BREC - Biorefinery pilot plant concept

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CIRCULAR ECONOMY
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Content

1 Biorefinery pilot plant concept

Part of the BREC-project: Bridging the gap between research and education for the circular bioeconomy (BREC) was to identify and design pilot plant version for emerging and commercially available technologies and practices that promote the local circular bioeconomy. The general the pilot plants will be operated as demonstration plants in co-operation with agricultural schools to teach students and farmers about the operation of biorefinery modules and environmentally friendly practices. The purpose of this deliverable (D 1.1.) is to increase the capacity of the target groups by giving them an overview of several emerging relevant pilot plant technologies. Another purpose is to set the groundwork for building new or upgrading existing pilots in the near future. Based on a previous mapping and survey in the partner regions in project phases 2 and 3, existing pilot plant systems and technologies in the partner regions were identified (see Figure 1).

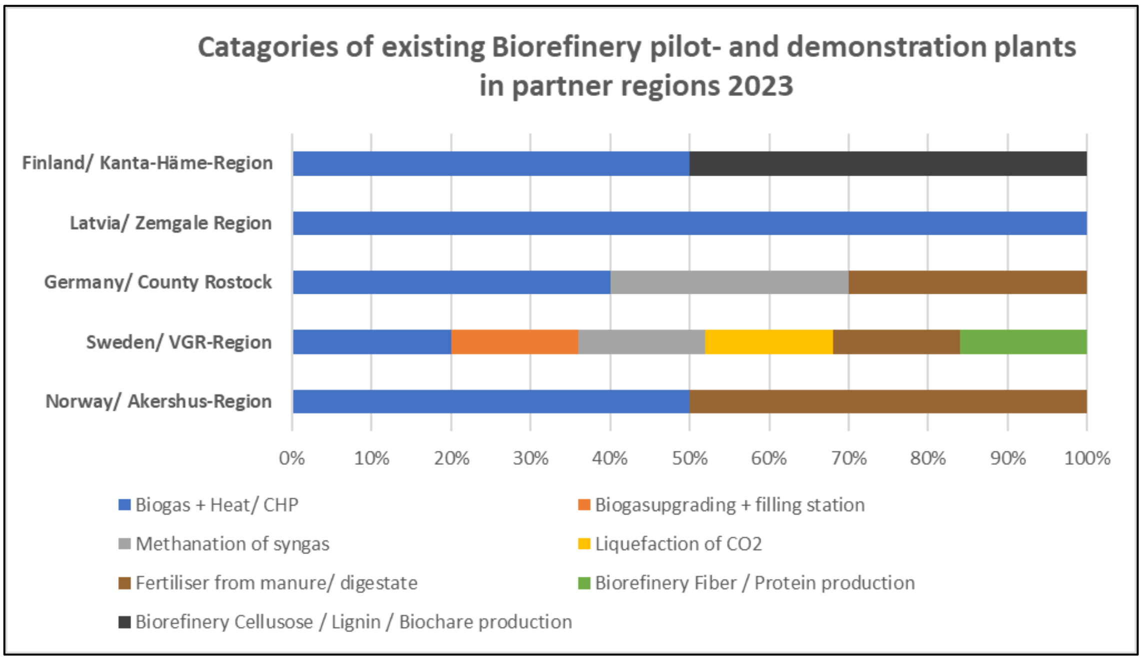

Figure 1: Current existing Biorefinery pilot plants in BREC-Partner regions

According to the result of the mapping there are current existing 16 Pilot plants in der BREC-Region: Finland/ Kanta-Häme Region: 2; Latvia/ Zemgale Region: 1; Germany/ County Rostock: 3; Sweden/ VGR-Region: 6; Norway/Akershus-Region: 4. Based on the digestion process for biogas production, there has been an expansion of plants towards biorefinery plants, particularly in Germany and Sweden. Nevertheless, it requires more effort and motivation to ensure appropriate process steps and results in relation to the available regional resources and needs at the individual location.

1.1 Overview of relevant biorefinery technologies

The development and description of a possible pilot plant concept is presented below, which should serve as a basis for future pilot projects. The following biorefinery concept with selected technology steps was created as a process path model based on the results of the mapping of the regions in the BREC project. The aim is to produce various **bio-based renewable products** with the pilot plant, such as

- **Protein** for animal feed
- **Fertiliser** for crop-production and forage production
- **Biogas** as energy source for heat and power production
- **Biomethane** as vehicle fuel
- **Liquid CO2** as raw material for platform chemicals

The following process scheme (Fig.2) contains technology steps (so-called plants) as well as intermediate products and output products (terms highlighted in black).

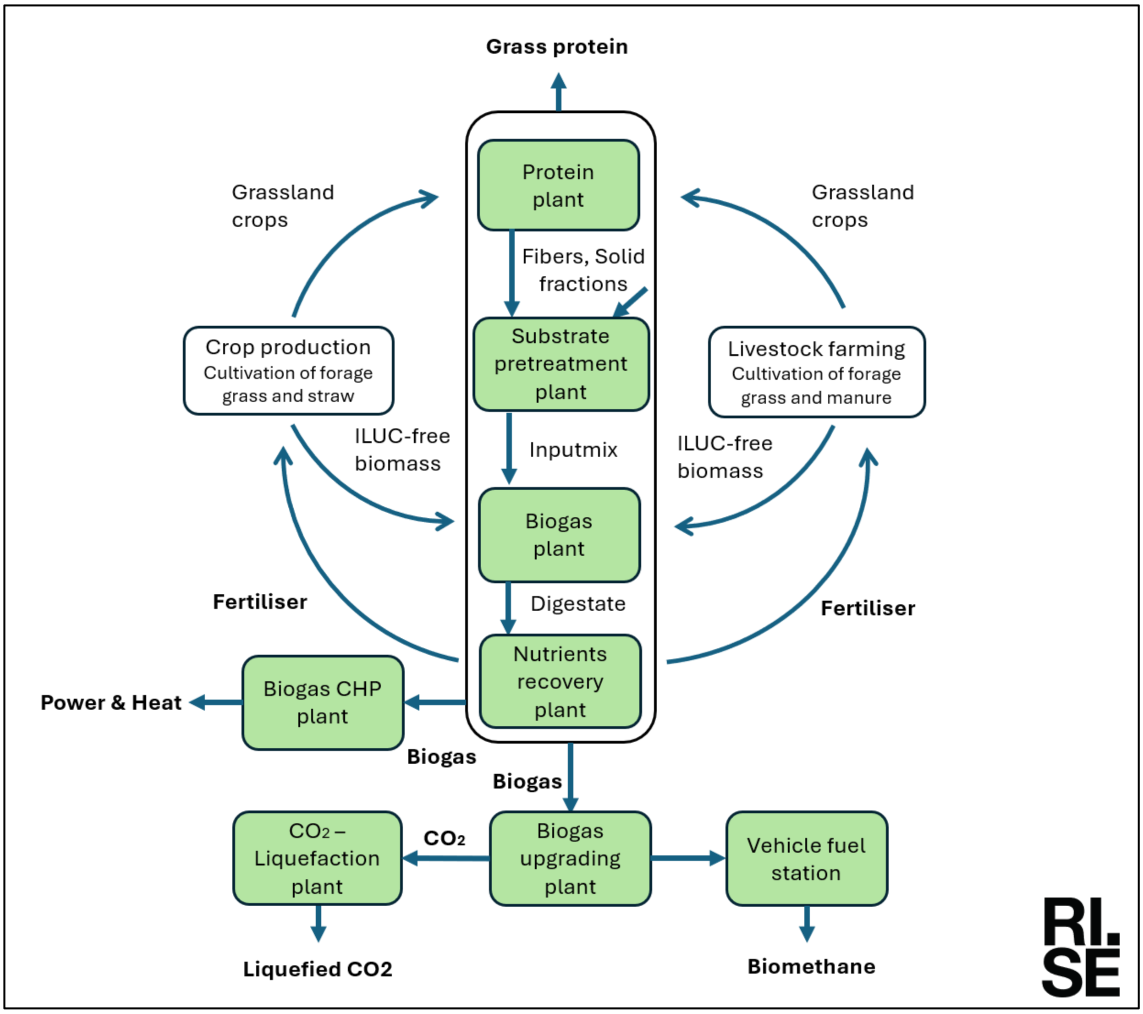

Figure 2: Process schemata farm-based biorefinery pilot plant (RISE)

The products can be utilized both locally and regionally in the agriculture, local energy and fuel industries as well as the basic materials industry. The region can thus become more independent in energy and other input goods. The focus of the pilot plant concept is on adapting existing agricultural and horticultural regional structure and waste streams in conjunction with other trades and industries for a regional bio-based economy. Starting with the residuals from agriculture as well as grass cuttings or ley-grass mixtures (grass, clover, leys), these materials are provided and accepted as input materials for the process. From animal husbandry, mainly solid manure, liquid manure and feed residues are used. Crop residues such as wheat straw or grass silage are used from arable farming. The material flow of manure and crop residues is fed directly into the biogas plant and the fresh grass or grass silage is fed into the protein plant. The increasing biofuel production from agricultural rest products has been suggested to cause indirect land use change (iLUC). This increases interest in biofuel feedstocks that qualify as iLUC-free biomass: (1) residues without a market, (2) crops from previously unused arable land, (3) additional crops and (4) biomass from intensified production. Grass / ley crops are fed through a protein extraction step with the aim of obtaining grass proteins – the liquid phase press juice - as a feed substitute for soya-based animal feed. The residual products from this process - the press cake (fibers) - is used in the following biogas process. In the biogas substrate pretreatment plant, the input materials are mechanically pretreated and mixed. As a rule, mechanical shredding units are used for the pourable/ bulk substrates. Together with the liquid input materials (manure), a homogeneous substrate mix is created and pumped into the fermenter for the biogas process. In the biogas plant, biogas is produced in the absence of air and under mesophilic process conditions (approx. 37 - 40 C). Depending on the feedstock mix, the produced biogas has a methane content of approx. 53 - 60% and CO2- content of approx. 40 – 47%. The liquid digestate contains important fertilisers and is passed on to the nutrient recovery unit. In the suggested pilot plant concept part of the biogas is fed into an energy generation unit as fuel gas to produce electricity and heat in a combined heat and power unit (Biogas CHP plant). The other part of the biogas flow is used in a treatment plant for biomethane production so called biogas upgrading plant. Here, the methane gas (CH4) is enriched and separated from the CO2. The biomethane contains a methane content of approx. > 98 % and can be dispensed as fuel at a vehicle fuel station for CNG- vehicles otherwise it can be fed directly into an existing natural gas grid. The separated carbon dioxide can then be dosed in a purification and liquefaction plant and used as liquid CO2 for intermediate storage (CCS: Carbone capture storage) or further processing (CCU: Carbon capture use). Fertiliser mainly phosphorus and nitrogen can be returned to agriculture from the nutrient recovery plant. The following technological steps are described below on a pilot scale for small and medium scale application. These technologies can be used as a stand-alone system or integrated into an existing agricultural-based biogas plant.

1. Protein extraction plant
2. Pretreatment plant for lignocellulose rich material
3. Biogas plant
4. Nutrients recovery plant (Nitrogen enrichment)
5. Biogas upgrading plant
6. Carbon dioxide (CO2)- Liquefaction plant

1.1.1 Protein extraction plant

Background

Green biorefineries based on fresh or ensiled grass and grass-clover leys is an interesting opportunity to produce sustainable products to phase out the fossil-based society. There is a great need to develop more sustainable and domestically produced protein for both feed and human consumption. Security of supply of local food/feed is of growing importance in times of climate change, pandemics and political instabilities.

Grassland and grass-clover leys also provide many ecosystem services benefits to the crop production such as improving soil fertility soil structure and nutrient balance as well as positive effects on biodiversity. To include grass/clover in the crop rotation is particularly important in grain-dominating areas. Grass/clover leys and grasslands is well suited for cultivation in large parts of Sweden as well as northern Europe.

Description of the technology

The refining can be done using fresh or ensiled grass. If fresh grass is used it is cut and harvested from the field without wilting, to reduce losses and degradation of the proteins. If silage is used the grass is harvested using the established technology used for silage for feeding. Benefits of using ensiled biomass is that the biomass is available all year around compared with fresh grass that only is available during the harvest season. The ensiling also improves the storage stability of the products. Disadvantages of ensiling is fermentation losses, potentially reduced hygienic quality and degradation of protein which makes it more difficult to separate out to a concentrate. Also, the taste and smell is altered. The first step of the process is to separate the grass into a liquid fraction (press juice) and a solid fraction (press cake), see Figure 3. The separation or fractionation is usually done with a screw press. To have an efficient separation the biomass is mechanically pretreated or cut before pressing.

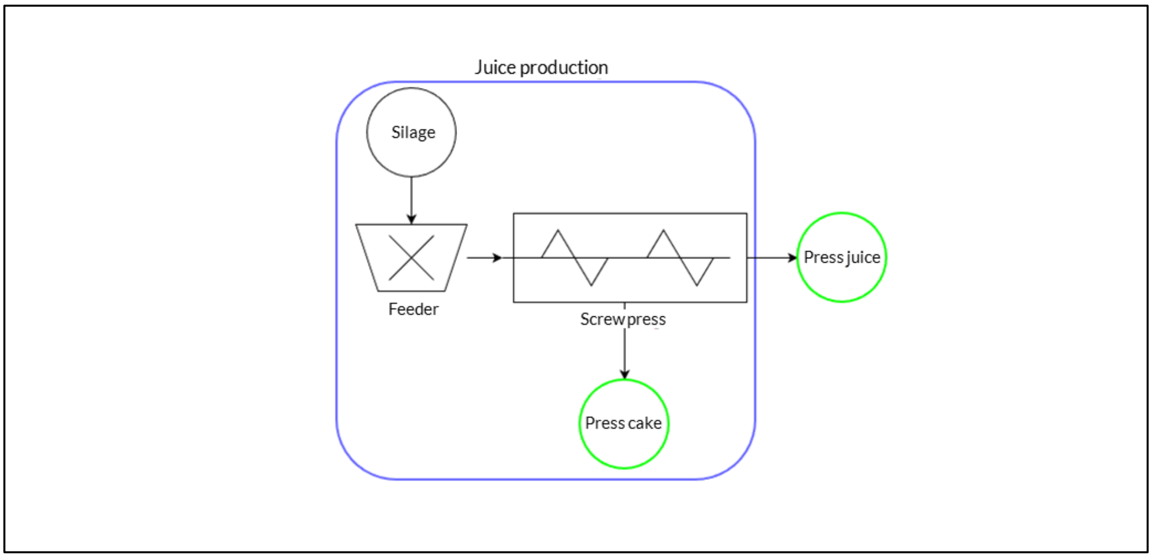

Figure 3: Fractionation of the grass into a liquid and a solid fraction (RISE).

The press juice is usually used as a protein- rich feed for monogastric animals but could also be used to for example make novel food. The press cake can be used as a fibre rich feed for ruminants but also to produce biogas or different biomaterials. If fresh grass is pressed the press juice can be further processed to a protein concentrate but precipitating and separation, Figures 4 - 6. By heating or pH-adjusting the press juice the protein coagulates that can be precipitated. The concentrate can be dried and used as a component in dry feed mixtures to pigs and poultry.

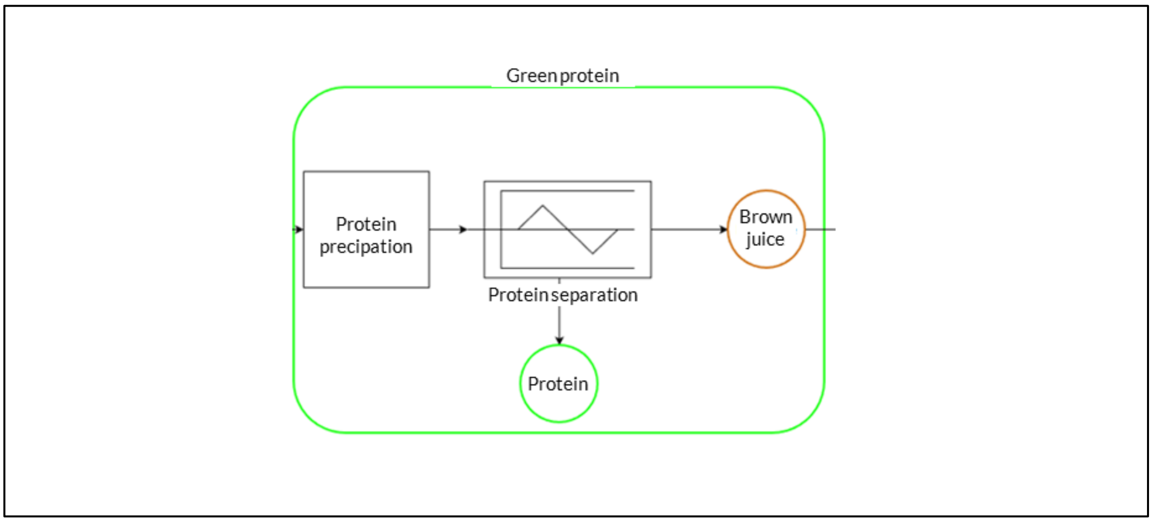

Figure 4: Precipitation and separation of protein in the press juice (RISE).

During the ensiling process the proteins are degraded to peptides, free amino-acid or ammonia. Monogastric animal cannot utilize ammonia, but peptides and amino-acids can be metabolized. Therefore, the press juice from silage can be used directly for feeding pigs in a wet feeding system. The main equipment needed for the green biorefinery is mentioned in Table 1.

Table 1: Main equipment needed for the green biorefinery

	Protein concentrates from fresh grass for	Press juice from ensiled grass
Bio feeder for receiving and feeding the grass	x	x
Screw press for fractionation	x	x
Equipment for transport of grass and products	x	x
Sieve for removing larger particles after pressing	x	
Storage tank press juice	x	x
Heat exchanger and steam injector for heating the press juice	x	

	Protein concentrates from fresh grass for	Press juice from ensiled grass
Centrifug for separation of the coagulated protein	x	

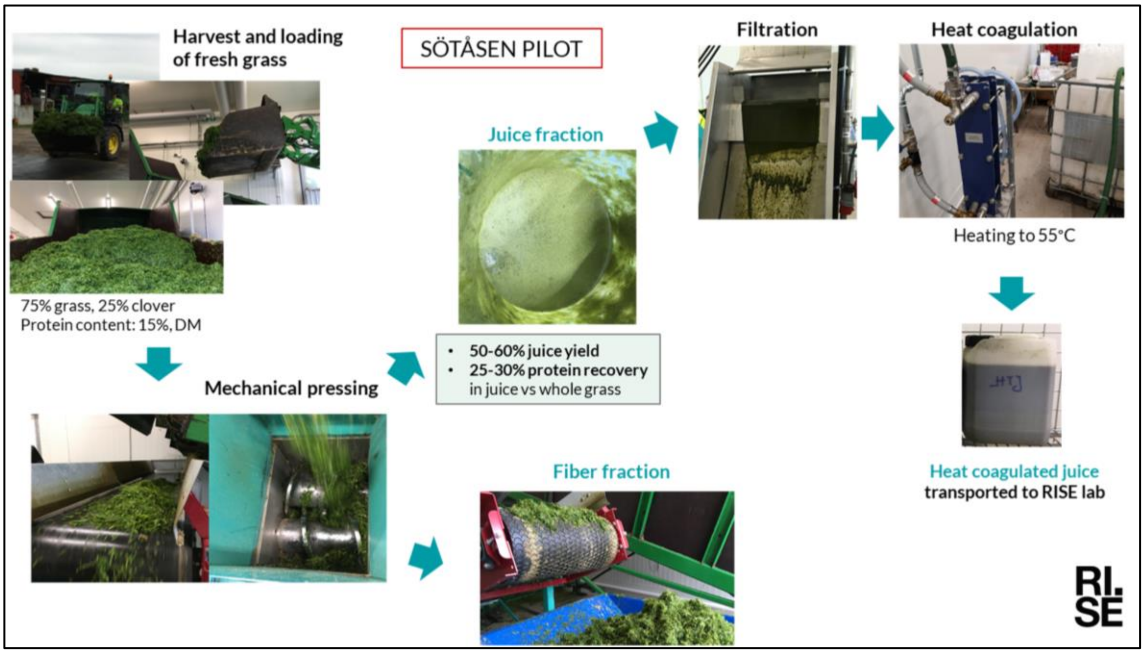

Figure 5: Process steps in protein extraction pilot plant Sötåsen (RISE)

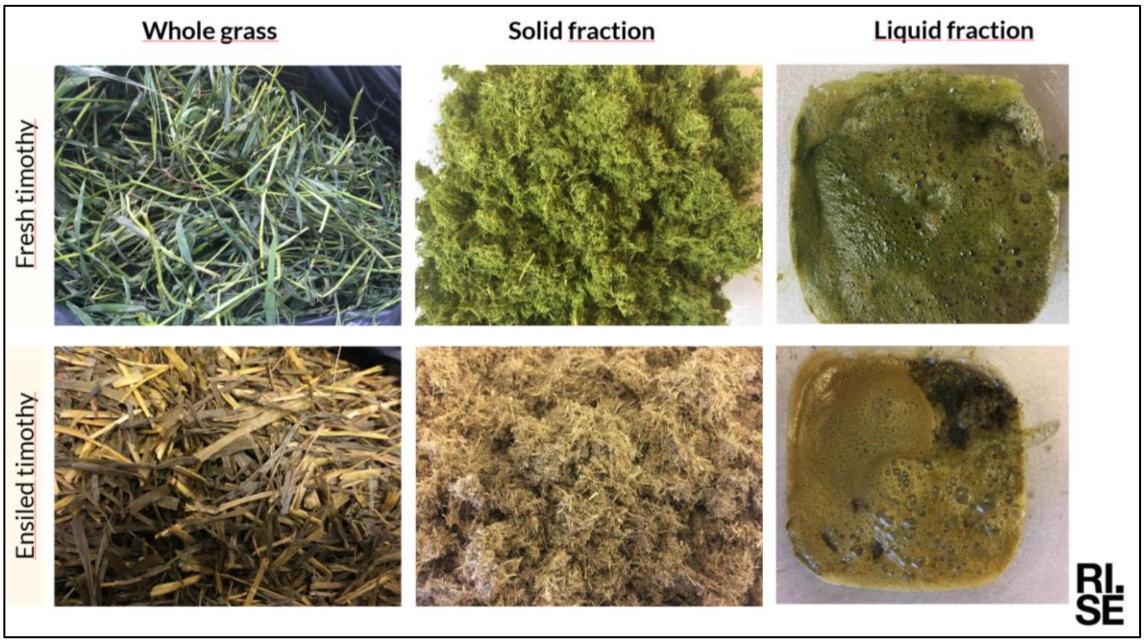

Figure 6: Fresh and ensiled grass fractions during protein extraction steps (RISE)

1.1.2 Biogas substrate pretreatment plant

Substrate pretreatment increases the surface area of the aggregate surface area of the input, which is required for biodegradation and thus for biogas production. Roughly speaking, although the reduction of particle size accelerates the rate of biodegradation, it does not necessarily increase the biogas yield. The interaction of hydraulic retention time and degree of shredding is one of the factors that influence methane production. Therefore, it is important to choose the right technology. The plants for the shredding of solid substrates can be installed externally upstream of the feed-in point, in the pre-digester pit, in the pipe or in the digester. The range includes chippers, mills, crushers and shafts and screw conveyors with rippers and cutting units. For a pilot plant, a mechanical substrate pretreatment system should be robust and be able to run in batches. In addition, a storage feeding volume should be integrated. Impact crusher systems have proven particularly effective for crushing lignocellulose-rich substrates, such as solid manure, horse manure, straw and grass silage (see example in Fig. 7).

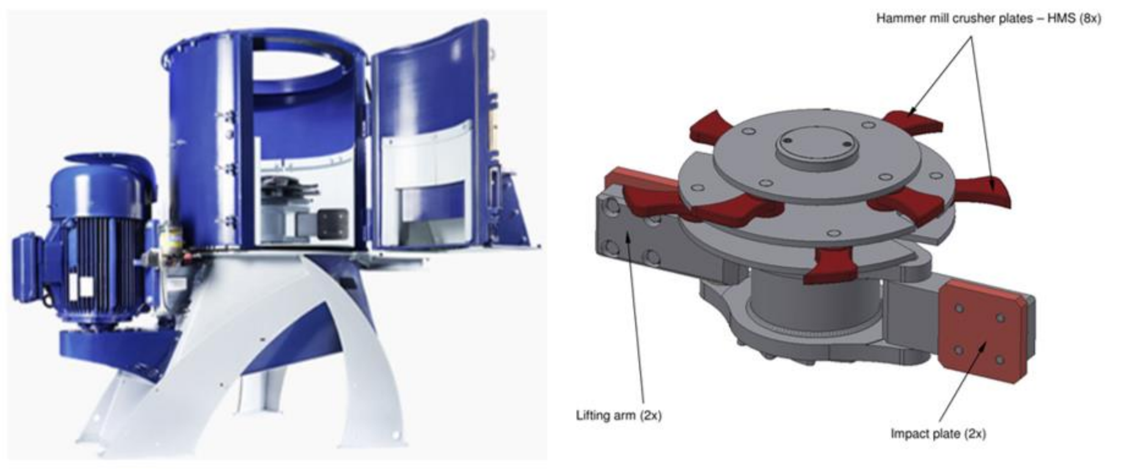

Figure 7: Impact crusher unit (LIMATOR)

The BIOG Biofeeder system is a compact mobile pilot pretreatment unit with 8 - 12 m3 walking floor feedhopper, impact crasher unit (75 - 90 kW) and pump unit and is shown as an example in the Fig. 8.

Figure 8: Substrate pretreatment unit with impact crusher system (Example: BIOG, Austria)

1.1.3 Biogas plant

Biogas is produced in a biological anaerobic process. In the absence of oxygen (anaerobic means without oxygen), organic matter is degraded to form a gas mixture known as biogas. This process is widely found in nature, taking place in moors, for example, or at the bottom of lakes, in slurry pits and in the rumen of ruminants. The organic matter is converted almost entirely to biogas by a range of different microorganisms. In a farm-based biogas plant the resulting gas mixture consists primarily of 53 – 60 vol. % methane and 40 - 47 vol. % carbon dioxide. Biogas also contains small quantities of hydrogen, hydrogen sulphide, ammonia and other trace gases. The composition of the gas is essentially determined by the substrates, the fermentation (digestion) process and the various technical designs of the plants. In principle, the anaerobic digestion process involves four steps (hydrolysis, acidification, acetic acid formation, and methane formation), each respectively involving different groups of microorganisms. Biogas offers a diversity of options for use, e. g. the decentralised production of electricity and heat, the distribution via local heat networks, the feed-in of upgraded biogas into the natural gas grid and its following use as a natural gas substitute for energy, as fuel for vehicles or in the chemical industry (Fig. 9). Independently of the use selected, the objective is to make the energy utilisation as efficient as possible.

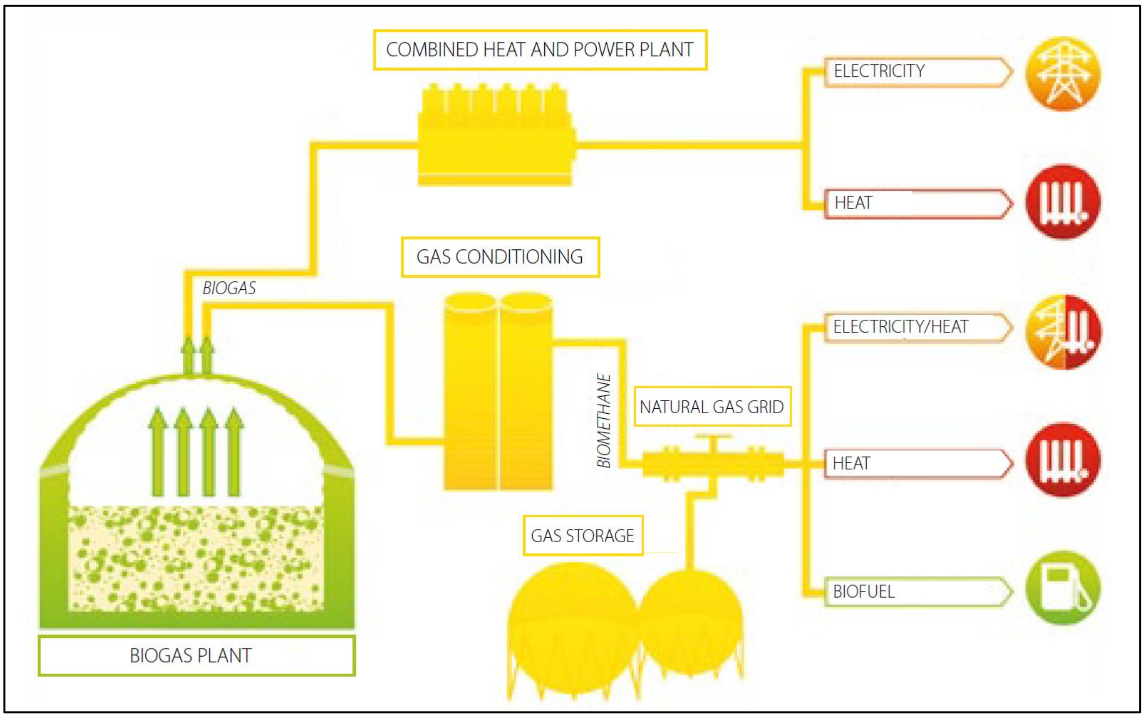

Figure 9: Option for using decentralized produced biogas (FNR)

Whenever a biogas plant, also in pilot plant scale - is being designed and built, most attention is normally paid to economic considerations. Consequently, when the size of digester is being chosen the focus is not necessarily on maximum gas yield or on complete decomposition of the organic matter contained in the substrate. If it was intended to achieve complete degradation of the organic matter, sometimes very long retention times would be needed for the substrate in the digester, together with correspondingly large tank volumes, because some substances take a very long time to break down – if at all. The aim must therefore be to obtain optimum degradation performance at acceptable economic cost. In this regard the organic loading rate (OLR) is a crucial operating parameter. It indicates how many kilograms of volatile solids (VS, or organic dry matter – ODM) can be fed into the digester per m3 of working volume per unit of time. The organic loading rate is expressed as kg VS/(m3 x d). Another relevant parameter for deciding on the size of the reactor is the hydraulic retention time (HRT). This is the length of time for which a substrate is calculated to remain on average in the digester until it is discharged. The amount of biogas produced in a biogas plant essentially depends on the composition of the substrates. In order to determine this, if possible, a digestion test should be carried out with the relevant substrate mixture. Failing that, the gas yield can be estimated from the sum of the gas yields of the substrates making up the input, assuming that the gas yield values for the individual substrates are available from reference tables for example from KTBL Germany. The anaerobic process temperature in the digester can be in the mesophilic (37 – 43 °C) or thermophilic range (50 - 60 °C). Cylindrical, upright stirred-tank reactors are used primarily in agricultural plants for biogas production. The main components of an agricultural biogas plant are usually substrate storage, digester, post-digester and digestate storage tank. What follows for the gas generated and its utilization are gas storage, gas cleaning, and usually Combined heat and power plant (CHP-plant) or respectively biogas upgrading unit. For biogas pilot plants, digester sizes can be from a few cubic meters to about 1000 m3 usable volume.

Table 2 shows an example of two pilot plants currently in operation at the German Biomass Research Centre DBFZ in Leipzig, Germany and at the School of Natural Resources in Sötåsen, Sweden.

Table 2: Main components and dimensions of biogas pilot plants (Examples)

Research biogas plant DBFZ, Germany	**Biorefinery pilot plant Sötåsen, Sweden**
1 x feedhopper 1x hopper shaped progressing cavity pump 1x wet input substrate cutter with heavy material separator (Rotacut) 2x main digester (190 m3) 1x plug flow fermenter (53 m3) 1x small fermenter (88 m3) 1x post-digester (215 m3) with gas storage 1x liquid manure storage tank (174 m3) 1x digestate storage tank (215 m3) 1 x CHP unit with an electric power of 124kW, including emergency flare	1x feedhopper 1 x main digester (270 m3) 1 x post-digester (270 m3) 1 x digestate storage tank 1 x CHP unit with an electric power of 20 kW, including emergency flare 1 x biogas upgrading unit based on wood ashfilter system 1x vehicle fuel biomethane tank station 1 x protein extraction plant
	
www.dbfz.de/en/research/research-infrastructure/research-biogas-plant	www.vgregion.se/f/naturbruksskolan-sotasen/

1.1.4 Nutrients recovery plant (based on N2-applied)

Nitrogen is essential for modern agriculture and is commonly obtained through the production of ammonia from hydrogen gas and nitrogen gas (Haber-Bosch method). However, this process is not climate neutral as hydrogen gas is typically produced using steam reforming of natural gas. A Norwegian company N2-applied, has developed an alternative small-scale technology for production of nitrogen fertilisers based on Birkeland Eyde method. This technology uses electricity instead of natural gas to produce nitrogen fertiliser. The principle of this technology is that a plasma module, driven by electricity, splits the bonds N2 and O2 in the air, which are then bound to NOx. When this is injected into the digestate, nitrate nitrogen is formed, the digestate is enriched with more plant-available nitrogen. This digestate treatment also causes the pH value of the digestate to fall. N2-Applied calls its machine NEO: Nitrogen Enriched Organic

Fertiliser. This process has several advantages. Firstly, renewable electricity in production of nitrogen fertiliser can be used instead of natural gas and secondly, emissions of methane and ammonia are reduced. In addition, the treated slurry is more or less free of odor and sanitized. The production capacity of the NEO is to add 1 kg of nitrate nitrogen per hour to the treated digestate and the amount of added nitrogen by the NEO is approx. 1.4 times the concentration of ammonium nitrogen in the digestate (RISE). The big challenge with the process is that the plasma module in NEO unit requires a lot of electricity generating heat. Therefore, the plasma module must be cooled, and heat can be recovered and used for heating. With an increasing installation of local renewable electricity, for example via wind turbines or biogas-CHP, the price for electricity varies a lot NEO unit has fast start and stop times. Therefore, the machine can easily adapt the operation to periods with low electricity prices. It is therefore particularly interesting to investigate in pilot plants how such plasma technology could be integrated into an existing farm-based biogas plant for production of fossil-free nitrogen and to significantly reduce emissions of ammonia and methane during digestate handling.

Figure 10: N2-applied unit – pilot plant container (N2APPLIED)

1.1.5 Biogas combined heat and power plant (CHP)

In principle, CHP units consist of a combustion engine fuelled by biogas, driving a generator used for producing electrical energy. For this, several kinds of engine constructions and combustion processes are available. In particular, it is gas spark ignition engines and pilot ignition engines (Otto-engines) that are used. When the methane concentration level is at least 45 %, gas spark ignition engines can burn the biogas directly. To burn the biogas, pilot ignition engines (Diesel-engines) need an ignition oil in order to initiate the combustion process. For optimised pilot ignition engines, a quantity of 2–4 % ignition oil is sufficient. When selecting the CHP unit, care must be taken to ensure high efficiency and a low level of repair requirements. When used in CHP units, the coupled products generated are electricity and heat. In environmental terms and also for efficiency, it is purposeful and necessary to use the heat generated. Accordingly, a suitable heating concept plays a decisive role when planning new installations. Depending on the type of installation and the time of year, around 10–30 % of the waste heat is required for heating the digester. When losses (approx. 15 %)

are deducted, 50–60 % are then available for external use (FNR). Smaller CHP units in the range of 50 - 200 kWel are often used for pilot plants.

1.1.6 Biogas upgrading plant

RISE and SLU have developed a new technology for small-scale upgrading of biogas where wood ash is used to capture carbon dioxide and hydrogen sulphide, which means that the biogas is refined into biomethane. The technology is called ash filter and the process provides double benefits because the ash is also stabilized during the gas purification process (RISE). The latter is a prerequisite for wood ash to be returned to forest land. Today, far from all wood ash produced in Sweden is recycled. This is partly due to the fact that it is more expensive to return ash to the forest than use it as construction material on landfills. This new system for ash management leads to more recycling of wood ash to the forest to close the cycle of important minerals and nutrients. At the same time, the new ash handling system means that ash filter technology can be used to refine biogas into vehicle fuel, which in turn can replace fossil fuels in our transport sector. The performance of the ash filter technology has been verified in applied scale and during 2020 - 2021, a first full-scale test and demonstration facility will be built at Sötåsen High School of Natural Sciences (Fig.11). The pilot plant addresses issues that are important for ash filter to be implemented and in the long run generate more circular flows through increased ash recycling to forests (RISE).

Figure 11: Positioning of ash filter container at pilot plant Sötåsen (RISE)

Another technique to separate gases in small scale units is done using the selective permeability properties of one or a set of membranes (see Fig.12). For biogas upgrading, hollow polymeric fibers are used. One crucial factor is the selectivity of the membrane to allow the flow of CO_2 and avoid CH_4 slip. Typically, the membranes used are sensitive to liquids, oils, and impurities. Some conditioning should be carried out before the upgrading. Low concentrations of H2S will be separated with CO2, in addition, they do not harm the membrane markedly. Co2 can then be captured and stored for further use. Nevertheless, if condensates of water are present, they will react to form acids that do harm the membrane and will significantly lower the lifespan of the system. Other contaminants, like NH3 when dissolved in water from condensation, or volatile organic compounds (VOC) can harm the membrane irreversibly. Commonly a set of filters or a scrubber is used before passing the gases through the membrane. Commonly, operating pressures are around 10 – 20 bar. Compared to other upgrading processes, the pressure is high. This elevated pressure can be useful for subsequent compression for storage or compressed biogas as vehicle fuel. Nevertheless, for some other applications, the pressure must be reduced meaning that the energy stored as pressure will be lost or has to be recovered using additional equipment. Depending on the application, the process can consist of one, two or three stages of membranes. Adding stages will further reduce the recycled gas and the CH4 slip, but it will increment the energy intensity of the process (EVONIK).

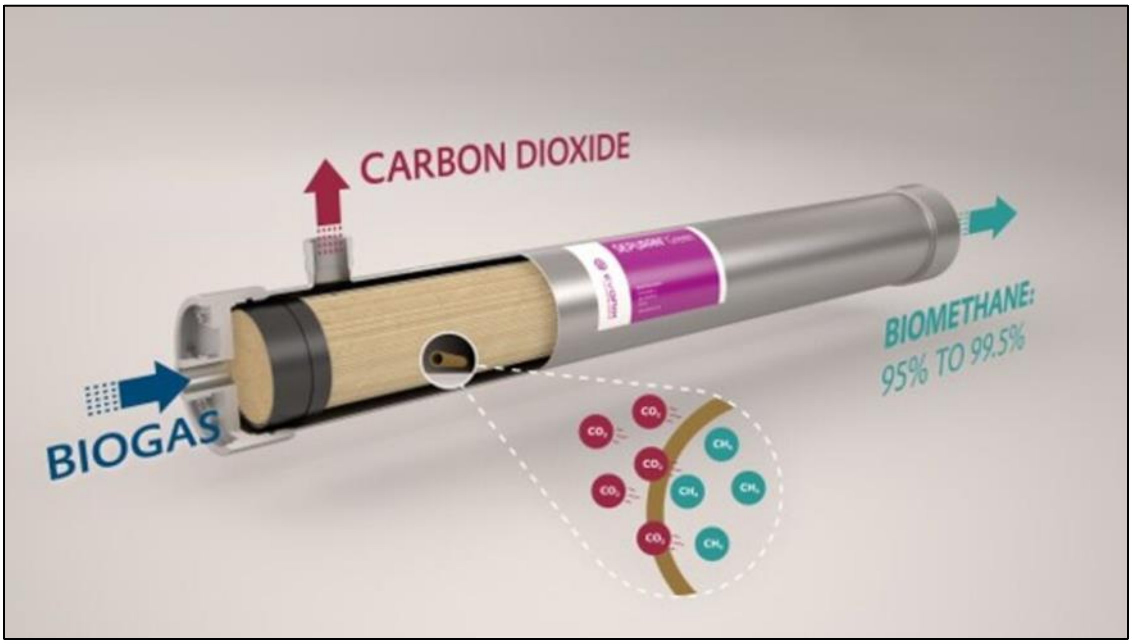

Figure 12: Upgrading of biogas to biomethane with membrane module (Example: EVONIK SEPURAN® Green membranes)

1.1.7 CO2-Liquefaction plant

The CO2-Liquefaction pilot plant (TB12) is a facility in the RISE Bioeconomy Arena of RISE AB in Sweden (see Fig.13). It can be used to remove impurities and liquefy a gas flow which mainly consists of carbon dioxide. This is achieved by a number of unit operations which can be switched on and off one by one in order to get the desired product quality without involving unnecessary treatment steps. This way, it is possible to tailor the process to different industries' specifications, such as CCS (Carbon Capture and Storage) or different kinds of CCU (Carbon Capture and Usage, e.g. food industry, electro fuels etc.).

Figure 13: Container unit CO2-Liquefaction plant TB12 (RISE)

The pilot plant is intended for use mainly by entities having waste streams with a high carbon dioxide content, and who are evaluating the possibilities to invest in technology in order to make use of their carbon dioxide, but who need a better understanding of the technology prior to their investment decision. The test bed may be used as a proof of concept and demonstrate the possibilities of utilizing the waste streams, as well as to identify the unit operations which are actually needed in a full scale plant to accomplish the required treatment. TB12 is built as a fully mobile plant, placed in a standard 20 foot high-cube sea container.

Process Description

In the following, the different unit operations in the standard setup are described (see Fig.14). If required, the plant may be modified to meet the projects or customer's needs.

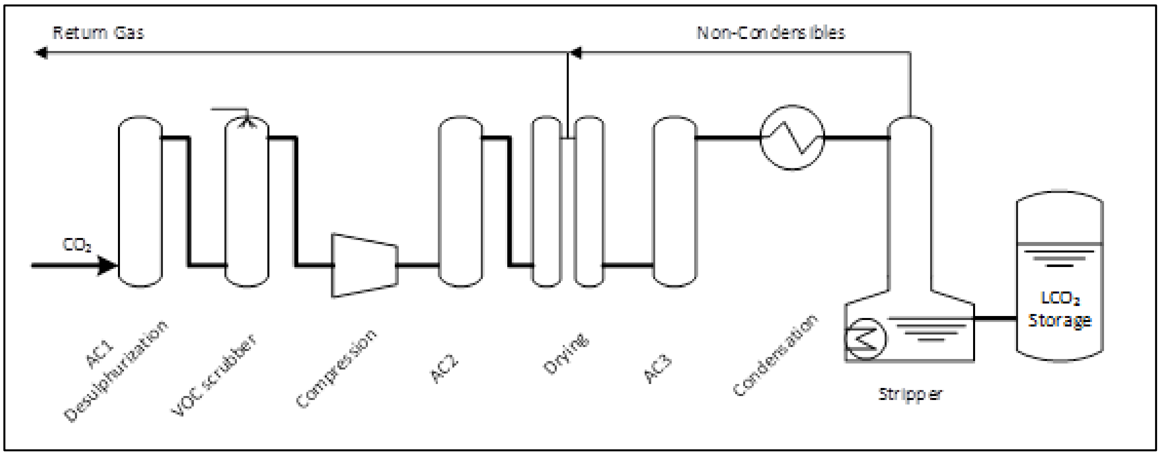

Figure 14: Block flow diagram with unit operations in TB12 (RISE)

Gas Inlet and Storage

The incoming gas stream goes through a low pressure gas storage in order to equilibrate gas flow and gas quality. After the gas storage, the gas is analyzed for CH_4, CO_2, O_2, H_2S and H_2. If the gas quality is out of specification, the gas is rejected and does not enter into the process. Usually, a minimum CO_2 content of 95 % would be enforced in order to be able to condense the gas stream at reasonable temperatures.

Activated Carbon Steps

The plant includes three different activated carbon filters which can be equipped with different material in order to adsorb different impurities.

- AC1 is placed in the low pressure system and is normally used for desulphurization.
- AC2 is placed directly after the compressor. Often, this step is not used, so there is no “normal” function.
- AC3 is also located in the high pressure system but after the drying step, and may be e.g. used to remove smelling and/or tasting compounds.

Water Scrubber

A simple, non-regenerating water scrubber in the low pressure system may be used to remove water soluble compounds such as VOC, ammonia etc. Exhausted water is disposed off and replaced with fresh water in order to keep the plant simple.

Compression

The gas is compressed up to 16 bar which is necessary for efficient drying and condensation of the gas stream at reasonable temperature.

Gas Dryer

The gas is dried to a dew point of approx. –50 °C in order to avoid ice formation in the condensation step. The drier in the test bed is regenerated with a small portion of the dried gas stream. In a full scale plant, it may be more economical to use waste streams from the liquefaction and/or LCO2 storage.

Condensation

The plant is equipped with a cooling machine which provides cold at down to –60 °C, which is enough to condense the gas stream to liquid CO2 (LCO2). Gas streams with large amounts of non-condensable gases such as O2, N2, H2 or CH4 may be only partially condensed. The remainder gas flow would then contain mainly those non-condensable gases and can be recycled to the main process.

Stripper Column

Here, traces of non-condensable compounds are stripped off the LCO2 stream by heating the bottom of the column. A usage example is the removal of oxygen to ppm level in order to meet the requirements of some CCS systems. The stripper column can also be used to recover valuable non-condensables such as methane.

LCO2 Product Tank

The liquefied product is collected in a cryogenic tank. From here, it may be bottled and exported.

Gas Analysis

The gas is analyzed online at several places, namely after the initial gas storage, after AC3, as well as the top and bottom streams of the stripper column. Compounds which are analyzed are CO_2, CH_4, O_2, H_2 and H_2S. For further (external lab) analyses, the plant is equipped with sample points in each relevant position.

Plant Specifications

Plant size: 20 foot high-cube container

Gas inlet flow rate / capacity: 7..10 Nm^3/h

Product flow rate: 10..15 kg/h

Min inlet CO_2 concentration: 90 %

Inlet water content: 0..100 % RH (non-condensing)

Gas inlet pressure: –20..30 mbarg

Max gas inlet temperature: 40 °C

Product pressure: 7..15 barg

Consumables:

- Electricity, 3 phase, 32 A
- Water
- Activated carbon

Automation: Fully automated, with remote access

1.2 Biorefinery pilot plant suggestion (Example for Oslofjord region)

A site in Norway at the NOME agricultural school in the Oslofjord region was selected as an example of the pilot plant concept. In the BREC-Project an Excel-based tool was created for the calculation. Specific substrate data parameters were obtained from biogas industry sources mainly from Sweden and Germany. In addition to the existing livestock farming and crop production, there are also increased apple production in the Oslofjord region. During apple juice production season, apple press residues: apple juice pomace are produced and is to be used as well as a substrate. According to the farm-based biorefinery plant concept in Fig 2., the following suggestion was calculated.

Input subtrate

The input substrates intended for the biorefinery pilot plant concept are listed in Table 3.

Table 3: Annually input substrate in mass value of fresh matter (FM/a) for biorefinery pilot plant

Input substrate	Mass per year [t FM/a]
Cow manure	680
Pig manure	48

Input substrate	Mass per year [t FM/a]
Horse manure	200
Apple juice pomace	400
Grass silage	500

The first three substrates mentioned in Tab.3: Cow manure with 680 tonnes of fresh matter per year [tFM/a], pig manure with 48 tFM/a and horse manure with 200 tFM/a are produced throughout the year. Grass silage is available at 500 tFM/a. Apple juice pomace with 400 tFM/a is produced approx. 3-5 months a year. However, if stored appropriately, it can be used as a co-substrate all year round. The concept is based on two pathways: the protein extraction pathway and the biogas process pathway.

Protein extraction pathway

The grassland silage with an annual quantity of 500 tFM/a is fed into a protein extraction stage (protein plant). A screw press technology of CIRTECH is calculated for the production of liquid grass press juice. The protein-rich pressed juice of 285 t/a can be used as animal feed. The raw protein content in the press juice is around 12 t/a (RISE). The resulting grass press cake of approx. 215 tFM/a is then fed into the biogas process pathway.

Biogas plant path

The methane yield data of the planned input substrates are important for biogas production step. Table 4 shows the specific characteristics and biomethane yield values (Fig. 15) of the intended substrates based on average data of KTBL, FNR and RISE.

Table 4: Specific characteristics of the input substrates with methane potential (KTBL, FNR, RISE)

Substrate	[tFM/a]	[% DM of FM]	[% VS of DM]	[LCH4 /kgVS]	[m3 CH4/tFM]
Cow manure	680	9	80	230	17
Pig manure	48	6	80	250	12
Horse manure with straw	200	32	82	214	55
Apple juice pomace	400	35	97	301	102
Grass silage press cake	215	55	97	264	141

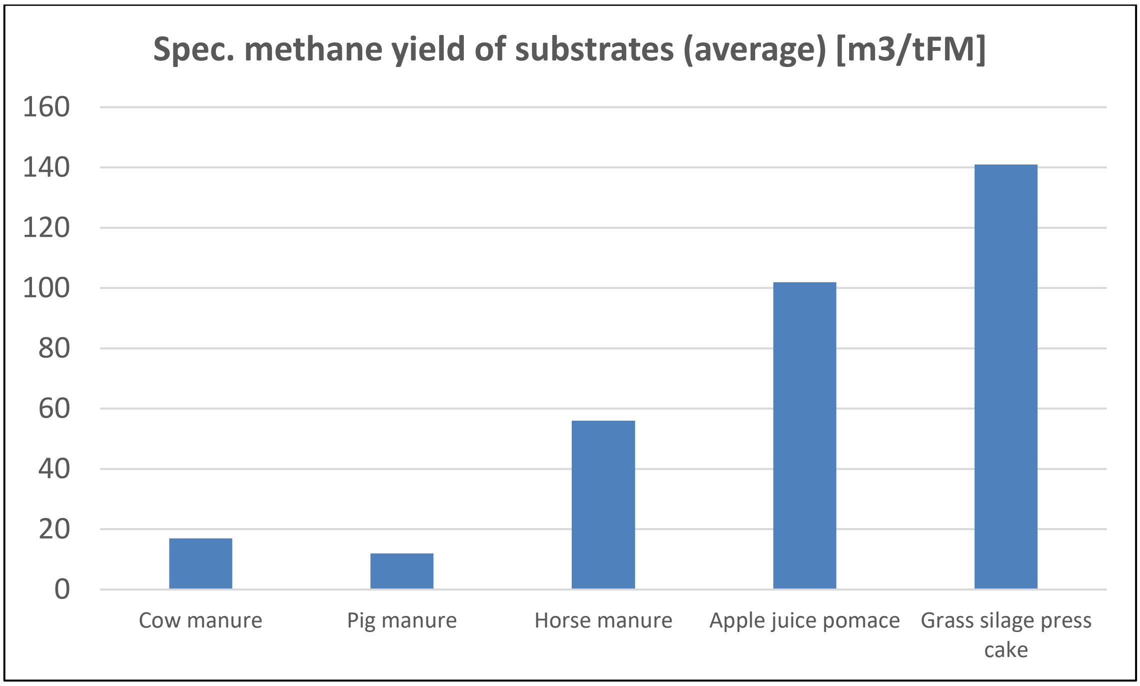

Figure 15: Average specific methane yield of input substrates (KTBL, FNR, RISE)

In the pilot plant concept, the biogas process is to be run in mesophilic mode. The fermenter temperature should therefore be in the range of approx. 37 - 40 C. A continuous stirred tank reactor (CSTR-Digester) with an operating volume of 300 m3 and a secondary digester tank (post-digester) of 300 m3 volume are calculated. In order to keep the input substrate, mix pumpable and stirrable for the reactor process, the solid substrate must be mechanically pre-treated, shredded and mixed. Furthermore, process water of 2200 m3/a must be added. The necessary process water can be taken from the separation step of the downstream digestate treatment (recirculate flow).

Substrate pretreatment plant

The pretreatment of the solid substrate, such as solid manure, straw rich or lignin-rich substrates, is shredded in a mechanical shredding unit including a dosing container, defibration unit, and mixing pump such as Biofeeder with impact crusher of BIOG and homogenized together with the liquid substrates and pumped into the digester.

The shredding unit is robust and can be an impact crusher system. The dosing container should have a volume of 8 - 10 m3. The daily solid substrate throughput using the impact crusher will then be 1.5 - 2 tFM/d.

Biogas plant - Anaerobic digestion

In wet anaerobic digestion plants using various types of manure and agricultural residues in CSTR digesters, the organic loading rate should be in the range of 2.8 - 3.5 kg VS/m3 *d. A higher loading rate of 4 - 5 kg VS/m3 is possible. It leads to smaller tank sizes but also to shorter hydraulic retention times of the substrate mix in the process. A more flexible operation, possibly with other input substrates, is therefore more limited. The dry matter content of the substrate mix in the CSTR-Digester should be below 10 % in order to minimize wear on the pump and agitators.

The organic loading rate in the presented pilot plant digester is 3,2 kg VS/m3*d. The hydraulic retention time in the digester is calculated with 30 days. The following process data for biogas production step result from the calculation for the pilot plant (Table 5):

Table 5: Process data biogas plant

			Mass fraction, ca. [%]
Cow manure	1,863	tFM/d	18
Pig manure	0,132	tFM/d	1
Horse manure	0,548	tFM/d	5
Apple juice pomace	1,096	tFM/d	11
Grass silage press cake	0,589	tFM/d	6
Process water/ Recirculate	6,027	tFM/d	59
Input substrate mix, total, daily	10,25	tFM/d	100
Input substrate mix, DM content	10,3	% DM	
Organic loading rate digester	3,2	kg VS/m3*d	
Digester volume, netto	300	m3	
Post-digester volume, netto	300	m3	
Output Biogas, daily, mass	0,56	t/d	
Output Biogas, daily, vol.	468	m3/d	
Methane content in biogas	55	%	
Output Methane, daily	258	m3/d	
Output Energy content biogas, daily	2575	MWh/d	
Output Energy content biogas, annually	0,94	GWh/a	
Output Digestate, daily	9,69	t/d	
Output Digestate, annually	3538	t/a	

The daily substrate mix for the biogas process of 10 tonnes is made up of around 4 tonnes of agricultural residue and 6 tonnes of liquid process water. 470 m3 of biogas with a methane content of 55% is produced daily. The amount of digestate from the anaerobic digestion process is 9.4 tonnes per day. The mass proportions are shown comparatively in Fig.16.

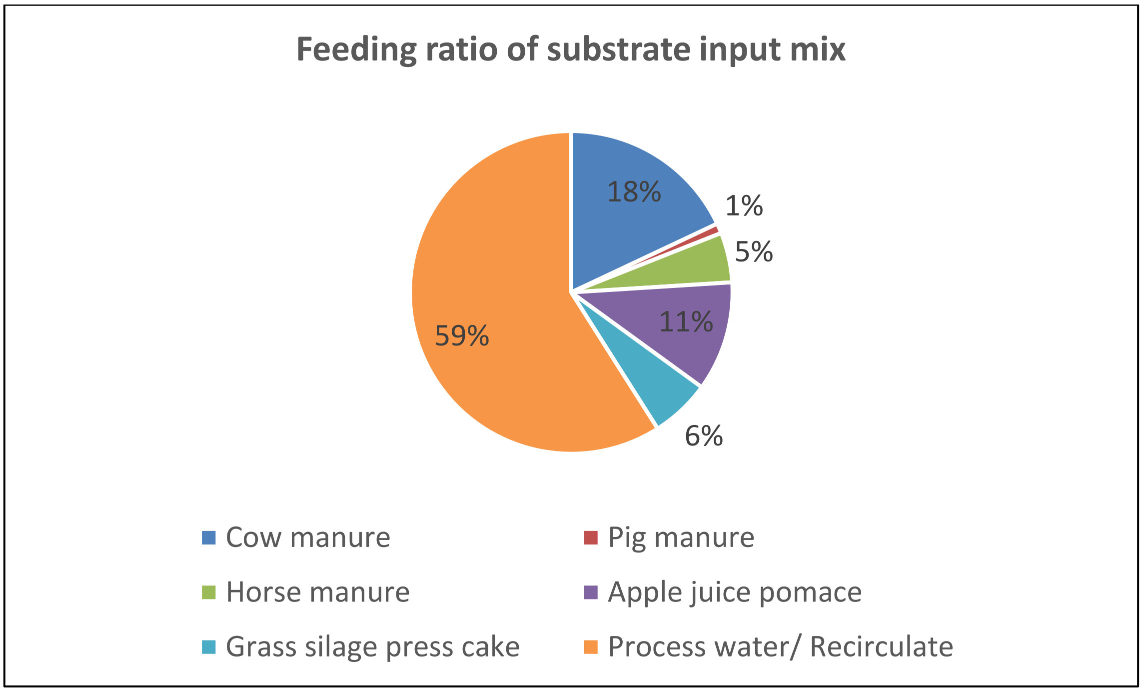

Figure 16: Feeding ration of substrate mix in the biogas process

Based on the calculation, 171431 m3 of biogas with a potential thermal energy quantity of 0.94 GWh/a will be produced annually. Hereby, the pilot plant is designed for an energy production of around 1 GWh/a.

Biogas conversion

In the pilot plant concept, the annual biogas yield of 171000 m3/a is now divided into two utilization paths. Half of the biogas yield (85500 m3/a) is utilized in a CHP plant for local power and heat production. The other part of the biogas volume is used in a biogas upgrading plant to produce biomethane for use as a vehicle fuel.

Biogas CHP plant

The CHP module has an installed electrical output of 20 - 25 kWel. Depending on the CHP module, in these low CHP capacity classes, the electrical efficiency is around 32 % and the thermal efficiency around 52 %. This means that electricity of around 150 MWh/a and useful heat of 240 MWh/a can be produced (Table 6). Alternatively, the operation of a biogas boiler with capacity of 1 - 2 MW for local heat production can also be considered.

Table 6: Characteristics of CHP plant

CHP plant (small scale unit)	
Input Biogas	85500 m3/a
CHP- module installed electrical capacity	20 kW
Electric efficiency	32 %
Thermal efficiency	52 %

CHP plant (small scale unit)	
Output annual power production, ca.	150 MWh/a
Output annual heat production, ca.	240 MWh/a

Biogas upgrading plant (Biomethane production)

The other half of the biogas yield is fed into a biogas upgrading plant for biomethane production. The biomethane has a purity level of approx. 98 % methane and can be stored in a downstream filling station plant for CNG vehicles. The biogas upgrading plant can be operated in this small capacity range, e.g. with membrane technology or a water scrubbing process. Membrane technology is particularly suitable for the further use of captured CO2 (Tab. 7).

Table 7: Biogas upgrading module

Biogas upgrading plant	Volume	Mass
Input Biogas	85500 m3/a	103 t/a
Output Biomethane, annually	46084 m3/a	33 t/a
Output Biomethane, daily	127 m3/d	91 kg/d
Output Carbon dioxide (CO2)	37000 m3/a	70 t/a

In the pilot plant, 33 t/a of biomethane and 70 t/a of carbon dioxide are produced from 103 t/a of biogas using membrane technology. The daily biomethane production would be 91 kg/d.

Biogas flare (safety device)

If the two biogas conversion paths mentioned above are not in operation, controlled flaring of the continuously produced biogas must be ensured. For this case, a safety device - a biogas flare with a capacity of 20 - 25 m3/h of biogas stream - must be installed, which is capable of burning the entire daily amount of biogas produced of 470 m3/d. Methane gas must be prevented from entering the atmosphere.

Carbon dioxid (CO2) liquefaction plant - CCS/CCU-application

A Co2 cleaning and liquefaction plant can be used as a carbon capter storage (CCS) unit. With a connected CO2 bottling device, the biogenic liquid CO2 (BLCO2) output product can be further offered in a transportable CCU unit.

When using the CO2 cleaning and liquefaction plant, a minimum purity level of CO2 of 95% in the offgas from the biogas upgrading system (e.g. membrane system) is required. The system has a capacity flow of 8 – 10 kg/h CO2. At a density of 1030 kg/m3 (liquid CO2; -28 degrees, 16 bar), 195 L/d of liquid CO2 can be produced per day. Collection in bottles as a transport unit is possible.

Table 8: Characteristics of the Co2 liquefaction system

CO2 purification and liquefaction module	Volume	Mass
Input Co2-rich gas from biogas upgrading plant (> 95% Co2 content)	37000 m3/a	70 t/a
Input Co2-rich gas from biogas upgrading plant (> 95% Co2 content)	102 m3/d	193 kg/d
Output, liquid Co2 (LCO2), annually	68134 L/a	
Output, liquid Co2 (LCO2), daily	187 L/d	

With an input of 102 m3 of Co2-rich gas per day, 193 liters per day of LCo2 can be produced (Tab.8).

Digestion separation

The standard process planned here for mechanical separation of solids in the agricultural sector is the screw press separator. The degree of solids separation can be varied by choosing the mesh size of the sieve basket in the screw press. The liquid phase from this process always contains smaller particles (< 0.5 - 1 mm in diameter), so that their solids content is at least 3 - 5%. The solids content of the solids phase is in the range of 20 to 30%. The actual separation performance of the press screw depends heavily on the properties of the digestate. After the separation step the pilot plant can generate, 8,7 t/d liquid phase with 5% dry matter content and around 1 t/d solid phase with a dry matter content of approx. 30% (Tab.9). Solid phase → Soil improver: Liquid phase → Nitrogen enrichment plant (Tab.10).

Table 9: Process data of digestion separation plant

Screw press separation module	Mass [t/a]	Mass [t/d]	DM-content [%]
Input digestate	3538	9,7	8
Output liquid phase	3184	8,7	5
Output solid phase	354	1	30

Nitrogen boosting / enrichment in liquid phase of digestate (N2-Applied)

Table 10: Data nitrogen boosting flow (RISE, N2Applied)

Nitrogen boosting module	Mass [t/a]	DM-content [%]
Output liquid phase - NEO enriched	984	6

Summary

The Sankey diagram in Figure 17 shows a summary of the mass flow of input and output products of the biorefinery concept example.

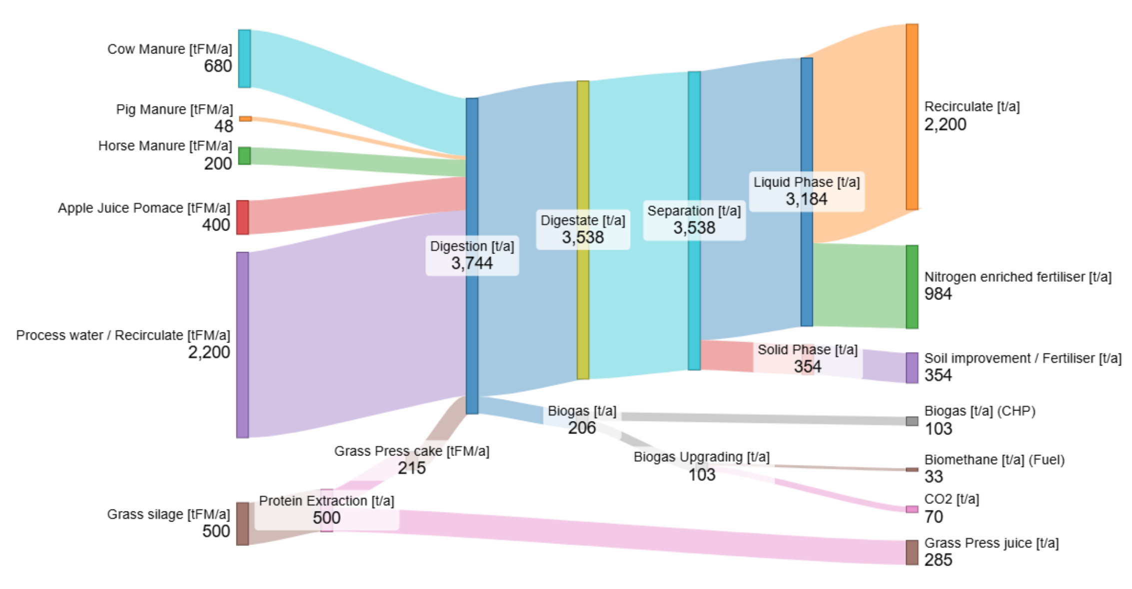

Figure 17: Total mass flow of biorefinery pilot plant concept (Sankey-diagram via SankeyMATIC)

Cost estimation biorefinery pilot plant modules

Based on reference projects in EU and specific cost inquiries from manufacturers, cost estimates for the plant modules described above are listed in the Tab. 11.

Table 11: Cost estimates for the plant modules

Plant module	Capacity range	Invest estimate	Source
Protein extraction plant	8 – 20 m3/h grass silage Twin screw press system incl. Feeder system, Press juice buffer tank	480.000 €	RISE/ CIRTECH
Substrate pretreatment plant	8 -10 m3 Feeder + 55 kW Impact crusher	250.000 €	BIOG / DBFZ
Biogas production plant	2 x 300 m3 CSTR-Digester concept incl. pump and pipelines	600.000 €	DBFZ/ FNR
Biogas CHP plant	20 – 50 kW CHP installed electrical power capacity incl. safety flare	150.000 €	DBFZ / FNR
Biogas upgrading plant	Membrane technology 30 – 60 t/ a ca. Biomethane production	350.000 €	DBFZ/ FNR

Plant module	Capacity range	Invest estimate	Source
	70 – 150 t/ a ca. CO2 production		
Nutrients recovery plant	1000 t/ a Nitrogen enriched liquid fertilizer	300.000 €	RISE/ N2APPLIED
CO2Liquefaction plant	70 – 150 t/ a ca. CO2 liquified CO2	400.000 €	RISE

A plant investment of around €2,5 – 2,7 million is estimated for a pilot-scale biorefinery plant that will serve as a research and show case facility with an annual input material flow of 1700 - 1800 t FM/a of agricultural residues.

References

BIOG – BIOG Solutions for Green Energy GmbH, Austria, www.biog-biogas.com

CIRTECH – Circular Technologies Cir-Tech A/S, Danmark, www.cir-tech.dk

DBFZ - Deutsches Biomasseforschungszentrum gGmbH, Germany, www.dbfz.de

EVONIK – Evonik Industries AG, Germany, www.membrane-separation.com

FNR – Fachagentur fuer nachwachsende Rohstoffe, Germany, www.fnr.de

KTBL - Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V, Germany, www.ktbl.de

LIMATOR - Lindner Recyclingtech GmbH, Austria, www.lindner.com

N2APPLIED – N2-applied Norway, www.n2applied.com

SLU - Swedish University of Agricultural Sciences, www.slu.se

RISE – Research Institutes of Sweden, Sweden, www.ri.se

VGR - Västra Götalandsregionen, Sweden, www.vgregion.se