet, a survey had shown that farmers were highly positive towards renewable energies and valued their contribution to the country’s self-sufficiency [11].

Solar photovoltaic (PV) panels on existing rooftops have proven to be an efficient and viable sustainable energy resource for urban areas [13-16]. In addition, solar panels can have an important role in integrating decentralized renewable energy resources in neighborhoods [17, 18]. PV represented only 3% of the Swiss electricity supply in 2018 but is expected to cover up to 50 % in 2050 [19]. In previous studies, the potential for electricity generation from PV in Switzerland has been estimated [19]. Regarding the solar data, different levels can be found, considering general irradiation within a locality, specific identification of suitable locations (roofs, facades…) [20], and/or electricity production for different panel orientations to favor summer or winter electricity production [9]. The technical potential was found to be 65 TWh without economic consideration and between 22 to 54 TWh for a range of production costs.

The possible complementarity that could stem from using both resources has been little studied until now till now. Complementarity at the energy level can be defined as the capacity of two or more variable resources to work in a complementary way, thus improving the system’s overall reliability and reducing periods of insufficient generation. For example, at the grid level, combining renewable energy with different temporal availability can limit the need for storage: hydrological and geothermal energy as base load, solar panels during the day, and wind throughout the year. Some of these complementarities between different renewable energies have been studied, such as PV and wind [21, 22], wave and wind [23], or PV, wind and hydro [7], and reviewed partly in [24], both for temporal and spatial complementarities.

A promising setup for complementarity can be found in the agricultural setting, where specific combination of resource availability, location characteristics and framework conditions can be found,

The development of self-sufficiency thanks to decentralized energy generation based on available, local resources seems especially attractive as the world is transitioning to a new energy system and has, at the same time, to cope with instability on the world market. The world of agriculture has already started for a few decades to generate energy in addition to producing food, and the value of autonomy, if not autarchy, is strong among farmers. Indeed, farms are often further away from the main settlements, and the value of autonomy is quite strong in this community [11, 25].

Here, we investigate the solar and biomass resources at the local level in Switzerland, considering their spatial and temporal variability using Geographic Information Systems GIS. Indeed, to evaluate the spatial features and distribution of complementarity, GIS applications provide a wide range of analysis and visualization possibilities. We then review and identify the technologies that could allow complementarities to develop. Also, we look at a case study regarding the possibility of a farm reaching electrical self-sufficiency throughout the year. Finally, we present possible advantages of combining solar and biomass resources for energy by describing a case study. We will conclude with the pertinence of our system boundaries and how relevant the combination of solar and biomass can be for the energy transition.

2.2 Materials and Methods

2.2.1 Temporal and spatial resources potentials

Agricultural solar potential

We apply a hierarchical GIS methodology to estimate the spatial and temporal rooftop solar PV potential of agricultural buildings in Switzerland. The methodology consists of three main steps: (i) The theoretical potential that quantifies the total annual irradiation (average value for the years 2004 - 2014), taking into account the shading (ii) the technical potential, which reflects the technical constraints of the available roof area, and to lesser extent, building facades and greenhouses roofs, and (iii) the agri-technical potential, which relates to technical potential on agricultural buildings.

In Switzerland, the federal government conducted an extensive country-wide solar potential analysis to plan the expansion of solar PV [26, 27]. The study distinguishes between different suitability for PV. The Feature Analysis extraction tool in ArcGIS was applied to remove less suitable areas from the theoretical potential to obtain the technical potential. E.g., roof areas smaller than 10 m2, and those classified as having a "low" or "medium" suitability [20] were subtracted from the theoretical potential. Thus, 78 TWh/a of the total estimated theoretical solar roof potential of 99 TWh/a could be technically used. The same approach was also applied to facades. For these surfaces, the technical potential is defined by areas larger than 20 m2 and classified as having at least “medium” suitability.

Farm coordinates [28] were used to locate buildings with an agricultural setting. Considering the typical structure of Swiss farms, a 50-meter buffer around the main farm point was used to detect the presence of additional farm buildings (Figure 1). This 50-meter buffer was also confirmed as appropriate as its potential results closely match combined heat & power (CHP) plant the rough estimate according to Swisssolar [20]. Hence, this buffer was used to assess the temporal estimation with a monthly resolution based on a 10-year average (2004-2014). Greenhouses often located a little further away from the farm building were also included in the overall PV potential assessment - but cannot be specifically assigned to one farm. In addition, we also used a 75-meter buffer around the main farm points for sensitivity analysis and to see how the local network could impact the solar potential (using agricultural buildings and neighbors’ roofs).

Figure 1: Identification and assignation of roofs of agricultural buildings in relation to the closest farm to estimate the local PV potential.

Agricultural biomass potential

The spatial potential of agricultural biomass was estimated based on data from the national agricultural inventory [28]. Here we used the available potential of manure and agricultural residues technically available according to current practice [8]. The animal manure potential is the total annually collected amount, which is the generated amount after removing losses occurring in the pastures. Only a small percentage of the theoretical potential of crop by-products was considered available since most of them cannot be readily collected today. The potential biogas production in the present study was calculated using the specific biogas yield from fresh biomass [8]. Neither the potential of co-substrates from industrial or municipal organic wastes nor energy crops were considered, but only biomass arising at the farm level.

Manure is by far the main agricultural input (>90%). Its monthly temporal resolution was performed considering the number of days the animals spend in the field according to official surveys [29] and splitting this number following the local regulation and additional expert knowledge [30].

2.2.2 Possible complementarities

Many complementarities are conceivable between biomass and solar potentials. Broad literature research and several insightful meetings with experts? [31] allowed defining the most promising one within the Swiss agricultural system (Table 1, Figure 1). They mainly consist of seasonal and technical complementarities, described in more detail thereafter.

Seasonal balance

Solar energy's low yield in winter can be offset by larger energy generation from agricultural biomass in winter. Indeed, the animals spend more time in winter inside the stables, and more manure is collected than when they are in the pastures. The biogas plants are also not dependent on the day/night cycle. Moreover, biomass storage is also a possibility to increase this effect: biomass collected in summer could be kept for energy use later in winter. This can, however, lead to a loss of biogas potential that is not negligible [32]. It is also important to note that manure storage for 2-3 months is standard practice (especially in wintertime when it is not allowed to spread the manure to the fields), and there is thus flexibility on when to use it.

Technologies

The technologies with the most promising complementarities are chosen and described in detail. They include some that are already commercialized and others that are being developed at the moment. Their technical requirements, such as size and energy consumption, are identified. This includes the technologies‘ descriptions as well as, when available, necessary conditions (e.g., a minimal amount of local resources). Here, we consider technologies for conversion into electricity, heat, as well as further technologies to produce storable energy carriers (biomethane, hydrogen).

Table 4. Identified promising technologies for complementarities between biomass and solar resources for energy in the Swiss agricultural setting.

Technology	Description
Anaerobic digestion, combined heat & power (CHP) plant	Manure and agricultural by-products are fermented in a digester and the produced biogas is then used to produce electricity and heat with a combined heat & power (CHP) plant. This represents the standard case today (if the agricultural are used for energy).
Raw manure separation	Raw manure collected from the stables is separated with a screw press into two fractions: solid and liquid.
Biomethane upgrading	Electricity generated from PV can be used to purify biogas into biomethane. Thus, part of the energy can be stored in the natural gas grid.
Power to X, Electrolysis	The biogas provides CO_2 for the methanation process, while the electrolyzer is operated with PV electricity to produce the required hydrogen. The product is Synthetic Natural Gas and can be stored in the natural gas grid.
Cold generation	The heat produced during biogas combustion in a CHP can be converted to cold with a heat pump powered by PV electricity.
Photovoltaic on biogas facilities	PV panels can be installed on extra infrastructure provided by the biogas facilities, mainly on additional biomass storage halls.

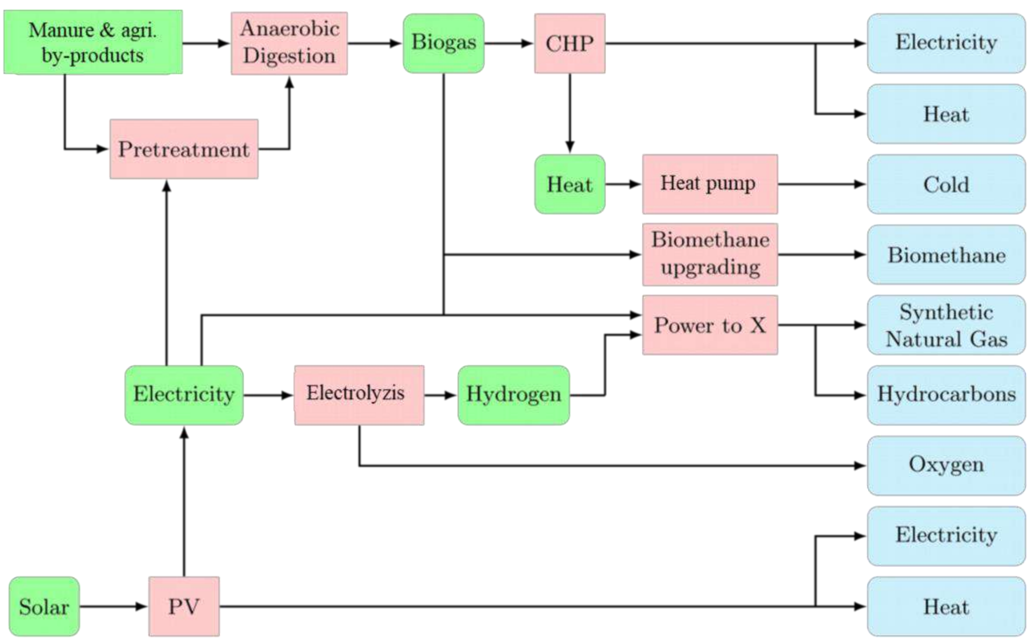

Figure 1. Overview of the various technologies identified as possible complementarities between solar and biomass resources and the possible links between the conversion paths. Conversion processes are shown in red, intermediate energy carriers in green, and final energy carriers in blue.

2.2.3 Case studies at farm level for decentralized energy generation

Additionally, a case study regarding an individual farm was investigated. Therefore, the detailed load profile of a farm, measured over 8 months (from January to August), was used [33]. This farm counted 67 cows, 9 fatted calves, and 500 laying hens, leading to a production potential of 470 GJ biogas yield [28]. The largest roof was 770m^2, and the total roof area was 2063 m^2. According to the load profiles, the power demand for this farm was 38,000 kWh. We calculate the quantity of electricity that the farm could produce with PV and a biogas plant run only with its own manure resources for its own consumption (right amount at the right time). hence, we estimated how this produced electricity participated in the self-sufficiency of the farm and how much still must be provided by to the electricity grid. The heat was not included in the analysis because no data on the heat demand was available. We assumed that the total available surface of all farm roofs may be used for photovoltaic. We calculated the self-sufficiency when the agricultural residues of the farm (mainly manure) are fermented in an anaerobic digester according to their spatial distribution. The biogas is fed directly into a CHP, producing electricity and heat as base load.

2.3 Results

2.3.1 Resources

2.3.1.1 Spatial distribution

Agricultural solar potential

The agri-technical irradiation potential was found to sum up to 71.9 TWh/a for the roofs of agricultural buildings within a 50m buffer. The spatial distribution shows that high irradiation potentials can be found across the whole country (SI). In addition, an agri-technical irradiation potential of 29.3 TWh/h was estimated for the facades of these buildings (thus +40%) and 4,8 TWh/a for greenhouses (+14.8%) that were not yet included in the 50m buffer.

Regarding the electricity yield itself, a total of 9.6 TWh/a could be produced. This includes roofs on agricultural buildings (50m buffer) (Figure 2). Additionally, 39.9 TWh/a could come from facades (+40%) as well as 0.7 TWh / a from greenhouses (+14.8%).

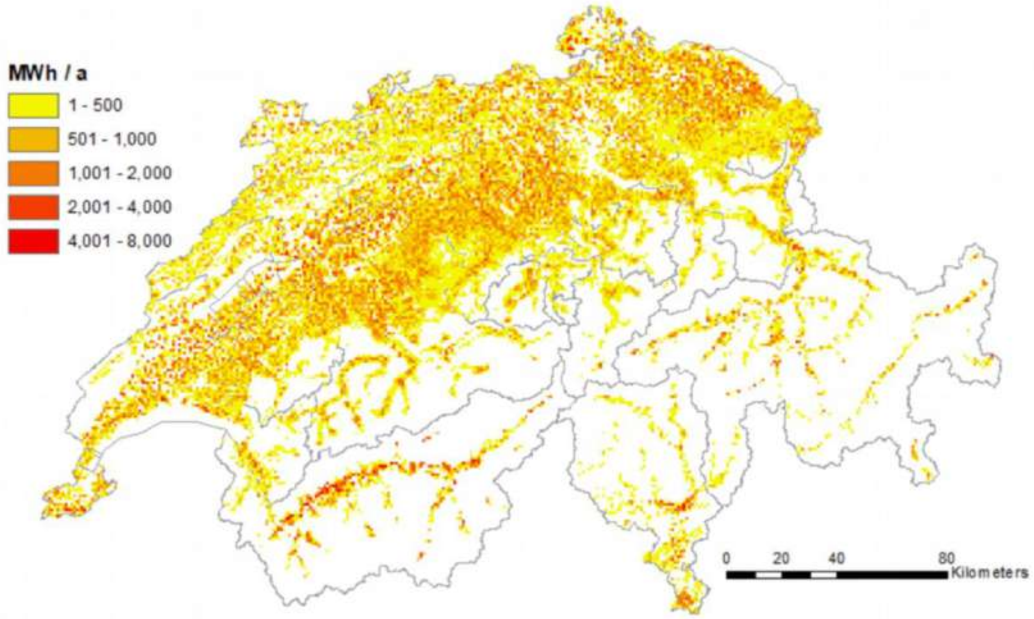

Figure 2: Electricity production potential per year on agricultural roofs only.

Agricultural biomass potential

As can be seen on figure 3, agricultural biomass is widely distributed which, complicate its exploitation for energy purposes. An increased occurrence is observed along Alpine valleys and in the central Plateau, where most animals are. After subtraction of manure losses through grazing, the technical potential for biogas yield is 15.154PJ.

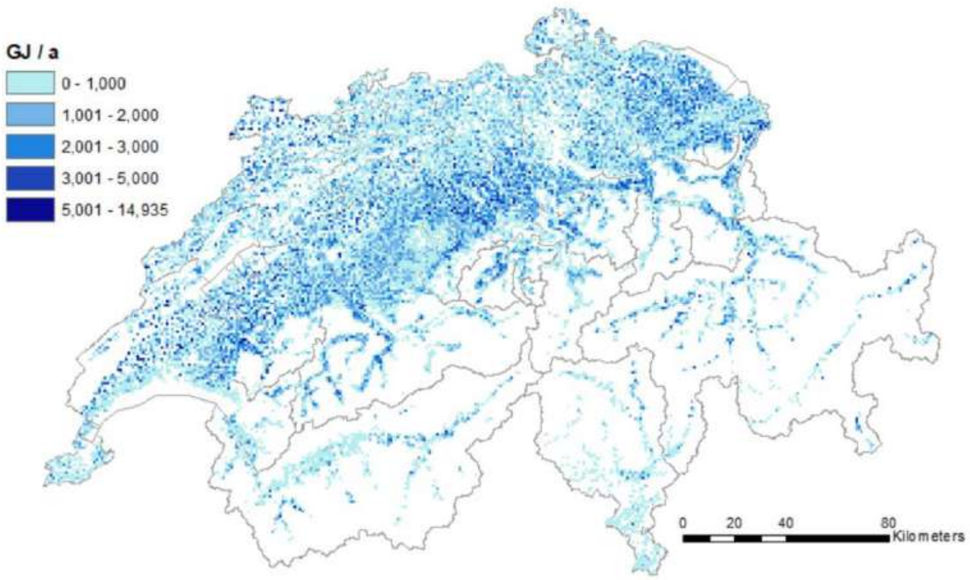

Figure 3. Technical potential of manure and agricultural residues in GJ per year of biogas yield.

2.3.1.2 Temporal distributions

The temporal distribution of both resources shows a possible temporal complementarity.

The temporal distributions of both resources throughout the year are very different. As expected, solar energy reaches a peak in summer (July) of almost 10,000 GWh, whereas it drops below 2000 GWh in winter (December). Biomass presents a far less drastic change throughout the year, reaching 1,500 TJ in winter (December) and 1,000 TJ in summer (July).

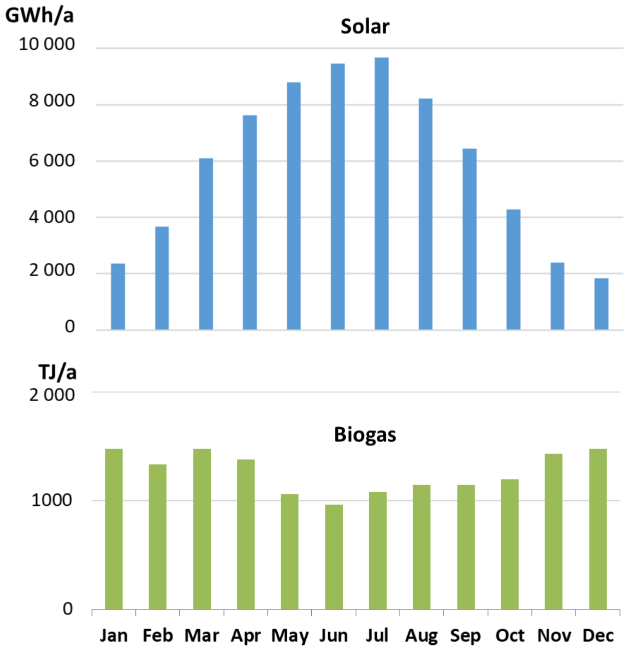

Figure 4: Solar and biomass resources agri-technical potential availability per month.

2.3.2 Identified technologies combining solar and biomass resources

We provide here a description of the identified technology combination following analysis and discussion with experts of the different technologies involved. The focus is set on the complementarity between solar and biomass energy resources, opportunities, and challenges. A summary table is provided regarding the main requirement for each complementarity considered (Table 2).

2.3.2.1 Separation

Raw manure consists of about 15% solids and 85% liquids in terms of volume [34]. This makes it difficult to store and transport. Moreover, during storage, part of the available primary energy is lost through the easily degradable substances in the liquid fraction through fermentation. Separation of raw manure in a liquid (10 - 15% vol.-%) and a solid fraction (85 - 90% vol.-%) allows easier handling of the liquid slurry [35]. Both fractions contain about 50% of the primary energy. The liquid fraction is digested locally, and the solid manure is transported to a regional biogas plant. This manure pretreatment has several advantages: cost and emission reduction for the transport of the solid fraction to a regional biogas plant compared to raw manure and increased overall biogas yield due to earlier digestion of the easily degradable substances in the liquid fraction.

. Screen press screws are usually used for separation. The separation leads to an increased concentration of primary energy in the solids. With a subsequent rapid fermentation of both the solids in a conventional regional biogas plant and the liquid manure in a high performance membrane bioreactor (MBR) on site, a maximum energy yield can be achieved [34]. A pilot plant of an MBR under laboratory conditions with low solids slurry was able to achieve twice the gas yield. In this process, the mass is led against a screen through which the liquid fraction can flow and the solids are retained [36].

In principle, separation can occur on any farm collecting manure. Nevertheless, only farms with a minimum potential for which the use of a dedicated biogas plant is realistic should be considered. The power demand depends on the volume of the collected slurry and is calculated with equation 1. The power demand corresponds to the largest power demand in the study from Meier et al. (2018) [35]. In this possible complementarity, PV provides the power for the separation process.

Power demand = Volume raw manure [m^3] $*$ 1.5 [kWh/m^3_{lm}] (1)

2.3.2.2 Power to X

Power to X describes the conversion of electricity into something else, such as hydrogen, synthetic natural gas, liquid fuels, or chemicals. In the first step of our complementarity, electrolysis is used to split water into hydrogen and oxygen [4]. There are three different technologies for this: alkaline electrolysis cell, solid oxide electrolysis cell, and polymer membrane electrolysis cell (PEM) [37]. PEM electrolyzers have the advantage of being quickly adjustable, possibly operated in load mode between 10-100 %, and thus following the fluctuating production profile of PV.

The following step consists of a methanation process. The produced hydrogen is mixed with biogas to convert the carbon dioxide it contains into methane and water. [4]. On the one hand, this makes it possible to improve the biogas quality to a high concentration of CH_4. On the other hand, part of the electricity from PV is also converted into chemical energy in the form of methane (power-to-methane). In addition, the excess heat from the exothermic methanation reaction and the downstream condenser can cover the heat demand of the anaerobic digestion. The produced synthetic natural gas (SNG) can be either fed to the grid or stored in a local fuel station. Methanation can be done using either a biological or a catalytic reactor (Figure 6). An economic study has shown that a system with a catalytic reactor is advantageous since the large reactor volume in the biological variant results in much higher costs and requires more space [38].Thus, we only considered the catalytic reactor further. Upstream, a desulfurization step is first needed to protect the catalyst, followed by a membrane unit to ensure the minimum methane content of 96 %. The retentate is mixed back into the feed-in gas to minimize CO_2 and H_2 losses. The potential to store fluctuating PV electricity needs to be balanced with higher conversion losses due to the two conversion processes.

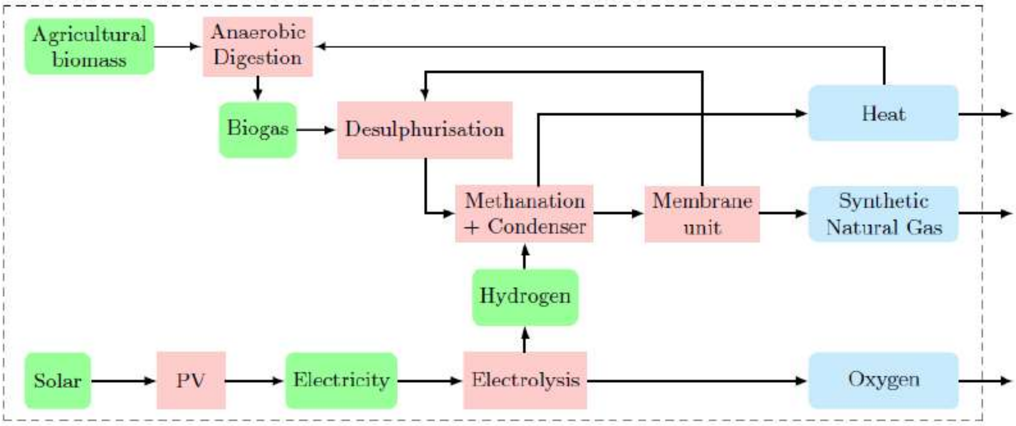

Figure 5: Power to X process flowchart using biogas as CO_2 source to produce synthetical natural gas [56, 57]. Resources and intermediate energy carriers are depicted as green, process red, and final products and energy carriers as blue.

We estimated that the conversion of the produced hydrogen of a PEM electrolyzer with an installed capacity of 2 MW and 4'360 operation hours per year would require at least 23.8 TJ biogas [39]. The operating time was chosen for approximately half a year to account for the lack of electricity potential from PV during winter and night. The installed capacity is given in the context of the studied electrolyzers in Gantenbein et al. (2022) [38] to represent the scale of installations currently under research. According to data for 2018 [40], biogas plants nowadays can vary in size between between 2 and 70 TJ, with an average of 17TJ and a median of 14TJ. The installed CHP capacity in Switzerland for agricultural biogas plant is under 1 MW.

2.3.2.3 Biomethane upgrading

In this complementarity, the electricity provided by PV is used to upgrade the biogas (60% CH_4, 40% CO_2) to natural gas quality (minimum 96 Vol.-% CH_4). Thus, the energy from biomass can be stored in the gas grid for later consumption, e.g., in winter.

To feed into the gas grid, the CO_2 contained in the biogas and other undesirable pollutants for engines, especially hydrogen sulfide (H_2O), must be separated (Figure 7). There are different methods for biogas upgrading such as physical and chemical absorption, membrane, pressure swing adsorption, and pressurized water scrubbing. Pressurized water scrubbing seems a very promising solution as it has a higher efficiency of about 95% with similar power requirements to pressure swing adsorption and does not require an upstream desulfurization step. In addition of purifying biogas, it is possible to collect the separated CO_2 in high concentrations with air stripping in order to use the carbon dioxide for other purposes [41]. The waste heat is lacking for heating the fermenter of the biogas plant, which is required additionally.

Unlike for Power to X, a maximum capacity is defined in addition to a minimum capacity. The defined range is between a potential of 7,890 GJ/yr and 39,450 GJ/yr, which correspond to biogas plants with installed CHP capacities of 100 kWh and 500 kWh, respectively, at 8'000 operating hours per year. This range does approximately cover medium to large biogas plants in Switzerland[42].

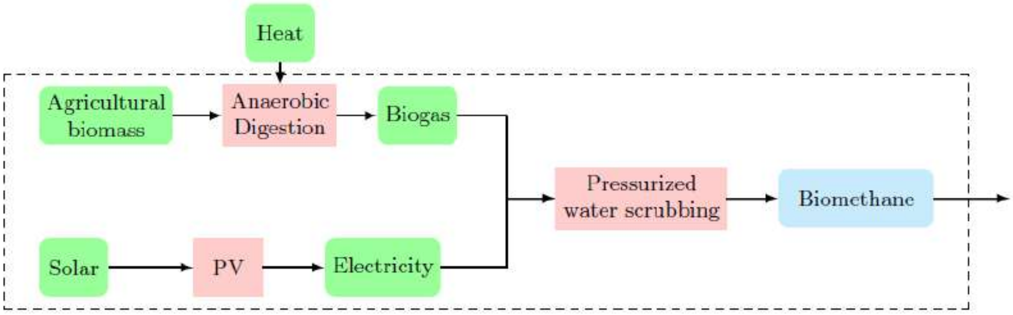

Figure 6: Process flowchart for biogas upgrading using pressurized water scrubbing. Resources and intermediate energy carriers are depicted as green, process red, and final products and energy carriers as blue.

2.3.2.4 PV potential at new biogas plant locations

The construction of biogas facilities offers new potential surfaces for PV panels. The additional infrastructure consists mainly of the biogas plant and the necessary substrate hall for storing biomass. Exhaust gases from the biogas plant, especially sulfur compounds, have a high material-aggressive effect on the PV modules and can lead to corrosion of the glass. Consequently, PV panels should rather not be installed on the biogas plant itself. The exploitable area for PV modules can be calculated with simple geometry considering a tilted, rectangle mono-pitch roof for the substrate hall with equation 2.

Area = total biomass from October to February (m^3) / height of the storage building (m)(2)

The size of the hall depends on the delivered volume of biomass. The minimum size of the storage building is specified by the national agricultural guideline [43], prescribing that the accumulating amount of manure can be stored for five months at least. The temporal distribution of manure indicates that the most biomass occurs between October and February. Considering a standard hall height of 6m and a total biomass from October to February (45% of total yearly production) of 9.25 million m3 leading to 1.5km2. Covering these roofs with solar panels assuming tilts of 11°, 20°, 30° a total of 183 GWh, 191 GWh and 196 GWh electricity could be produced.

2.3.2.5 Cold generation

Generated heat from the biogas plant can be used locally or fed into the district heating network. Alternatively, there is the possibility of generating cold (5-20°C) with an adsorption chiller powered by solar energy. A permanent cold consumer is necessary for a constant cold generation throughout the year such as an agro-industry factory or large office buildings. Otherwise, it is also possible to only generate cold during the warm months and use the heat directly during winter for building heating at the farm level but also if possible at the district heating level.

2.3.3 Case study

The farm has an electricity consumption defined by its individual load profile. The goal is to cover the demand in a direct mode with power from PV and a local small biogas plant. Using both energy resources and optimizing the biogas plant's temporal power generation, a higher coverage degree of the own energy consumption can be achieved, leading to a higher autarchy level for the farmer. In addition, waste heat from the biogas plant (CHP) can replace other resources for heating.

For the specific farm described in the method, when a constant operation is taken for the CHP plant, the farm electricity production over the 8 month would cover 79% of the demand (Figure 8) as the power production for the total period of 8 months is 149.4 kWh for PV and 47.7 kWh for the CHP plant. The self-consumption, however, is only 15.3 % as the electricity is not always produced when it is needed. This autarchy level could increase to 100% if we consider biomass storage and operation of the CHP plant following the demand. Assuming that the produced biogas can be stored for a short time as well, the CHP plant is now operated when the PV system cannot cover the demand.

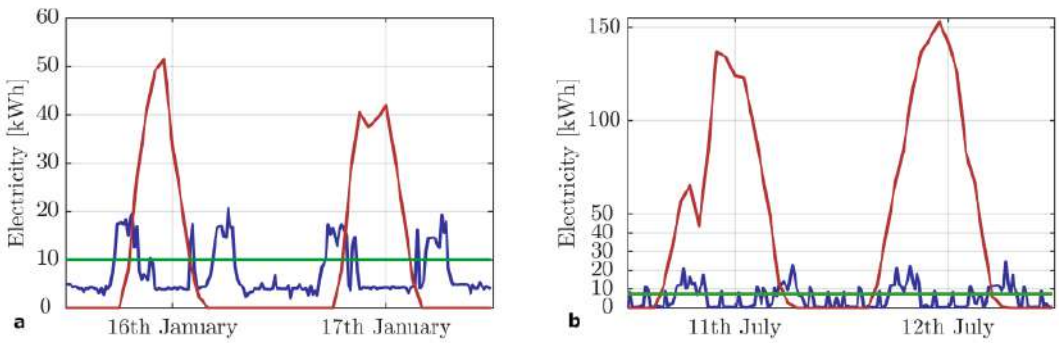

Figure 7: The graphs show the farm's power demand (blue), the solar generation (red), and the electrical yield of the CHP plant (green) for two selected days. Figure a depicts the situation in mid-January, and figure b shows the situation in mid-July.

2.4 Discussion

Here, we use GIS methods to assess the distribution of agricultural biomass and solar resources, focusing on their technical potential for energy use. Using today's current technologies, these potentials result in a yield of 15 PJ/a biogas from biomass and 10 TWh/a or 36,000 TJ/a of electricity from solar panels. In comparison, in 2018, agricultural biogas plants produced 1.44 PJ biogas yield (+1.24 PJ from industrial biogas plants) and solar panels produced 7.84 PJ electricity (2.2 TWh) [44]. Compared with the 834 PJ/a final energy used in 2018 [45] the agri-technical potentials of solar and biomass resources could respectively cover 4% and 2% of the final energy consumption in Switzerland. Other studies have investigated other complementarities between resources for energy at different scales.

A global atlas of solar and wind resources' temporal complementarity was devised at the world level [5]. Depending on regions, the complementarities are more substantial, and each resource should be used accordingly. The different complementarities found in the literature at different spatial and temporal level using different methods stresses, however, the necessity to use consistent methods for assessing the different resources to compare them adequately. Some studies also consider a globalized energy system, where for example, the diversity in local wind patterns can be used so that wind power production sites located on different continents may result in higher system resilience [6]. It would also point towards better integration of different countries' energy grid, up to intercontinental electricity interconnections.

The energy transition is increasingly seen as a promising opportunity for the economic development of rural areas [46], mainly associated with establishing and owning decentralized, small-scale installations. In fact, renewable energy-based rural development is often shown as a beneficial by-product of the energy transition. However, its potential is still largely untapped, strongly depending on the energy resource considered. We have shown here only two resources. The progression in solar is steady, and its economics and handling are favorable to that farmers are increasingly installing PV on their farms. Regarding bioenergy, both hope and skepticism are there [47], and despite the clear interest, many factors stand in the way [11].

However, conflicts between renewable energies can also occur at the spatial scale [48]. Both bioenergy (energy crops in many countries) and free-standing solar panels can compete for marginal or even agricultural land. Depending on the local regulation, this competition can be exacerbated and lead to a less than optimal use of resources. Within the Swiss context, energy crops are not current practice and hence not an issue, even when looking at overall energy from biomass space requirements [49]. The legal framework is not particularly good in Switzerland compared to other EU countries [50]. Regulations can also change (e.g., recent law change in Switzerland for free-standing PV in mountainous areas), and it is important that this is done following informed recommendations from holistic studies.

We did not find strict synergies, which is would be a mutually advantageous conjunction or compatibility of distinct elements, here between solar and biomass resources, but several possible complementarities exist. Regarding spatial complementarity, the biogas installations can offer some new surfaces but only to a limited extent, as it would be on storage buildings alone. Temporal complementarity is limited at the farm level and presents much more possibilities at a larger scale, as most farms are connected to the grid anyway. Biogas production can be modulated daily or seasonal to partly compensate for the much lower solar irradiation at night or during winter. However, the case study indicates that it is unlikely to achieve autarchy at very local scales without additional storage. Anaerobic digestion is the most common technology in place for agricultural installations in Switzerland. However, this is not the only technology able to use biomass for energy purposes.

Several other technologies could be implemented and would allow for complementarities: pre-treatments to increase biogas production, biogas upgrading, methanation and Power to X. However, not all technologies can be implemented everywhere. Separation does not need large quantity of manure to be processed and the temporal complementarity does not depend on size either. Other technologies are much more demanding regarding the installation size needed: biogas upgrading, methanation and power to X all necessitate biogas quantity that are above the amounts that most of today's agricultural biogas plants produce. The installed capacity needed is also high compared to what is found today. Moreover, farm location, where new installations would need to be build, do not always have a suitable location, e.g. close to the gas grid, district heating or potential heat/cold consumers [39]. To reach such a minimum size, it is necessary that resources are pooled together between several farms but this is not a straight forward process [11]. All these technologies need electricity to function and this is where the complementarity with solar energy can play a role. This input could be provided by PV, particularly in summer when there is an overproduction of electricity from PV that is very difficult to store [4]. As we have seen, the combination between biogas and solar energy is unlikely to enable autarchy at the local scale but, if we include other resources or access to the electricity grid, it is possible to increase the energy self-sufficiency at a larger scale.

Indeed, here, we only looked at agricultural residual biomass and at energy generation. However, other biomass types, such as green wastes, would also be available for biogas production, and heat is also an important form of energy. The possibility of heating the fermenter of a biogas installation with a solar heat panel has shown an increase in the efficacy of the digestion process [51]. Also, the drying of wood in order to increase combustion efficiency is also an interesting solution to make use of the waste heat from the CHP [52]. The chosen system boundaries are also highly important. The possible complementarities will strongly vary depending on the size of the considered area (local vs regional vs international) and the storage put in place (batteries, intermediate carriers). At the end, it is however the economic aspects that will decide which installations are built and maintained in each specific energy system.

2.5 Conclusions

There is still considerable potential for energy generation from biomass and solar resources in the agricultural setting. It is essential for the energy transition that these resources are used, even if not always at the same locations. Synergies, as such, could not be identified in this study. However, there are potential complementarities between these two resources, and further business-scale studies should look at the economic viability of such systems. However, these complementarities are more likely to arise at a regional rather than local scale and should be studied within the larger context of the whole energy system.

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3 Biomass technologies overview

3.1 Introduction

Recently, the Joint Activity Scenarios and Modelling (JASM) prepared comprehensive reports on biomass potentials and conversion pathways [1,2]. These reports provide an overview of biomass in Switzerland and useful insights about potentials, prices and an extensive overview of different biomass technologies for different resources.

Figure 1 shows the relevant biomass conversion paths to methane, electricity and heat. Four types of biomass inputs are identified; wood, animal manure, green waste and sewage sludge and the outputs are biomethane, heat and electricity. In this report, first, the actual status and performance data of these conversion technologies are revised and examples are shown. Afterwards each biomass conversion path is analyzed based on its inputs, outputs, efficiency, cost data, reference size and an example. In the second part of the report (cf. to section 4.3 and 4.4, respectively), emerging technologies (biomass CHP with biochar by-product, decentral methanol synthesis) are presented for which the data base is less developed.

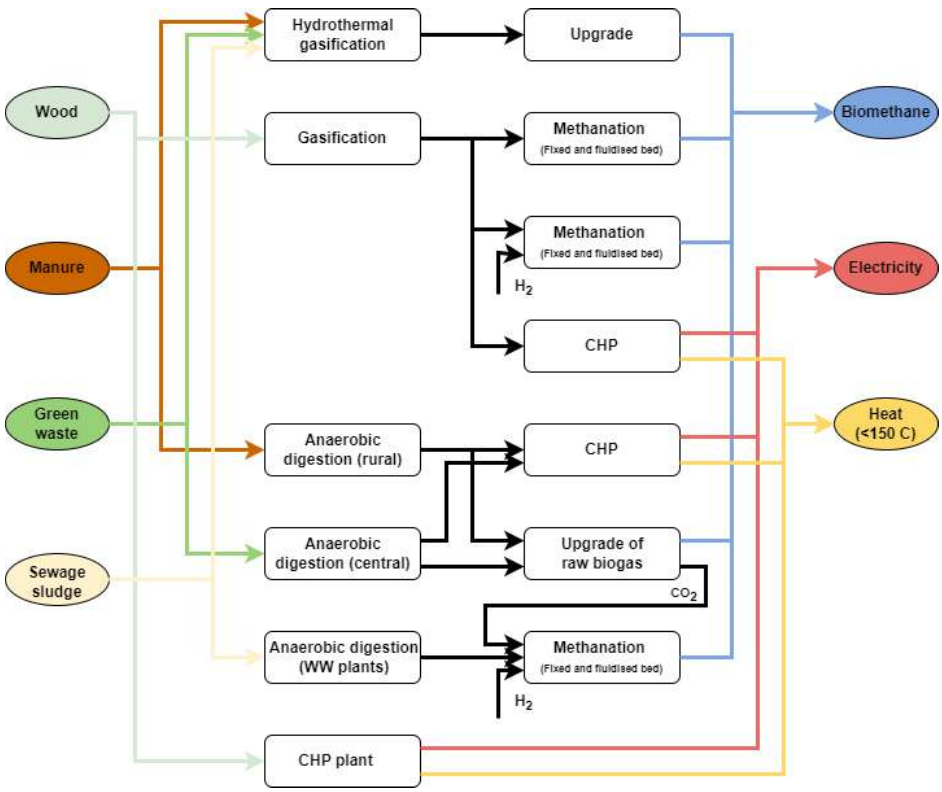

Figure 6. An overview of the biomass conversion technologies to biomethane, heat and electricity. Adapted from [1].

3.1.1 Hydrothermal gasification

Gasification of organic matter in supercritical water media (T>374 °C and P>22.1 MPa) is a method for the conversion of water-rich feedstock into gaseous product. The process is continuous and it is suitable to convert materials with high moisture content (<20 wt.% dry matter) into a combustible gas, which is mainly composed of CO, CO_2, H_2 and CH_4 [3]. In the presence of a suited catalyst (Ruthenium on carbon), the main product are methane, CO_2 and traces of hydrogen. This method to convert water-rich feedstock has several advantages compared with conventional technologies. It promotes the energetic utilization of biomass with minimization of residuals and maximization recovery of nutrients. Another advantage of this method is the omission of an energy-intensive drying process, as the wet biomass can be directly used. The reactions are fast with the average residence time inside the reactor of less than 5 min. Additionally, water in its supercritical condition has low density and dielectric constant. Therefore, it changes from a polar solvent into a non-polar solvent, and organic compounds can be easily dissolved in it. However, there are various challenges to be met and the Technology Readiness Level (TRL) of such systems is at 6-7. One of the major challenges is the combination of high temperature and pressure and the low concentration of organic matter that require a robust process design.

There are several pilot scale installations of hydrothermal gasification in Europe. The HydroPilot project at PSI is a semi-industrial plant with the capacity of 110 kg/h of wet biomass, which can produce up to 100 kW of biogas [4]. The VERENA pilot plant [3] at the KIT (Germany) with the maximum throughput of 100 kg/h is another example of such systems.

As listed in the Table 6, manure, green waste and sewage sludge can be fed to a hydrothermal gasifier, which then goes through an upgrading step to achieve high purity biomethane. According to [1], the efficiency of the system is higher when green wastes instead of manure or sewage sludge are used, but no change in the investment and operation cost is expected.

3.1.2 Gasification

Gasification technologies present a promising area for the use of woody residues. A gasification unit can turn woody biomass into a syngas. The composition of syngas is dependent on the temperature and the oxidative agent of the gasification process, but consists at least of CO, CO_2 and H_2 and impurities such as hydrogen sulphide, ammonia etc.. In low temperature gasification (850°C), species such as methane, ethylene, acetylene, aromatics and organic Sulphur compounds are found. Afterwards, the syngas can be upgraded to biomethane or fed to a CHP system and produce heat and electricity. Depending on the type of biomass, biomass particle size, moisture content and several other parameters, the proper type of gasifier should be used. There are several types with high level of maturity at TRL of 8 and 9. Fixed bed gasifiers are classified as updraft or downdraft according to the flow directions of the oxidation agent (usually air), which are the simplest reactors for gasification. Fluidized bed reactors re another type that can be differentiated as bubbling, circulating or dual fluidized bed gasifiers. The fluidized beds are attractive technologies due to high flexibility of biomass and high heat transfer.

According to the IEA Bioenergy report in 2021 [5], there are over 1700 gasification facilities for CHP and fuel synthesis at the TRLs of 6 to 9 in operation in Europe. The wood pellet based CHP operated by AEW in Rheinfelden [6] with a power output of 165 kW_{el} and 260 kW_{th} is one of them.

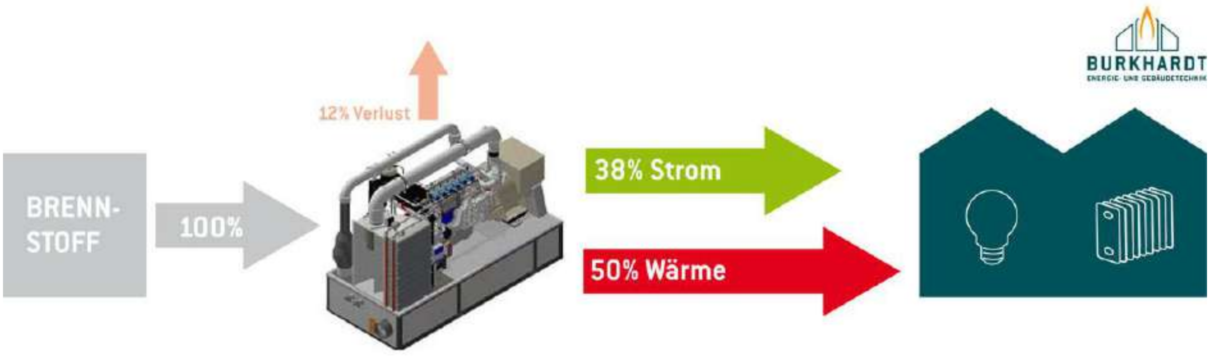

Figure 7. Burkhardt pellet gasifier CHP in Rheinfelden.

The Swindon Advanced Biofuels Plant [7] is an example of Gasification to fuel synthesis at the TRL of 8. The input to this plant is organic residues, waste streams and waste woods at the rate of 8000 t/y and produces 1500 t/y of SNG (2.6 MW) and 500 t/y of hydrogen (1.9 MW). The investment cost of this plant was 30 Mill GBP.

3.1.3 Methanation

A potential pathway on the use of product gas from a gasification unit is methanation, which produces synthetic natural gas (SNG). During the methanation reaction, CO and CO_2 in the syngas are converted to CH_4 according to the exothermic reactions in Equation 1 and 2. Two types of methanation reactors, fixed bed and fluidized bed, are taken into account in this study.

$$CO + 3\,H_2 \leftrightarrow CH_4 + H_2O \qquad (1)$$

$$CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O \qquad (2)$$

There are several examples of syngas methanation projects at larger scale: the GoBiGas plant in Sweden (not in operation, but moff-balled) has a capacity of 20 MW_{SNG} and was built as demo plant for a never realized 80-100 MW_{SNG} commercial plant. Within the EU project BioSNG, in Austria a 1 MW_{SNG} output plant was built and operated. Further examples of such installations are the Swindon plant and the GAYA project in France with a capacity of 400 kW SNG [8]. The plant efficiency of woody biomass-to-SNG is 60-70% (LHV), depending on the humidity of the feedstock [9].

3.1.4 Anaerobic digestion

Anaerobic digestion is described as a series of processes involving microorganisms to break down biodegradable material in the absence of oxygen. The result of anaerobic digestion is the biodegradable organic material into methane, carbon dioxide, hydrogen sulfide, ammonia and new bacterial biomass. The anaerobic digestion process of complex organic polymers is commonly divided into four inter-related steps: hydrolysis, fermentation, acetogenesis and methanogenesis. The energy efficiency of anaerobic digestion depends on the nature of the digested biomass and the operating conditions. Overall efficiencies (LHV biogas vs. LHV of dry biomass feedstock) range from 0.1 to 0.4 in the literature depending on the plant size and raw material.

3.1.5 Upgrading

There are different technologies to convert raw syngas or biogas into biomethane. The product gas should contain of at least 96 vol.-% methane, and the harmful trace compounds such as sulfur compounds and siloxanes should be removed. These technologies are often multi-staged, i.e. first a cleaning step and then upgrading process. During the cleaning step, the trace components harmful to the gas grid, appliances or end-users are removed. In the upgrading process, inert gases, mainly CO_2, are separated. There are four categories of these technologies available in the market: adsorption (e.g. pressure swing adsorption, PSA), absorption (e.g. water scrubbing, physical or chemical absorption), membranes and cryogenic upgrading.

Water scrubbing is the most common technology in biogas upgrading, with a share of 40% of the installed plants. The operation is performed in pressurized vessels and allows for a large methane recovery (above 98%). Large capital costs are needed (2500- 5000 €/(Nm^3 biogas/h)) for this technology, which is due to the large water consumption and regeneration. Amine scrubbing uses chemicals (i.e. amines) instead of water, and this results in lower capital costs (1500- 3000 €/(Nm^3 biogas/h)) and higher product purity. However, a heat source for the regeneration of the solvent is needed, leading to higher operation costs. The market share of chemical scrubbers in the biogas upgrading is ca. 22%.

PSA is a well-established gas separation technology, which involves the selective adsorption of CO2 on a solid material. The recovery rate for PSA is relatively low, maximum 96% recovery of methane, compared to the other technologies, as some amount of CH4 is lost in the off-gas. The market share of PSA is about 20% and the capital cost of a PSA unit is between 1500- 3000 €/(Nm^3 biogas/h).

Membrane-based technologies for upgrading is a promising alternative to conventional technologies such as water scrubbing or PSA. The main advantages of membrane are the direct application in the gas stream and the modularity. The investment cost is high at 3500-7500 €/(Nm^3_{Biogas}/h) [10]. The market share of membranes is currently limited, but it is expected to increase considerably.

3.1.6 Combined heat and power systems (CHP)

A number of different technologies are available such as internal combustion engines, gas turbines, micro-gas turbines and fuel cells. Internal combustion engines have the longest history in biogas applications, and are still the most widely used technology. Thousands of engines are operated at sewage plants, landfill sites and biogas installations. They can be found in a size range from a few tens of kW to MW scales. The amount of fuel energy converted to electricity generally increases with size, ranging from 30% for small units to 40% for large engines. Thermal energy conversion is from 45 to 60% resulting in overall efficiencies up to 90%. Operating and maintenance costs can be a significant portion of the total electricity cost as internal combustion engines require frequent oil changes and minor overhauls. Gas engines do not have high quality requirements as they can withstand hundreds of ppm concentration of sulfur compounds.

Gas turbines are well-known for large-scale installations going up to hundreds of megawatts. Turbines are also sensitive to biogas impurities, and require fuel conditioning, especially removal of particles and aerosols. Micro-turbines are smaller versions of combustion turbines; developed to be economical at low output ranges where the large combustion turbines are not. Use of biogas to fuel micro-turbines began in the late 1990s. The available capacity range of 25 kW to 500 kW is well-suited to many biogas applications, and they have been installed at municipal wastewater treatment plants, landfills, and some dairy farms. The greatest technical challenge for micro-turbines in these applications has been assuring proper fuel treatment. Micro-turbines have the advantage of a small footprint, low exhaust emissions and modular installations. Instead of one large engine, several micro-turbines can be installed at the same site, and then individually started and stopped as needed. Due to their low efficiency of electricity production (15 – 30%), micro-turbines are best applied when a thermal source is required.

Fuel cells are an emerging energy technology that could replace a large part of current combustion-based energy systems. Varieties of fuel cells are in different stages of development. They can be classified by the type of electrolyte used and, consequently, by the operating temperature range in low temperature fuel cells (60 – 250°C) such as Polymer Electrolyte Membranes (PEM) and high temperature fuel cells (600 – 900°C) such as Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs). Low temperate fuel cells are operated on pure hydrogen, but the high temperate ones can be operated with natural gas and biogas due to the high operation temperature.

High temperature fuel cells have several advantages compared to the other CHP systems, for the main reason that they reach higher electrical efficiency (>50% net *ac*) at low power level (already at 1 kWe), including for fluctuating gas input. Due to absence of moving parts, the maintenance level is low and they show negligible emissions: very little noise, no methane slip, no NOx, and no SOx. However, there are only few installations at large scales, and the cost of such technologies are very high compared to the other ones. Table 5 compares ICE and SOFC installation on a farm produces 65 m^3/h of biogas.

Table 5. Technical and cost data for an ICE installation in a Swiss farm and estimation cost of SOFC system (internal communication with CONVION Ltd. [11]).

Data	unit	ICE CHP	SOFC
Biogas flow	m^3/h	65	65
Unit power	kWe	150	200
CHP CAPEX	Fr	300’000	1'300’000
CHP CAPEX	Fr/kWe	2’000	6’600
CHP OPEX	Fr/an	35’000 (11.6%/yr of CAPEX)	
elec. production	MWhe/yr	1’224 (1080 net)	1’667
elec. efficiency	%	37%	>50%
CHP OPEX	Fr/kWhe	0.0286	
heat production	MWh/yr	1501	1’316
heat efficiency	%	46%	40%

3.2 Conversion paths; techno-economic data

In this section, conversion paths for each biomass source are shown and techno-economic data are presented. To simplify evaluation of each path, the initial letters of the biomass sources and conversion units are used. For example, the process of wood-gasification-methanation via a fixed bed reactor is called WGM1 as shown in the Figure 8.

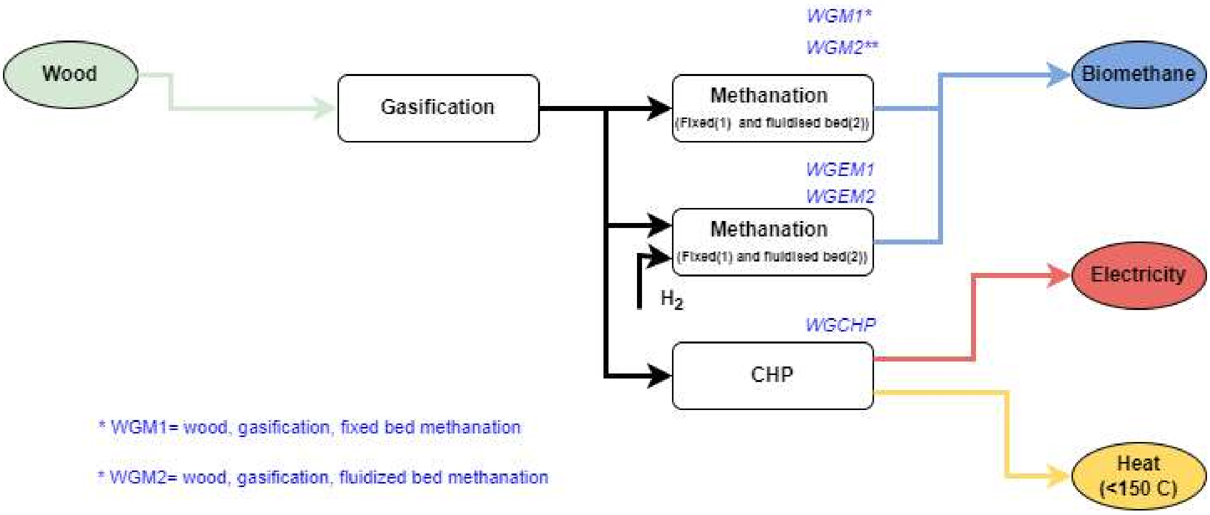

Figure 8. The conversion pathways for wood via gasification.

Table 6. Hydrothermal gasification conversion path to biomethane [1]. FOM = Fixed operational costs, i.e. without feedstock and consumable costs.

Feedstock	Product	Efficiency	Inv. cost	FOM	TRL
		(LHV out/LHV in, %)	(CHF/$kW_{chem,LHV}$)	(CHF/$kW_{chem,LHV}$)	
Manure	Biomethane	65	5788	517	6
Green waste		70			
Sewage sludge		60			

Table 7. Gasification conversion path to biomethane [1,12].

Path	Efficiency	Inv. cost	FOM	Electrical use	Heat production	TRL
	(LHV out/LHV in, %)	(CHF/$kW_{chem,LHV}$)	(CHF/$kW_{chem,LHV}$)	($MWh_{el}/MWh_{chem,LHV}$)	($MWh_{th}/MWh_{chem,LHV}$)	
WGM1	62.5	3500	40	0.094	0.09 (at 80 °C)	8
WGEM1	62.5	4008	105	0.1	0.126 (at 80 °C)	7
WGM2	62.5	2315	40	0.094	0.09 (at 80 °C)	7
WGEM2	62.5	2706	91	0.11	0.127 (at 80 °C)	7

Table 8. Gasification conversion path to heat and electricity (CHP) [13]. LCOE = Levelised costs of electricity

Path	Efficiency	Inv. cost	LCOE	TRL	Ref. size
		(CHF/kW_{el})	(Rp/ kWh_{el})		
WGCHP	η_{el}:20-25, η_{th}: 40-50	1300-1520	12	8	1
WGCHP	η_{el}:27.5, η_{th}: 36.2		12.25	8	2.5

Table 9. Anarobic digestion path to biomethane, heat and electricity [1,12].

Feedstock	Path	Efficiency	Inv. Cost	FOM
		(LHV out/LHV in, %)	(CHF/$kW_{chem,LHV}$)	(CHF/$kW_{chem,LHV}$)
Manure	MADUP	30	1053	93.75
Green waste	GADUP	27.5	1053	93.75
Green waste, sewage sludge	G-, SADUP1	27.5	2068	222.75
Manure, sewage sludge	M-, SADUP2	30	1834	195.75

3.3 Pyrolysis

Pyrolysis is a process in which biomass is heated in the absence of air whereby present humidity can contribute to gasification type reactions. Typical products are hydrogen, CO, methane, CO_2, condensable hydrocarbons and solid carbon/char. In a recently commissioned plant in Frauenfeld, Switzerland, otherwise unused wood from forest and landscape management is converted in a pyrolysis type thermochemical process at 850°C to a gaseous fuel and biochar, see Figure 9. While the wood gas is converted in four gas engines to produce renewable electricity for around 8,000 households and heat that is used by a sugar factory and the regional district heating network, biochar is also discharged from the process. Part of the CO_2 stored in the wood is therefore not released and is permanently removed from the atmosphere in the form of biochar. The biochar is used in agriculture to improve the soil, as a feed additive or as active carbon for water cleaning.

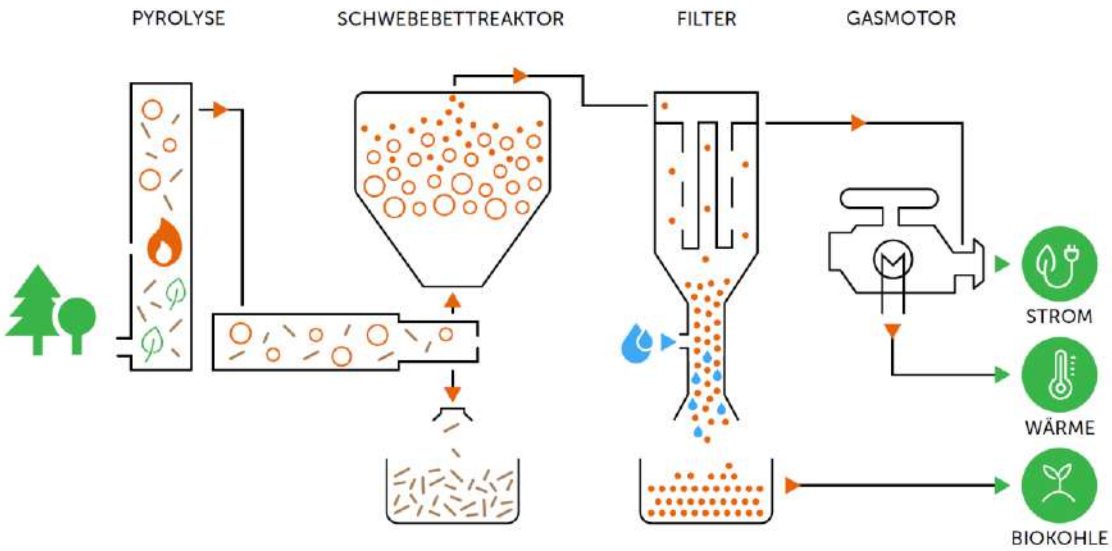

Figure 9. Scheme of the pyrolysis plant of Bioenergie Frauenfeld AG [14].Technology supplier Syncraft, Knoblinger; Operation started in May 2022. Input 25000 t/y Wood chips; Output: 30 GWh/y electricity, 40 GWh/y heat, 3500 t/y biochar.

The plant is at commercial scale. Assuming 8000 operation hours per year, 25000 t wood chips per year with 30-35% humidity represent around 10 MW_{th} input (LHV); the produced electricity corresponds to 3.75 MW_{el} and the heat to max. 5 MW_{th}. The biochar contains most of the residual energy; as overall efficiency, 92% is indicated due to thorough heat integration. The plant offers a decent efficiency to electricity (>35%), while up to one fourth of the energy is separated as solid carbon which can be considered as negative emission if used in agriculture.

The combination of CHP and biochar for negative emission is the first of its kind in Switzerland or even Central Europe. So far, no economic numbers are available, but the economic feasibility will depend on the wood price on the one hand, and the value of heat, electricity and biochar (or negative emissions), on the other hand. Still, the plant shows that it is possible to combine production of energy carriers or heat and electricity, and realization of negative emissions at the same time.

3.4 Methanol

There are different ways to produce methanol from biogenic sources. The technically simplest one is to take advantage of the fact that most methanol plants in Europe are based on natural gas. Then biomass can be converted to biomethane according to one of the processes mentioned above (wood to methane, anaerobic digestion, both with or without PtG) and injected to the gas grid. The existing centralized methanol plants then have to buy the biomethane (or the according certificates), but otherwise operate as normally. This option could be realized immediately (path C in Figure 10).

By downscaling the standard process to biogas plants, it is possible to first reform the methane in the biogas and then convert the produced syngas in a methanol synthesis reactor at high pressures and a recycle of unreacted syngas to methanol (path A in Figure 10). This concept has been realized in parts. Biogas reforming is costly, but first pilot plants exist. In Iceland, a demonstration plant converting hydrogen and CO_2 to methanol is operating. The high operating pressures of 50 to 100 bars need however large compressors and additional electricity consumption, because, unlike the standard process, it is not possible to obtain the compression energy by internal heat recuperation

	Biomass as feedstock	**MSW as feedstock**

from the natural gas reformer.

To avoid this issue, recent studies focus on low-pressure methanol synthesis based on H_2 and CO_2 from biogas at lower pressures and without methane conversion (i.e. with biomethane as by-product). To reach sufficiently high conversion to methanol in this equilibrium-limited synthesis, removal of reaction products is considered (path B of Figure 10).

Preliminary cost calculations within an on-going SFOE project at PSI found production costs between 950 and 1100 CHF/t of methanol, with Biogas-steam reforming (path A) as best option so far. Ongoing work in the methanol with in-situ adsorption aims to decrease costs to slightly lower values. With respect to overall energy efficiency, i.e. the heating value of methanol and bio-methane product compared to the biogas input, values between 56% and 75% could be reached, with the combined methanol/bio-methane process (path B) as best solution, which is also mirrored by the highest CO_2 mitigation potential.

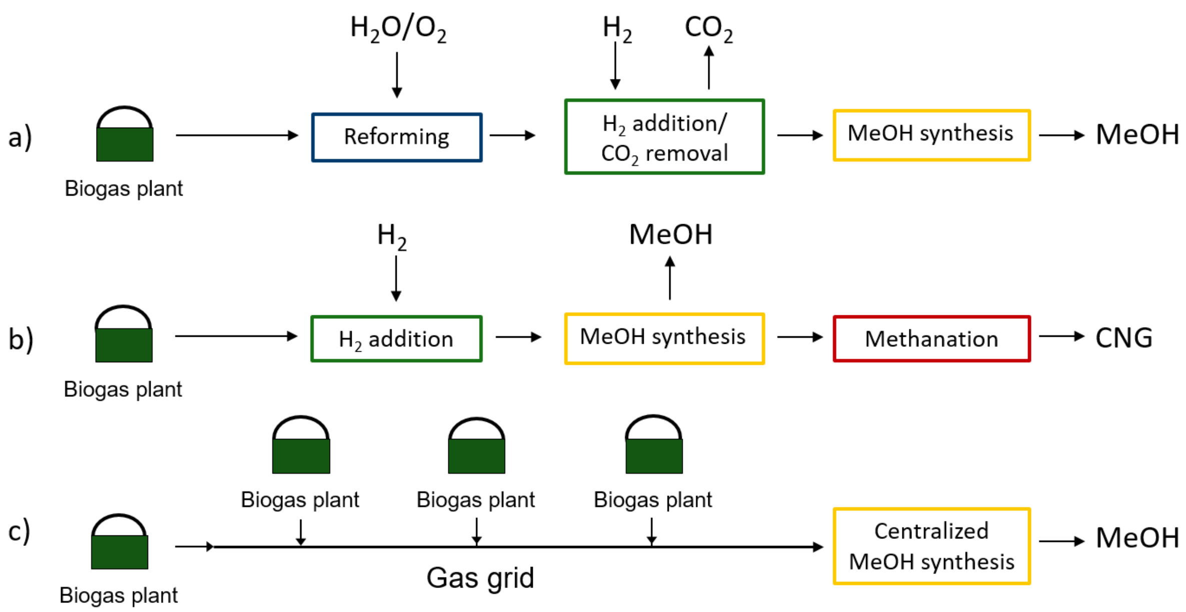

Figure 10. Methanol production pathways from biogas.

There are several gasification-based projects in planning, engineering or start-up phase for the production of methanol in Europe. Enerkem is constructing two plants in Europe both for the production of renewable methanol. These plants are in engineering phase and located in Rotterdam (NL) and Saragossa (SP). Municipal solid wastes are going to be used in bubbling fluidized bed gasifiers and each plant produce 215 kt/y of methanol [15]. The LowLand Methanol project in the Netherland is at its start-up phase (early 2023) (by NextChem Technology), with the capacity of 120 kt/y. The table below is taken from a presentation given by Ingvar Landälv in March 2021, senior advisor at Fuels & Energy consulting on the total production cost for biomethanol from biomass and MSW [16] which are in similar order of magnitude as the ones found at PSI in the ongoing SFOE project.

Table 10. Total production cost for biomethanol from biomass and MSW [16].

		Low		High		Low		High	
CAPEX/y, USD/t MeOH		206		293		264		367	
Overall conversion efficiency, %		60	70	60	70	50	60	50	60
Feedstock cost, USD/t MeOH	At 15 USD/GJ	498	426	498	426	-	-	-	-
	At 10 USD/GJ	332	284	332	284	-	-	-	-
	At 6 USD/GJ	199	171	199	171	-	-	-	-
	At 3 USD/GJ	100	85	100	85	119	100	119	100
OPEX at 5%, USD/t MeOH		78		111		100		139	
OPEX at 10%, USD/t MeOH		156		222		200		278	
Cost of methanol (USD/t MeOH)		455-860		575- 1013		414-583		556-764	

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