Increase of biogas production by incorporating residual streams from agriculture

by

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Abstract

To expand the biogas production in Region Västra Götaland (RVG), residual streams from the agricultural sector can function as a large-scale supplier of biomass. The production of biogas decreases the dependence of fossil fuels and the digestate that is formed can also be returned to the agricultural sector, creating a closed loop. The expansion was assessed in this thesis by the investigation of the biogas producers in RVG and the total potential of agricultural residues. An interview study was conducted for co-digestion and farm-based biogas plants, to investigate their capacity, interest and ability to introduce agricultural residues in their process. The utilisation of mechanical pretreatment was analysed to facilitate the implementation of fibrous residues.

This study shows that the total theoretical potential of agricultural residual streams is equal to 1.31 TWh/year in RVG. The current biogas production in RVG is 300 GWh/year, where co-digestion plants account for 56 % and farm-based biogas plants for 5 %. The most used agricultural residue, with 91 % is slurry from cattle and pig. The interview study concludes that the biogas plants could increase the current capacity with 184 GWh/year by incorporating agricultural residues. Large co-digestion plants have the greatest opportunity of adapting its current facilities, but their main limitation is to receive a permit allowing them to expand the production and utilise other substrates. Out of all agricultural residues, manure is of highest interest for the biogas plants to include in its production, whereas fibrous residues are associated with challenges. The higher water content and receiving the manure-gas aid contributes to that manure is prioritised over other agricultural residues.

The fibrous residues consisting of solid manure fractions, excess and discarded ley silage and straw account for around 68 % of the total theoretical potential and to include these substrates into the biogas production, pretreatment is needed. The present study shows mechanical pretreatment is currently the best choice of handling dry and fibrous substrates, with the hammer mill being the most suitable for large-scale operations and the mixer-wagon for small-scale operations. The energy spent on mechanical pretreatment is paid off if it increases the methane yield with 5 % and has an energy demand below 60 kWh/ton wet weight (ww) for manure, 150 kWh/ ton ww for ley silage, and 290 kWh/ton ww for straw. An economic evaluation concludes that an electricity price under 3 SEK/kWh with a biogas income of 0.8 SEK/kWh is needed for mechanical pretreatment to be profitable. The study concluded that further research and development is required to design a robust and reliable process to include straw and ley silage to a larger extent.

Sammanfattning

För att utöka biogasproduktionen i Västra Götalandsregionen (VGR) kan reströmmar från jordbrukssektorn fungera som en storskalig leverantör av biomassa. Produktionen av biogas minskar beroendet av fossila bränslen och rötresten som bildas kan också återföras till jordbrukssektorn, vilket skapar ett slutet kretslopp. I detta examensarbete granskades utökningen genom en kartläggning av biogasproducenterna i VGR och den totala potentialen av jordbruksrester. En intervjustudie genomfördes för samrötning och gårdsbaserade biogasanläggningar, för att undersöka deras kapacitet, intresse och förmåga att införa jordbruksrester i sin process. Utnyttjandet av mekanisk förbehandling analyserades för att kunna implementera fiberrika jordbruksrester.

Det här examensarbetet visar att den totala teoretiska potentialen av reströmmar från jordbruket 1.31 TWh/år i VGR. Den nuvarande biogasproduktionen är 300 GWh/år i VGR, där samrötningsanläggningar står för 56 % och jordbruksbaserade för 5 %. Den mest använda jordbruksresten, med 91 % är flytgödsel från nötkreatur och grisar. Intervjustudien konstaterade att biogasanläggningarna skulle kunna öka sin nuvarande kapacitet med 184 GWh/år genom att inkorporera jordbruksrester. De stora samrötningsanläggningarna i VGR har störst möjlighet till att anpassa sina nuvarande anläggningar men deras huvudsakliga begränsning är att få tillstånd att utöka sin produktion och röta andra typer av substrat. Av alla jordbruksrester är gödsel av högsta intresse för biogasanläggningarna att inkludera i sin produktion, medan fiberrika substrat anses vara förknippade med utmaningar. Den högre vattenhalten och gödselgasstödet bidrar till att gödseln prioriteras framför andra jordbruksrester.

De fiberrika restprodukter bestående av fasta gödselfraktioner, överblivet och kasserat vall ensilage och halm står för cirka 68 % av den totala teoretiska potentialen och för att inkludera dessa substrat i biogasproduktionen behövs förbehandling. Resultaten från den här studien visar att mekanisk förbehandling för närvarande det bästa valet för hantering av torra och fiberrika substrat, där hammarkvarnen är bäst lämpad för storskaliga verksamheter och mixervagn för småskaliga verksamheter. Energin som spenderas på mekanisk förbehandling lönar sig om den ökar metanutbytet med 5 % och har ett energibehov under 60 kWh/ton våtvikt (vv) för gödsel, 150 kWh/ton vv för vall ensilage och 290 kWh/ton vv för halm. En ekonomisk utvärdering visar att det behövs ett elpris under 3 kr/kWh med en biogasintäkt på 0.8 kr/kWh för att mekanisk förbehandling ska vara lönsam. Studien drog slutsatsen att ytterligare forskning och utveckling krävs för att utforma en robust och tillförlitlig process för att inkludera vallgrödor och halm i en större utsträckning.

Preface

This master thesis is the result of a degree project in Environmental Engineering at Lund University. The project was performed from January to June 2022 in collaboration with RISE, Research Institutes of Sweden at the Department of Chemical Engineering. To Mats Galbe, thank you for taking the time to answer my questions and thanks to Ola Wallberg for being my supervisor.

This thesis has come to be thanks to the people who have contributed with their time and knowledge. Especially thanks to everyone who participated in the interview study and for sharing your insights about the biogas sector in Sweden. I also want to direct my gratitude to RISE for taking me onboard for this project and welcoming me in the workspace. Thanks to Johanna Olsson, Carina Gunnarsson and Mats Edström for your valuable input. A special thanks to Filip Pajalic for proofreading and the support during this semester.

Stephanie Fjäll
Lund, June 2022

List of abbreviations

Abbreviation	Definition
BMP	Biochemical methane potential
C/N	Carbon/nitrogen
CD	Co-digestion
CSTR	Continuously stirred tank reactor
EROI	Energy return of investment
FB	Farm-based
HRT	Hydraulic retention time
HTL	Hydrothermal liquefaction
ILUC	Indirect land-use change
LBG	Liquefied biogas
MSFW	Municipal solid food waste
OLR	Organic loading rate
RISE	Research institute of Sweden
RVG	Region Västra Götaland
TS	Total solids in percentage
VS	Volatile solids in percentage
Ww	Wet weight in ton fresh matter
WWTP	Wastewater treatment plants

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1 Introduction

Biogas, the future, or an intermediate step? The transition from fossil resources is a must in a warming climate but the way forward is still unclear. Today, bioenergy accounts for about 10 % of the world's primary energy demand, biogas and biomethane stands for less than 3 % of the total bioenergy demand and 0.3 % of the total primary energy demand (IEA, 2020). Despite this, there are reasons to believe that energy coming from sustainable biomass extraction will become an integral part of our society. According to IEA's sustainable development scenario (SDS), more than two-thirds of the world's energy consumption will come from other sources than electricity like liquids and gases, even with a rapid growth in low-carbon electricity (IEA, 2020). Here biogas can provide a solution to decarbonise parts of the energy system where electricity cannot reach. A great illustration is in the heavy traffic sector where liquified biogas (LBG) can provide an attractive fuel that can be used today (Biogasmarknadsutredningen, 2020).

Biogas is predicted to be the fastest-growing form of bioenergy in the world to enable the transition from fossil fuels. It is produced by converting complex organic molecules through anaerobic digestion into methane and carbon dioxide which can be used as vehicle fuel and/or replace natural gas. Equally important is the nutrient rich digestate which remains from the process that can serve as an organic fertiliser. Biogas can provide a significant role in waste management and decrease potent greenhouse gases like methane and nitrous oxide from being released. It creates a local energy supply which increases the security of supply. Overall, biogas will provide a way to achieve a circular economy by utilising residues and recycling nutrients. (IEA, 2020)

Despite the numerous advantages that biogas provides, there are some obstacles facing the future expansion in the EU. Firstly, vehicles fuelled by biomethane are not classified as a 'zero- and low emission vehicle' in the EU since it is determined by a tailpipe emission that cannot exceed 50 g CO_2/km, according to the EU regulation 2017/1151. However, this fails to recognise the environmental benefits of biomethane and that it is climate neutral when using biomass from residual or waste streams. A better approach would be to consider the whole production cycle, the so-called well-to-wheel approach (EBA, 2021). This results in that electric and hydrogen fuelled vehicles are considered more sustainable and prioritised compared to biogas. This can for example be seen in Sweden by a shift from biogas driven buses to electric (Martin *et al.*, 2021). However, February 2022 marks the turning point of biogas. The response after the Russian invasion of Ukraine from the EU was to end the dependence of Russian fossil fuels. A plan was presented on May 18, 2022, called REPowerEU which sets out to increase the production of biomethane to 35 billion (b) m^3/year by 2030 (European Commission, 2022). From the current annual production of 17 bm^3 biogas and 3 bm^3 biomethane (EBA, 2022).

To achieve this is a sustainable and large volume of biomass required, which should not compete with food production. One key is to anaerobically digest residues from agriculture which today is unutilised to its full potential. However, most of the materials are difficult to digest since they contain fibres and less water, hence requiring a different process. The development of a process that can handle these biomasses in an efficient and robust way is therefore necessary. Pretreatment is one way to incorporate the material and at the same time increase its biodegradability (Abraham et al., 2020).

This study has examined this by investigating the interest and possibilities of biogas facilities in the western Sweden to develop a process that can facilitate the usage of untapped potential in the agriculture sector. By bridging the gap between research and commercialization of pretreatment of fibrous biomass.

1.1 Project description

This master thesis is part of a project with Research institute of Sweden (RISE) that deals with agricultural-based biorefinery in Region Västra Götaland (RVG), where biogas is an important component. The background to the project was to the potential of residual streams from agriculture in RVG. Interviews of biogas plants was performed to see what capacity, opportunity, and need/interest there is to realise this. Furthermore, the number of biogas plants that digest residual streams in RVG has been inventoried and the volume that is being digested today was investigated. Based on this, a commercial strategy for established biogas producers was designed to take advantage of unused residual streams in agriculture. The bigger picture of the project is to show that the fibrous digestate from the anaerobic digestion can provide a feedstock to a potential large-scale biorefinery in RVG.

1.2 Aim

The aim of this master thesis was to study how Swedish agriculture can function as a large-scale supplier of biogas through a sustainable extraction of biomass to increase the biogas production. The goal was to map biogas plants in the RVG and their opportunities and interest in anaerobically digesting more difficult substrates from agriculture by introducing mechanical pretreatment to the process.

1.2.1 Research questions

Q1. Which residual streams in agriculture in RVG has the most potential to be incorporated into the biogas production and how do they affect the process?

Q2. How can a commercial biogas process be designed for residues in agriculture in terms of equipment, energy usage and economic aspects?

Q3. What is the existing capacity, potential expansion, and interest for a biogas plant in RVG to utilise residual streams in agriculture?

1.3 Scope

This thesis will cover biogas substrates from agricultural residues and will exclude substrates coming from forestry, wastewater treatment plants and municipal organic solid waste. The biogas plants that will be investigated are mostly located in RVG except for two facilities. The biogas process will only cover the production, thus the upgrade to bio-methane and the end-use are not covered in this investigation. Furthermore, the focus will be on commercial biogas plants and not lab-scale or pilot facilities. The implementation of mechanical pretreatment will focus on the energy demand, and this will be compared with increased methane yield. Factors such as stirring, heating of the material, the viscosity, and the increased rate of degradation are not included.

1.4 Disposition

Chapter 2 is the starting point and describes the research projects at RISE of which this thesis is a part of. Background knowledge about the biogas production, agricultural residues and different pretreatment techniques is included. In addition, an overview of the biogas production in Sweden and Region Västra Götaland (RVG) is provided.

Chapter 3 presents the methodology. It includes the choice of methods and explains how the potential calculations, energy and economic analysis were performed. In addition, how the interview study was designed.

Chapter 4 contains a literature review about the agricultural residues and mechanical pretreatments on which the results are based. It includes key values and how assumptions were made

Chapter 5 illustrates the results that the thesis arrived at. The potential of agricultural residues in RVG is first presented. Then the answers from the biogas plants from the interview study. Lastly, the analysis of introducing fibrous residues in RVG by the implementation of mechanical pretreatment.

Chapter 6 and 7 discusses and draws conclusions of the results to provide a deeper understanding and highlight the important findings.

2 Background

Sustainable extraction of biomass is a prerequisite for a successful biogas production. Biomass is considered sustainable when it does not compete with food for agricultural land or pose a threat for the ecosystems, such as deforestation (IEA, 2020). Sustainable biomass with the most potential consists of different kinds of organic waste and residues from agriculture, municipal solid food waste, industrial food waste and municipal wastewater sludge (IEA, 2020). Previously energy crops were used to a great extent in European countries. However, this has been criticised due to the intensive cultivation and competition with food production. The European Union has established legislative actions in the Renewable Energy Directive, Directive (EU) 2018/2001 (REDII). It addresses emissions linked to indirect land-use change (ILUC) which has the purpose of regulating what type of substrate should be used for producing biofuels. First-generation biofuels from food crops can only count for 7 % according to RED II. Instead, biomass that has no or low indirect land use/emissions should be utilised (European Parliament and of the Council 2018/2001). Biogas producers using energy crops have since 2016 not been granted tax exemption in Sweden. As a consequence the use of energy crops in biogas production has been minimised (Swedish Energy Agency, 2016). The second-generation biofuels will incorporate more lignocellulosic biomass, primarily coming from agriculture, enabling more biomass to be available (Abraham *et al.*, 2020).

Biogas can be produced via anaerobic digestion or biomass gasification. Anaerobic digestion is a biochemical process where microorganisms decompose organic matter in the absence of oxygen. The process has a low energy demand of heat and electricity. It produces biogas containing 50-80 % methane, 30-50 % carbon dioxide and trace compounds like water, hydrogen sulphide and ammonia (Lora Grando *et al.*, 2017; Aryal *et al.*, 2018). The biogas must be upgraded to pure methane to be used as a vehicle fuel known as biomethane. Carbon dioxide and trace compounds are removed to achieve a purity of at least 95 vol.% biomethane. The most common techniques include water scrubbing, pressure swing adsorption and chemical absorption (Li *et al.*, 2015). Liquefied biogas (LBG) can be produced by exposing the purified gas for cryogenic or low-temperature conditions to condense the methane to a liquid, about -160°C for 1 atm. LBG is beneficial for heavy transport travelling far since it is more energy dense compared to compressed biomethane (Pellegrini *et al.*, 2018). Gasification is another technique to produce biomethane from biomass which utilises heat with controlled temperatures (>700°C) and oxygen levels. The advantage of the process is the ability to produce biomethane on a large scale. However, it has a lower overall efficiency and a more complex process compared to the anaerobic digestion (Li *et al.*, 2015). At present there are no gasification facilities in operation in Sweden (Swedish Gas Association, 2021).

This thesis will mostly focus on biogas production from anaerobic digestion in the Region Västra Götaland (RVG) with biomass coming from residual and side-stream flows from agriculture. Biogas facilities in RVG and two adjacent areas will be investigated to perceive how substrates from agriculture can be incorporated in their current process by introducing a pretreatment step.

2.1 Biorefinery concept

Agricultural biomass such as manure, straw, catch crops and ley crops that can be used to produce biofuels have a high content of lignocellulose. The biodegradability of lignocellulosic rich materials to carbon is low, it is about 40 % for cattle slurry and straw and about 60 % for ley crops. The lignin is not degraded during anaerobic digestion and surrounds the cellulose fibres, which also prevents the degradation of cellulose and hemicellulose. By releasing the cellulose fibres in the biogas process a digestate will be generated which is enriched with lignin. There is a possibility of generating a decentralised biorefinery by utilising the dewatered digestate from local biogas plants as a feedstock to produce bio-oil in a hydrothermal liquefaction (HTL) plant, as shown in Figure 1. (Olsson *et al.*, 2021)

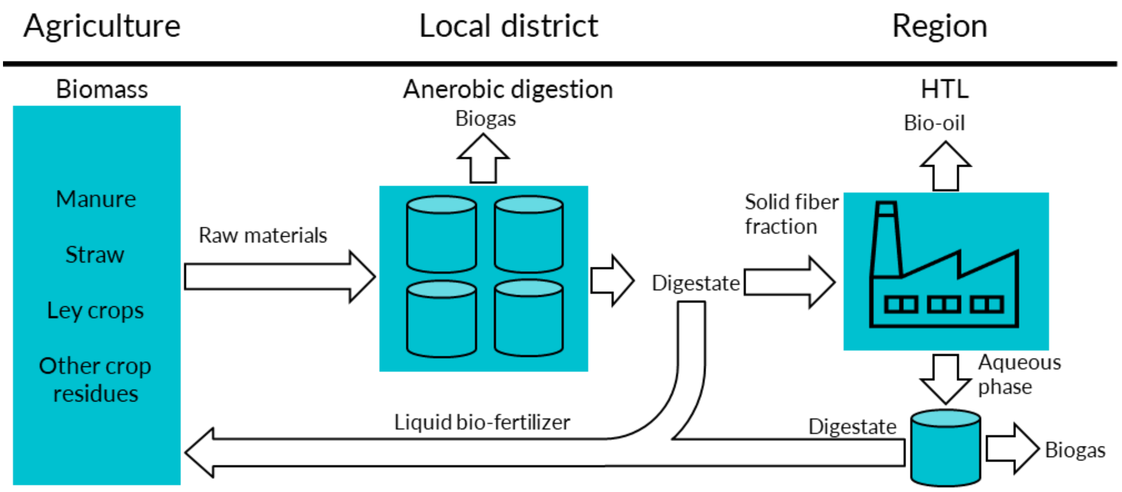

Figure 1. Biorefinery concept from the agricultural sector to local districts and regional level.

The HTL process consists of high temperatures and pressures (250-370°C, 5-25 MPa) which enables a conversion of solid material into a major liquid bio-oil fraction and a minor solid biochar fraction. Additionally, a gas fraction consisting of carbon dioxide and an aqueous fraction consisting of water and soluble compounds. Bio-oil is energy rich and can be upgraded to crude oil in a refinery. Large volumes of an aqueous phase are generated in the HTL process (25-50 % of TS) which must be treated (Baky and Ahlgren, 2020). This can be done by anaerobic digestion to produce biogas and return the residual nutrients to the arable lands if it meets the certification rules of a bio-fertilizer like SPCR 120 (Avfall Sverige, 2021). Creating a closed loop, see Figure 1. However, one concern is that potential inhibitors can be produced in the HTL process (Ramasamy *et al.*, 2021).

More energy can be utilised from lignocellulosic biomass by pre-treating it with anaerobic digestion and further processing in a HTL plant. The large scale means that substrates with a high water content such as manure that are unfit to transport over long distances can be digested in local biogas plants. Biogas can complement large scale processes such as ethanol and bio-oil via HTL. Since it can operate at a smaller scale and therefore provide local processing of feedstocks that are expensive to transport like manure. A screw press can be used to dewater the digestate from local anaerobic digestion plants and generate a solid fibre fraction which can be transported to a HTL plant. The liquid fraction containing water soluble nutrients can be returned to arable lands and used as biofertilizer (Olsson *et al.*, 2021).

The benefit of this concept is an incentive to better utilise fibre rich biomasses and residues from agriculture by making the digestate a valuable product. This will result in an increased utilisation of agricultural biomass by improving the value chain and create a more sustainable crop cultivation by the utilising of ley crops. In addition, generate a flexible supply of feedstock to large-scale biorefineries. The goal of the biorefinery project is to provide solutions for a fossil-free society by making it viable to produce biofuels from manure and residual streams from agriculture and increase robustness for energy Sweden's energy supply (Olsson *et al.*, 2021). Henceforth, this thesis will focus on the anaerobic digestion that has the potential of delivering feedstock in the form of a solid fibre fraction to a HTL facility.

2.2 Biogas production by anaerobic digestion

The anaerobic digestion process is mainly affected by three factors, the substrate, the biochemical microbial process, and the operating conditions of the biogas reactor.

2.2.1 Substrate properties

The most suitable substrate for biogas production includes agricultural residues such as manure and crop residues, municipal organic food waste, slaughter waste, wastewater and residues from the food industry (Bharathiraja *et al.*, 2018). Substrates can be characterised according to some important parameters. One important parameter is the total solids (TS) which are defined as the material left after 15-20 hours in 105°C and is important for the processability and energy content (Bohman *et al.*, 2011). In addition, the contents of volatile solids (VS) can estimate the organic matter from the TS (Björnsson *et al.*, 2014). VS is the combustible part of the biomass and is defined as the dry material present after 2 hours in 550 °C excluding the ashes (Bohman *et al.*, 2011). The VS content is what can be anaerobically digested and contribute to the biogas yield. A high VS content generally gives high biogas yields, however not for lignin rich substrates (Carlsson and Uldal, 2009). Particle size is another important parameter. It should be sufficiently small to provide an available surface area for the hydrolysing enzymes. This is particularly important for plant fibres (Bharathiraja *et al.*, 2018). The potential methane yield can be expressed with the biochemical methane potential (BMP). The biodegradability of a substrate is defined as the ratio of the experimental and the theoretical maximum methane yield, see section 4.2 (Nwokolo *et al.*, 2020).

The properties of substrates are an important aspect for the biogas process as the anaerobic digestion is quite a sensitive process. The main building blocks of all substrates are carbohydrates, lipids and proteins, seen in Table 1. Substrates rich in lipids have a higher methane potential (see Table 1) but the degradation can lead to high levels of long-chain fatty acids which can cause foaming problems in the reactor (Schnürer and Jarvis, 2017). In addition, overloading of lipids releases volatile fatty acids (VFAs) that can cause a drop in the pH. The optimal pH in the digester is 6.8 and 7.5, a pH lower than that will result in a poor biogas yield due to inhibiting the methanogenic phase (see Figure 2) (Drosg *et al.*, 2013). Protein rich substrate has a great methane potential, see Table 1. The degradation releases ammonium which can help increase the alkalinity and increase the nutritional values in the digestate. High ammonium concentration can inhibit the methanogens due to a shift from ammonium to ammonia, which occurs around an ammonium concentration of 53-1450 mg/ml. But studies have shown that the microbial community can acclimate to higher ammonia concentrations and still produce biogas effectively (Nwokolo *et al.*, 2020). The carbon nitrogen (C/N) ratio can be used to ensure the balance of protein and carbohydrates. The optimum is around 25 and a value below 15 can cause ammonia accumulation. A high C/N value is the result of having a high carbon concentration. If the reactor is overloaded with easily degradable carbohydrates, accumulations of VFAs can arise. Complex compounds like cellulose, proteins or fats are hydrolysed more slowly, within several days compared to a few hours for soluble carbohydrates (see Figure 2) (Bharathiraja *et al.*, 2018).

Table 1. Methane yield and biogas composition of organic compounds (Nwokolo *et al.*, 2020)

Organic compound	Methane yield CH_4 m^3/kg VS	CH_4 %	CO_2 %
Carbohydrate	0.42	50	50
Protein	0.50	50	50
Lipid	1.01	70	30

2.2.2 Biochemistry of biogas

The substrate in the biogas process is broken down in series with the presences of different archaeal-bacterial consortia which utilises each other's decomposition products shown in Figure 2 (Aryal *et al.*, 2018).

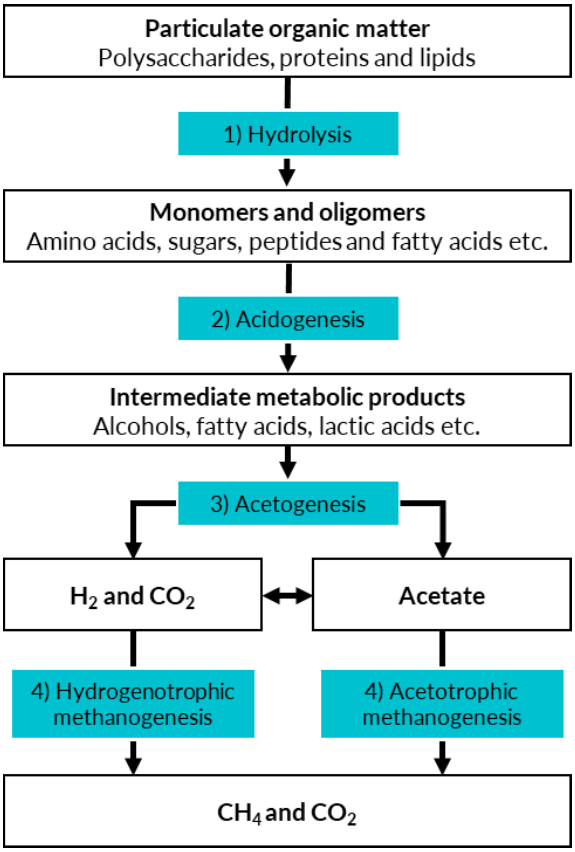

Figure 2. The biochemical process of anaerobic digestion

Hydrolysis is the first phase where complex insoluble organic materials such as lipids, carbohydrates, nucleic acid and proteins are hydrolysed by the use of extracellular enzymes to simple sugars, fatty acids and amino acids. To facilitate uptake of energy and nutrients into the cell (Bharathiraja *et al.*, 2018). Most of the hydrolytic bacteria are strict anaerobes and some are facultative anaerobes. In the second phase called acidogenesis are the previous products used as substrates by the microorganisms, many of them hydrolytic bacteria present in the previous phase (Jarvis and Schnürer, 2017; Bharathiraja *et al.*, 2018). The acidogenesis results in different decomposition products mainly consisting of volatile organic acids, alcohols, ammonia, carbon dioxide and hydrogen (Schnürer and Jarvis, 2017).

The third phase is acetogenesis, which consists of various anaerobic oxidation reactions where organic acids, alcohol and some amino acids are converted to acetate, carbon dioxide and hydrogen by acetogens, see Figure 2 (Jarvis and Schnürer, 2010). The main regulator of this phase is increased partial pressure of hydrogen since this inhibits the acetogens. The hydrogen is removed in the final methanogenesis phase, (Bharathiraja *et al.*, 2018). The continuous removal of hydrogen gas is performed by methanogens belonging to the archaea domain, which are the microorganisms generating the methane and carbon dioxide (Jarvis and Schnürer, 2010; Bharathiraja *et al.*, 2018). The two most common groups include the dominating acetotrophic group which degrades acetate into methane and carbon dioxide. The second group is the hydrogenotrophic group which degrades hydrogen and carbon dioxide to methane. The methanogens grow more slowly compared to the other microorganisms making this the rate-limiting phase. They are also the most sensitive for environmental disturbances (Schnürer and Jarvis, 2017).

2.2.3 Biogas plant

2.2.3.1 Biogas reactor types

The process design of the biogas production is initiated by the choice of a dry or wet anaerobic digestion. This choice is mainly influenced by the properties of the substrate. Dry digestion is suitable for substrates with TS content between 20-35 % and wet digestion can be applied for TS contents between 5-15 %. Wet digestion is often performed with substrates such as wastewater sludge, food residues and manure. Dry digestion can be an option for substrates such as solid manure, residues from agriculture and organic solid food waste. The addition of liquid can be necessary for both operations to keep an optimal TS content in the reactor. This can be done by adding fresh water, liquid substrates or returning part of the liquid digestate phase. Adding digestate can increase the biodegradability but there is a risk of accumulating inert organic matter and/or inhibiting substances and also affecting the pH. (Schnürer and Jarvis, 2017)

The wet or dry digestion can be performed with various configurations of reactor and operation modes. This includes continuous, semi-continuous or batch operation using either continuously stirred tank reactor (CSTR), plug flow reactor (PFR) or batch reactor (Murphy and Thamsiriroj, 2013). See Figure 3 for a summary of different configurations. Continuous operation can be used for wet digestion using a CSTR where substrates with TS content below 5 % are continuously pumped into the digester. But it can also be used for dry substrates using a PFR where the substrate is pushed forward with a screw or rotating baffles. Semi-continuous operation for wet digestion most commonly uses a CSTR which is fed 1-12 times a day with a TS content between 5-15 %. Semi-and/or continuous operation provides an even supply of substrates to the microorganism and biogas production. On the contrary, a batch reactor is only fed once and remains throughout the process likewise the digestate. The gas production is generally the greatest in the beginning and subsides with time, but several reactors can be initiated at different times to get an even gas supply. Batch operation provides the microorganism with more time to break down the organic content and does not pose the risk of being flushed out. Batch reactors are commonly used for dry digestion using crops or residues from agriculture. It can also be used to digest slaughter waste or such like in thermophilic as a hygienic procedure (Schnürer and Jarvis, 2017).

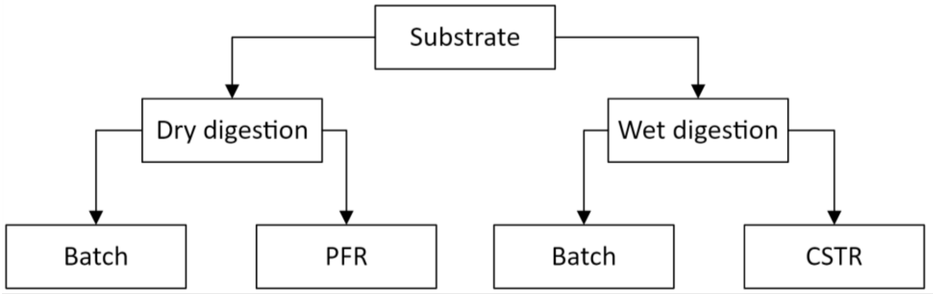

Figure 3. Summary of the reactor types for biogas production

The most common mode of operation in Sweden is wet digestion using CSTR with a semi-continuous feeding of the substrate to the reactor. However, batch reactors with dry digestion are common in other European countries like Germany (Schnürer and Jarvis, 2017). The wet CSTR reactor has the advantages of being easy to operate, simple design, a mature technology and low capital cost (Nizami and Murphy, 2010). The drawback is that the mixing and diluting of feedstock makes it energy and water intensive (Fu and Hu, 2016). In addition, it may not be the best option for high solids loading using lignocellulosic substrates such as agriculture residues. Materials with high TS content over 10-15 % often need to be diluted to work with the feeding system, pumps, and agitators (Carlsson and Uldal, 2009). On the contrary, dry digestion operates with a higher TS content, around 20-35 %. This requires less amount of fluid, smaller dimensions of pipes and pumps as well as a lower energy demand. Storage and transportation of substrates are more efficient due to the water content being less. Foaming and floating layers can also be avoided. The disadvantage is that it can be difficult to achieve a high and even digestion of all the material in the reactor, especially for high TS contents, over 35 % TS (Schnürer and Jarvis, 2017).

At the end of the anaerobic digestion is the digestate most commonly stored in a second covered post-digestion tank, ensuring that no greenhouse gases are released. In addition, many plants collect biogas from the second chamber to increase the methane yield (Schnürer and Jarvis, 2017). Furthermore, the digestate can be dewatered, most commonly using a screw press, where a solid content of 20 % can be achieved. The removal of excessive water makes transportation more economical. The digestate can be used as a fertiliser on arable lands. The composition is about 75 % phosphorus, 30 % of total nitrogen and 12.5 % of potassium in the solid fraction (Andersen *et al.*, 2022).

2.2.3.2 Biogas process design

The design of the chosen reactor starts with an oxygen-free closed tank. This often is built from reinforced concrete and steel, equipped with insulation material and heating pipes inside the walls. The digester volume is characterised by two factors which are the organic loading rate (OLR) and the hydraulic retention time (HRT). OLR is defined in equation 1 and illustrates the amount of VS introduced into the digester each day. OLR should be around 2 to 5 kg VS/day m^3 for CSTR and up to 10 kg VS/day m^3 for PFR. The HRT refers to the theoretical residence time substrate stay in the digester and it is expressed as days seen in equation 2. (Bachmann, 2013)

$$OLR\ \frac{kg\ VS}{m^3\ day} = \frac{Substrate\ input\,\frac{kg}{day} \cdot TS \cdot VS}{Digester\ volume\ m^3} \tag{1}$$

$$HRT\ days = \frac{Net\ digester\ volume\ m^3}{Substrate\ input\,\frac{m^3}{day}} \tag{2}$$

The substrate can enter the reactor in different ways depending on the substrate and reactor type, but mostly through a screw conveyor feeding system (Andersen *et al.*, 2022). Agitation inside the reactor is needed to distribute the substrate, microorganisms, heat and for removing gas bubbles. The most common techniques are mechanical, hydraulic and pneumatic agitation. All techniques are applicable for wet digestion reactors. Hydraulic agitation requires pumpable and liquid substrates and can therefore not be applied to dry digestion (Bachmann, 2013). The electric demand is normally around 7 % of the energy produced and is utilised through pumping, mixing and pretreatments. The heating demand is about 3 % of the energy produced and increases with higher moisture contents (Murphy and Thamsiriroj, 2013). The biogas produced is collected at the top of the tank and the digestate is removed by pumping it through an overflow pipe (Schnürer and Jarvis, 2017).

External heating is required to reach an optimal temperature for the growth of the microorganism. There are two established temperature ranges, mesophilic with temperatures ranging from 30°C to 40°C and thermophilic with temperatures from 50°C to 60°C. The mesophilic range is the most commonly used in Sweden, since it has a moderate energy demand and acceptable retention times (Swedish Gas Association, 2021). The thermophilic range is mainly used for substrates with a hygiene risk such as manure, food waste and slaughter waste (Bachmann, 2013). The advantage with the thermophilic condition is a more active digestion, 25-50 % compared to the mesophilic. Resulting in a faster process but the disadvantage is a more sensitive process more prone to destabilise. Sanitation treatment can be done prior to entering the reactor for mesophilic conditions. This generally consists of heating of the material to 70°C for one hour (Schnürer and Jarvis, 2017).

2.2.3.3 Co-digestion

Another measure of utilising agricultural residues is co-digestion which is how most of the biogas in Sweden is produced (Swedish Gas Association, 2021). This method consists of creating a blend of different substrates which fulfil the microorganism requirements (Berglund Odhner *et al.*, 2012). Lignocellulosic biomass with a high C/N ratio can be co-digested with substrates with a low C/N ratio like slaughter waste and manure to maintain an optimum C/N ratio and increase the stability (Abraham *et al.*, 2020). Trials have shown the positive effects of balancing the C/N ratio using manure and wheat straw. The studies concluded that the positive effect originated from balance in nutrients and carbon and better regulation of the microorganisms consortium in the reactor (Victorin *et al.*, 2019). Other benefits are increased methane yield resulting from the increased loading of readily biodegradable organics, an improved nutrient balance and a balanced water content (Zhao *et al.*, 2018). The main advantage is a low cost, but it requires consistent supply of different types of substrates (Berglund Odhner *et al.*, 2012).

2.3 Agricultural residues

The agriculture sector has a great potential of contributing with substrates to the biogas production in Sweden (Börjesson, 2016). The residues can be classified into two broad categories, manure and crop residues. The anaerobic digestion of manure is being performed at a large scale today. Whereas crop residues and especially lignocellulosic biomass are not commonly used in Sweden today (Swedish Gas Association, 2021).

2.3.1 Manure

Manure can be collected by different kinds of animals like cattle, pigs, sheep, horses, and poultry. Manure can be categorised as liquid manure or slurry, solid manure, and deep litter manure. Slurry is liquid manure and today cattle slurry is the most commonly used agriculture residue as it is highly suitable for wet digestion (Swedish Gas Association, 2021). Solid manure and manure containing large amounts of bedding material known as deep litter manure are drier. They have TS contents of around 25 % and 35 % respectively, compared to slurry that have around 8 % (Schnürer and Jarvis, 2017). In 2020 was 1 203 000 ton wet weight (ww) of manure used to produce biogas in Sweden which is about 9 % of the total substrate amount digested each year. Compared to 2019 the amount increased by 5 % (Swedish Gas Association, 2021). However, only 5% of the total potential is utilised meaning that there is great potential to increase the biogas production from manure (Olsson *et al.*, 2021). The environmental benefits of digesting manure besides decreasing the reliance of fossil fuels includes reduction of methane and nitrous oxide emissions compared to untreated manure (Tufvesson *et al.*, 2013). Additionally, manure contains high concentrations of nitrogen and phosphorus making the digestate favourable to use as a biofertilizer (Nwokolo *et al.*, 2020). The digested manure can obtain a higher proportion of plant-available nitrogen, ammonium, making it more effective and reducing the risk for nitrogen leakage.

Manure can be used as a substrate in biogas production continuously year round with the exception of decreasing for some animals during the grazing period (Björnsson and Lantz, 2011). The characteristic of manure depends on the management system, diet, digestive system, and location of the animal. Resulting in that the methane yield of manure varies significantly worldwide (Nwokolo *et al.*, 2020). The main component of manure is carbohydrates and there is a slightly higher proportion of protein compared to fat. Poultry and pig manure contains more protein compared to cattle and horses which can give higher methane potentials but also ammonia inhibiting effects (Schnürer and Jarvis, 2017). Manure is an advantageous substrate due to its balanced composition giving the process more stability and contributing with an increased alkalinity. Manure generally has a low TS content making transportations for long distances economically unfeasible. Local and farm-based biogas plants are therefore a good option for biogas production of manure (Victorin *et al.*, 2019).

The anaerobic digestion of slurry is a well-established technique in CSTR but is relatively energy-poor as a substrate and expensive to transport (Edström *et al.*, 2018). The drawback to slurry is that nutrients and organic material are diluted, meaning that large volumes are needed even though it may be well balanced. It is therefore beneficial to co-digest slurry with dry and/or energy dense substrate in order to increase the OLR without risking a wash-out of the microorganism. On the contrary, slurry can also be used to add liquid to incorporate dry substrates in wet digestion (Schnürer and Jarvis, 2017). Solid manure is significantly more energy dense compared to slurry, thus being more cost effective to transport. Limitations of utilising it in wet digestion are the TS content and bedding material present (Jadstrand and Lingmerth, 2017). Deep litter manure is not utilised to a large extent due to the large amount of bedding material present which may contain long straws and other materials like stones and gravel. This can damage the equipment, clog pumps and pipes and cause crust formation (Edström *et al.*, 2012). Mechanical disintegration is therefore necessary to make it compatible with wet digestion processes unless straw briquettes are used as bedding material (Gunnarsson *et al.*, 2021). Manure that is digested can contain a non-degraded part which mainly consists of plant fibres and usually decrease the methane potential (Olsson *et al.*, 2021).

2.3.2 Crop residues

Crop residues generally have a high TS content. It is therefore preferable to dilute crop residues with liquid substrates or alternatively recycle the digestate to make them compatible with wet digestion. Crop residues can provide the process with a source of carbon but often lack high concentrations of trace elements which can limit the process. As a result, it is more preferable to co-digest crop residues with nutrient rich substrates. Crop residues from agriculture in Sweden with potential to supply biogas plants with substrates includes straw, discarded grass silage, ley and catch crops as well as residual streams from crop cultivation such as sugar-beet and potato tops (Björnsson *et al.*, 2014).

Straw is the crop residues with the biggest unrealized potential and is a by-product of the cultivation of cereals and oilseed crops (Olsson *et al.*, 2021). Straw does not compete with food production, instead, it increases with increased food production. The technical aspects are given by the annual harvest for each cereals or oilseed crops, the straw-to-grain ratio and recovery rates of the harvest straw, which is between 60-80 % (Weiser *et al.*, 2014). The current use of cereal straw is mainly bedding for husbandry, however a fraction of this can be available as a substrate for biogas in the form of solid and deep litter manure. A minor part is used as heating and feed and the remaining potential, including the oilseed crops are incorporated into the soil (Prade *et al.*, 2017). The potential that can be supplied to biogas production has to take the current use into account but also consider environmental constraints. These relate to soil organic matter (SOM) where a certain amount of the straw must be left on the cropland to protect the soil fertility. Such evaluations can be done by performing humus balance models (Weiser *et al.*, 2014). The advantage of utilising straw to produce biogas over other alternatives such as ethanol is that the digestate can be returned to the cropland. Since it increases SOM in the top soil and contributes to closing nutrient cycles (Andersen *et al.*, 2022).

Ley crops can also be a substantial source of biomass that can be supplied to produce biogas. It is also a lignocellulosic material and can have a lignin content of 18 % depending on type and age but has generally a lower TS content (Ammenberg and Feiz, 2017). Ley crops consists of different grasses and ley legume crops, the most common in Sweden are Timothy, english ryegrass, red and white clover, and meadow fescue (Gunnarsson and Lund, 2020). The most common application of ley crops is fodder for cattle, sheep, and horses where it is often stored by ensilaging. Lund et al. (2018) concluded that the largest potential for ley crops is unutilised silage from fodder production consisting of surplus silage and discarded silage. Ley crops and catch crops can be introduced into the crop rotation to increase the soil organic carbon (SOC). This is important since the more frequent they are sown, the more other crops and residues such as straw can be removed without having a negative long-term effect on soil fertility (Prade *et al.*, 2014). A study by Gunnarsson and Lund (2020) demonstrated that farmers are interested in sowing ley to improve the soil fertility in Sweden. But a prerequisite is that there should be a market for the crop and profitability that corresponds to the crop that was replaced. One option is as a substrate in anaerobic digestion. However, ley crops are associated with high cost during harvest, relatively long HRT and large particle sizes (Odhner *et al.*, 2015; Lund *et al.*, 2018). Other supplies of ley which can be relevant in the future if there is economic incitement, includes cultivation of ley grass on previously unused arable land, on arable land as intermediate crops or ecological focus areas (EFAs) (Prade *et al.*, 2017).

Other agricultural crop residues that potentially could supply substrate for biogas production include more easily degradable biomasses such as tops from sugar-beet and potato but also discarded crops such as potatoes and cabbage. However, these fractions are available in smaller volumes compared to straw and ley (Schnürer and Jarvis, 2017). The tops are currently mostly incorporated into the soil and have no other use (Prade *et al.*, 2017). Instead, the tops can be collected and used to produce biogas. However, this is not performed today with the reason of not being economically viable due to the high water content and that it should be used fresh (Olsson *et al.*, 2021).

2.3.2.1 Properties of lignocellulosic biomass

Crop residues that are made up of lignocellulosic biomass like straw and ley crops are the most abundant and that do not compete with food production. However, they are more resistant towards microbial breakdown (Olsson *et al.*, 2021). Firstly, lignocellulosic biomass consists of 30-50 % cellulose, 20-35 % hemicellulose and 12-25 % lignin of the total solids content. This is mainly composed of the plant's cell walls and the composition varies between plants, origin and season (Bharathiraja *et al.*, 2018; Andersen *et al.*, 2022). The lignocellulosic material is bound in microscopic structures forming single fibres that are packed together to form microfibrils, these overlap in multiple layers to form the plant cell wall (Andersen *et al.*, 2022). The fibrils have both crystalline and amorphous structures. The crystalline structure is based on hydrogen linkages which generates a greater toughness, solidity and biological degradation to the molecule (Bharathiraja *et al.*, 2018). Cellulose is the core segment of lignocellulosic materials and is made up of a linear chain of D-glucose units. It is surrounded by a hemicellulose matrix and an outer layer composed of lignin (Abraham *et al.*, 2020). Hemicellulose is a heteropolysaccharide composed of different combinations of monomers, the most common is xylan (up to 90 %) (Bharathiraja *et al.*, 2018). The amorphous structure and lower degree of polymerization of the molecule makes it more susceptible to degradation compared to cellulose. Hemicellulose functions as a matrix material between lignin and cellulose, giving the whole structure more compactness (Abraham *et al.*, 2020). Lignin is a heteropolymer, the structure is complex containing covalent bonds and phenylpropane-based units. Resulting in a compact molecule that is insoluble in water, resistant towards microbial attacks and oxidative stress (Bharathiraja *et al.*, 2018). Lignin links and fills the space between cellulose and hemicellulose, working as a physical barrier against biological decomposition (Abraham *et al.*, 2020).

The complex structure must be separated into its three components to enable the microorganism to degrade lignocellulosic material. The hydrolysis can then take place and divide the hemicellulose and cellulose into oligomeric or monomeric sugar molecules and subsequently biogas will be produced (Streffer, 2014). The limiting factor in biodegradability is the lignin content due to its persistence towards microbial degradation and binding effects of the cellulose and hemicellulose. Therefore, the highest methane yields come from substrates with low contents of lignin (Nwokolo *et al.*, 2020). Pretreatment techniques that benefit biogas production the most are those that remove or reduce lignin content and reduce the cellulose crystallinity (Ma *et al.*, 2019).

2.4 Pretreatment in biogas production

Unused substrates from the agriculture sector with great potential often contain lignocellulose which degrades more slowly. Generally, there are three important objectives of performing pretreatments with the first being to increase the biological degradability of the substrate in order to increase the methane yield (Berglund Odhner *et al.*, 2012). Secondly, decrease the HRT in the reactor, meaning that the digestion rate is increased, more substrates can be added by increasing the OLR (Abraham *et al.*, 2020). The third objective is equally as important, and that is to enhance the processability of the substrate by facilitating the feeding, increasing homogeneity, decreasing foaming and crust formation (Björnsson *et al.*, 2014).

Commercial pretreatments will be introduced to discuss the benefits and drawbacks and motivate the choice of mechanical pretreatment. Pretreatments that are excluded are not economically viable and/or not available for large-scale operations. This includes gamma-ray/electron-beam/microwave irradiation, ionic liquids, ultrasound, application of enzymes, microorganism or fungi (Taherzadeh and Karimi, 2008; Berglund Odhner *et al.*, 2012; Bochmann and Montgomery, 2013; Schumacher *et al.*, 2014).

2.4.1.1 Chemical pretreatments

The chemical pretreatments consist mainly of oxidative treatments and the addition of acids or alkalis and can be performed at ambient temperature or elevated temperatures. The chemical pretreatments objectives are to increase the biodegradability of the substrate by decrystallisation and breaking down lignocellulosic compounds (Abraham *et al.*, 2020). Alkaline treatment is the most common. It works by removing acetate groups from hemicellulose and partly solubilizing lignin, resulting in degradation of the lignocellulose structure and increased accessibility for microorganisms (Bochmann and Montgomery, 2013). Acid hydrolysis is also an effective pretreatment, the addition of dilute acids causes the hemicellulose to break down into monomeric sugars and soluble oligomers. Resulting in an increased porosity of the material. However, the lignin is not significantly affected (Berglund Odhner *et al.*, 2012). The main disadvantage with the acid hydrolysis is the formation of inhibitory and toxic compounds and having a pH ranging from 1.5-5 (Björnsson *et al.*, 2014). Consequently, between the acid and alkali treatment is the alkali better suited for anaerobic digestion. The chemical pretreatments are the most effective in increasing the methane yield without having a high energy demand, but they are often not economically attractive due to the high cost of chemicals and the recovery and/or treatment of the liquid effluent (Schumacher *et al.*, 2014).

2.4.1.2 Thermal pretreatments

Thermal pretreatments were one of the first pretreatments performed, and it is used in large-scale operation in some countries (Carlsson *et al.*, 2012). The objective of the pretreatment is to facilitate the biological degradation of lignocellulose by solubilization and depolymerization. A classification of low temperature (<100 °C) and high temperature (>100 °C) can be done (Carlsson *et al.*, 2012). Hemicellulose solubilizes first at 150-180°C followed by the lignin. The temperature should be kept under 250°C to decrease the formation of inhibitory products such as phenolic and heterocyclic compounds (Berglund Odhner *et al.*, 2012). High temperature pretreatments are often performed by steam injection, known as steam explosion, where the biomass is heated in water under high pressures. The pressure is released quickly in a flash tank that ruptures the lignocellulosic structure (Berglund Odhner *et al.*, 2012). The steam explosion causes 80-100 % of the hemicellulose fraction to be solubilized and achieve depolymerization for some parts of the cellulose and lignin (Berglund Odhner *et al.*, 2012). Thermal pretreatment may be enhanced by the addition of acids or alkalis. The disadvantage of thermal pretreatment is that they are energy intensive and require a lot of heat as well as forming refractory and inhibitory compounds (Carlsson *et al.*, 2012).

2.4.1.3 Mechanical pretreatments

Mechanical pretreatments are of great interest to treat substrates with large particle sizes such as agricultural residues (Bochmann and Montgomery, 2013). The most common mechanical pretreatments techniques are grinding, milling and extrusion, the choice depends on the moisture content of the lignocellulosic substrate (Abraham *et al.*, 2020). The objective is to enhance the digestibility by increasing the surface area for the enzyme degradation and increase the processability of the substrate by decreasing flotation, making feeding and mixing easier (Björnsson *et al.*, 2014; Abraham *et al.*, 2020). Extrusion is a combination of mechanical and thermal principles (Montgomery and Bochmann, 2014). The most common techniques are hammer mills and knife mills. The advantage of milling is that it can add dry fibrous biomass into a continuous digestion process without causing additional wear on the equipment (Søndergaard *et al.*, 2015). The advantage of mechanical pretreatment is that no effluent or inhibitors are produced (Schumacher *et al.*, 2014). The main drawback is a high energy demand making the process costly and solid materials such as stones can damage the equipment (Bochmann and Montgomery, 2013). The methane yield obtained by this method is also lower compared to the chemical pretreatments (Schumacher *et al.*, 2014).

2.4.1.4 Comparison between pretreatments

A comparison performed on wheat straw utilising alkali hydrolysis, steam explosion and hammer mill concluded that the alkaline provided the plant with the most methane, but that the hammer mill produced the most revenue. The payback period (PBP) for plant sizes between 5-0.5 MW was 4.6-8 years for the hammer mill and 9.6-37 years for alkaline impregnation. The 0.5 MW biogas plant could not be paid back for the steam explosion but the PBP for 5-1 MW plant sizes was 19.7-43 years (Andersen *et al.*, 2022). Continuing this thesis will only cover mechanical pretreatment since the technique is readily available, commercial and the most economically viable.

2.5 Biogas production in Sweden

Energigas Sverige is a gas association which releases a government issued statistical survey about the production and use of biogas in Sweden (Swedish Gas Association, 2021). The survey performed in 2020 concluded that 2.2 TWh of biogas was produced and that 4 TWh was consumed. Denmark stood for 90 % of the import and the rest from other EU countries. The majority of the produced biogas, 1.4 TWh, is upgraded to fuel for vehicles or transported to the gas grid. Other applications include heating, industrial usage and electricity (Swedish Gas Association, 2021). In comparison, the total energy supply in Sweden was 548 TWh in 2019, where the transport sector accounted for 83 TWh (Swedish Energy Agency, 2022). One major application of biogas can be to replace the demand of imported natural gas. For example, 1.7 TWh/year of natural gas is used to produce mineral fertilisers whereas 2.3 TWh/year is used to fuel the agricultural sector's machines (Olsson *et al.*, 2021).

Around half of the biogas, 1.1 TWh, is produced by co-digestion plants, a third is produced on wastewater treatment plants (WWTP) and the remaining is produced by farm-based plants, industrial plants, and landfills (Swedish Gas Association, 2021). When producing more than 3 GWh/year are the biogas plants in Sweden subject to seek a permit from the county administrative boards, according to the Act (2010:1011) on flammable and explosive goods (LBE) (MSB, 2013). The substrate used to produce the biogas from the different facilities are mainly sewage sludge, municipal solid food waste (MSFW), slurry, slaughter waste and waste from the food industry. In 2020 3 million tonnes wet weight (ww) digestate was produced and 87 % was used as fertiliser.

The biogas interest in Sweden is big and there are several initiatives and aids for producing biogas. A gas-manure aid was introduced in 2015 and was previously set to end 2023 but it was extended in March 2022 to be available until 2040 (Swedish Board of Agriculture, 2021a; Government, 2022). Production of methane gas will be given an aid of maximum 0.30 SEK/kWh and the production of LBG can receive an additional 0.15 SEK/kWh (Government, 2022). In comparison, the selling price for biomethane is around 2.3 SEK/kWh and 2.2 SEK/kWh for LBG (St1 Biogas, 2022; Gasum, 2022). However, due to the previous lack of long-term policy instruments, the potential of digesting manure has largely been unrealized and big investment has not been made (Swedish Gas Association, 2021).

An investigation to increase biogas production and utilisation was released in 2019 called *Biogasutredning* (SOU 2019:63). The investigation presented a thorough examination on topics including environmental benefits and usability of biogas, national policies, increasing the biogas production and a comparison of EU countries. The investigation proposed two support packages and a quantitative goal of producing 10 TWh of biogas in Sweden 2030, with 7 TWh from anaerobic digestion (Biogasmarknadsutredningen, 2019). The first support package was released in the Swedish government budget 2022 with 500 million SEK and 700 million SEK for 2023 respectively 2024 (Committee on the Environment and Agriculture, 2021). However, the investigation states that around half of the proposed projects that apply for financial support are cancelled. The main reasons are a complex and long process of seeking environmental permits and immature technology. One solution mentioned is to gather the application process to two county administrative boards to concentrate the expertise in the field and make the handling more efficient and uniform (Biogasmarknadsutredningen, 2019).

ILUC-free biomass from agriculture will play a vital role in achieving the goal of 7 TWh/year by 2030 according to the investigation (Biogasmarknadsutredningen, 2020). Agricultural biomass is used to produce around 1 TWh/year of biogas with the majority (95%) coming from co-digestion and the rest from farm-based biogas plants (Swedish Gas Association, 2021). The production of biogas from ILUC-free biomass will dominate since it is excluded from the carbon and energy tax and ensure that non-food/feed crops are used (Government, 2020).

2.5.1 Biogas production in Region Västra Götaland

In 2020 was 300 GWh of biogas produced in RVG with its 45 facilities (Swedish Gas Association, 2021). RVG is connected to the European gas grid making it advantageous to distribute produced biogas. This also creates a different biogas market where it is affected by inexpensive imported biogas (Biogasmarknadsutredningen, 2019). An initiative was set for the period 2017-2020 to encourage the use and production of biogas in RVG called *Kraftsamling biogas*. The aim was to set goals and focus for the environmental committee's investments within the field of biogas. One target was to reach a biogas production of 2.4 TWh/year in 2020 with 1.2 TWh/year coming from anaerobic digestion. However, this goal was not met and instead the biogas production has decreased by 50 GWh since 2015. Goals were also set to increase the awareness of the benefits of biogas, competitiveness and the use of biogas in the public sector and heavy vehicles. Ways of achieving these goals were to introduce a common platform for collaboration and exchange of knowledge called *Biogas Väst*. But also cooperate with other regions in Sweden and fund regional biogas developments (RVG Environmental Committee, 2016).

RVG and the south of Sweden are the regions with the greatest potential of producing biogas especially from agricultural residues (RVG Environmental Committee, 2016). RVG has a large agricultural sector with 22 % of the land area consisting of agricultural land with both crop production and large areas dominated by animal farms (Olsson *et al.*, 2021). Manure is the most commonly used biogas substrate from agriculture (Olsson *et al.*, 2021). The livestock with the greatest biogas potential includes cattle, pigs, poultry and horses (Swedish Board of Agriculture, 2021b). In 2021 the gas-manure aid was distributed to 11 farm-based plants and 3 co-digestion plants according to correspondence with the Swedish Board of agriculture [1]. In addition, RVG has substantial crop cultivation and holds 18 % of arable land and 14% of pasture-and meadow area of Sweden's total agricultural area (Swedish Board of Agriculture, 2021b). Cereals, and pasture lands have the greatest fraction of the arable land in RVG with 44 % and 39 % respectively. These fractions generate significant amounts of residues that can be used to produce biogas. Additional crops with biogas potential in RVG are straw from rapeseed crops and residual streams from potatoes and peas (Swedish Board of Agriculture, 2021b).

[1] M. Johansson, Swedish Board of Agriculture, email correspondence on the 8th of February 2022.

3 Methodology

3.1 Theory of Agricultural residues

The theory section aims at gathering information needed to draw conclusions on how the potential of agricultural residues can be calculated, but also how they affect the anaerobic digestion. The agricultural residues with the most significant potential in RVG will be identified and how they can be included in the biogas production. Examples of large-scale biogas plants will be provided where residues from agriculture have been successfully incorporated into the biogas process. The theory section will highlight how values of methane yield can fluctuate and how these fluctuations can be interpreted for the application of pretreatments of biogas substrates. It will additionally include a survey of different mechanical pretreatments and aspects which has an effect on the anaerobic digestion. To include other effects that the calculations did not cover. The survey will include four different equipment types, hammer mill, knife mill, extrusion and mixer wagon. With the aim of choosing one to represent the implementation of mechanical pretreatment in RVG. In addition, examples of machines will be included to showcase the equipment available on the market.

3.2 Potential of agricultural residues in RVG

The agricultural sector in RVG must be investigated to assess how they can supply substrate. The report Olsson et al. (2022) has investigated the potential of agricultural residues in RVG and the amount generated in that report will be used in this thesis, where the energy potential of each residual stream will be calculated. The main steps will be described of how the potential calculations were assessed since the report is currently unpublished. The categories of substrates that have been identified include, manure from different animals, straw from cereals, ley crops and residues from potatoes and peas. The methane yield will be extracted from BMP analysis performed at RISE for each substrate. Similar potential studies for agricultural residues can be found in (Broberg *et al.*, 2022) for RVG and in (Prade *et al.*, 2017) for all of Sweden.

3.2.1 Manure

The amount of manure generated each year in RVG taken from Olsson et al. (2022). The data was generated firstly by the number of livestock for each municipality in 2020 from the Swedish Board of Agriculture (Swedish Board of Agriculture, 2021b). Except for the number of horses, where the latest inventory was performed 2016 (Swedish Board of Agriculture, 2017). The manure generated by each type of animal is categorised by slurry, solid manure, and deep litter manure. Calculations of the total manure volume is made by the number of animals and amount of manure produced for each animal per year, which is dependent on the number of days the animals are in the stable per year. The mass can be expressed by using the density of the manure. The fresh manure can be divided into the dry weight given by the percentage TS and residual water weight (water weight). To highlight the amount of manure produced that generate biogas and the amount consisting of water. Equation 3 shows how the amount of each manure category and animal is generated, see Appendix A and Table A.1-A.4 for further information.

$$M_{wet}\,\frac{ton\ ww}{year} = N \cdot\ M_{prod}\,\frac{ww\ m^3}{animal\ year}\ \cdot \%\ M_{type} \cdot \rho\,\frac{ton}{m^3} \qquad (3)$$

M_{wet}, wet weight manure production in ton ww/year

N, number of animals per year

M_{prod}, manure production per animal for one year in ww m^3/year

M_{type}, percentage of respectively manure type and livestock

ρ, density of manure type and animal in ton/m^3

The energy potential of the manure can be estimated by the dry weight of manure and the methane yield in normal (N)m^3 per ton TS for each manure type and animal, see Table 2 for the manure properties from the livestock present in RVG.

Table 2. Density and methane potential for the type of animal and manure (Olsson et al., 2022)

Animal and manure type	Density ton/m^3	Methane potential CH_4 m^3/ton TS
Cattle slurry	1	145
Pig slurry	1	200
Poultry slurry	1	167
Cattle solid	0.75	150
Pig solid	0.75	180
Poultry solid	0.9	184
Cattle deep litter	0.5	160
Horse deep litter	0.5	171

The methane potential was converted to energy potential by assuming that one Nm^3 CH_4 corresponds to 9.97 kWh and kWh was also converted to GWh per year by dividing with the factor 10^6, see equation 4. See Appendix A and Table A.2 for the TS content.

$$E\,\frac{GWh}{year} = M_{wet}\,\frac{ton\ ww}{year} \cdot TS \cdot\ CH_{4_{pot}}\,\frac{CH_4 Nm^3}{ton\ TS} \cdot \frac{9.97kWh}{Nm^3} \cdot \frac{1\ GWh}{10^6\ kWh} \qquad (4)$$

E, energy potential for respectively manure type and animal in GWh per year

$CH_{4_{pot}}$, methane potential for respectively in CH_4Nm^3 per ton TS

3.2.2 Crop residues

The total amount of crop residues in RVG was generated from Olsson et al. (2022). It was calculated from the data of the area of crop production for RVG, extracted from the Swedish Board of Agriculture for each municipality, see Appendix A and Table A.6. An average was used of data from 2016-2020 to take the crop rotation into consideration.

3.2.2.1 Straw potential

The amount of straw generated each year in the report was quantified for the cereal and oilseed crops in RVG (Olsson *et al.*, 2022). Only winter rape will be included since it is cultivated enough to make it significant. The straw potential can be calculated by taking the yield of each crop per hectare, the specific straw to grain ratio for each crop (accounting for a stubble length of 20 cm) and the TS content % and the salvage coefficient. The salvage coefficient is how much of the straw that can be collected by practical and technical limitations (Toro *et al.*, 2021). The principle of how the total straw potential can be calculated is seen in equation 5. The area and parameters for equation 5 can be seen in Appendix A and Table A.5-A.6.

$$Straw_{total} \frac{ton\ TS}{year} = A\ ha \cdot Y_{ha} \frac{kg\ ww}{ha\ year} \cdot SG_{ratio} \cdot S_{coeff} \cdot TS \cdot \frac{1\ ton}{1000\ kg} \quad (5)$$

$Straw_{total}$, total straw potential in ton ww per year for a specific crop

A, areal of respectively crop in ha

Y_{ha}, yield of crop each year in in kg ww per hectare

SG_{ratio}, straw-to-grain ratio for respectively crop

S_{coeff}, salvage coefficient for respectively crop

A major fraction of the cereal straw is used as bedding material for animals and must be subtracted from the total potential to get the amount of straw that can be used as a biogas substrate. See Olsson et al. (2022) for the calculations. However, this fraction will end up as solid and deep litter manure which can also be incorporated as a biogas substrate, whereas oilseed crops are unutilised.

The energy potential of straw was quantified similarly to the manure energy potential seen in equation 4. It was expressed in GWh/year by using the methane potential for straw and the dry weight of the straw potential that can be utilised for biogas production. A standard case was given for all cereal straw types with a TS content of 86% and a methane yield of 200 $CH_4\text{Nm}^3$/ton TS. The oilseed crop was given the same methane yield but a TS content of 91 %. The same TS content and methane yield was given for all cereal straw types due to having similar properties. But also due to that the properties fluctuate depending on a number of factors for each crop type.

3.2.2.2 Ley crop potential

Ley crops are mainly cultivated either as forage crops or pasture lands to produce roughage feed for livestock production and ensiled in silos or baled to conserve it (Prade *et al.*, 2017). Additionally, ley crops can be introduced in the crop rotation or as a catch crop to improve the soil fertility or can be grown on fallow or abandoned crop land, with the purpose of being a substrate to produce biogas. Excess and discarded roughage feed is a residue stream that exists today which can be used as a biogas substrate. Whereas the second category can become significant in the future when improving soil fertility becomes more important. The ley crop potential in RVG will therefore only include excess and discarded roughage feed in the form of grass ley silage and the amount is taken from (Olsson *et al.*, 2022).

The reason for excess of grass ley silage to arise is that more is grown to take losses and spoilage in consideration. Both the leftover and discarded ley silage can be used to produce biogas. The excess ley silage varies considerably between years and is therefore difficult to estimate. To quantify the potential was three scenarios used for the degree of disposal based on this report (Lund *et al.*, 2018), 1 %, 5 % and 10 %. The potential can be calculated by the area and the hectare harvest of forage crops and grazed pasture lands multiplied with the degree of disposal and the TS content, seen in equation 6.

$$Ley_{excess} \frac{ton\ TS}{year} = A\ ha \cdot H_{ha} \frac{ton\ TS}{ha\ year} \cdot Dd\ \cdot TS \qquad (6)$$

Ley_{excess}, excess ley silage in ton TS per year

A, areal of ley cultivation in ha

Hh, hectare harvest per year in ton TS/ha

Dd, degree of disposal in percentage

The energy potential of ley silage was also quantified similarly to the manure energy potential seen in equation 4 and expressed in GWh/year by using a TS content of 35 % and methane potential of 240 CH_4Nm^3/ton TS for the three different scenarios.

3.2.2.3 Vegetable residue potential

Vegetable residue streams which have a potential to be a source of substrates for biogas in RVG include, discarded food potatoes, potato tops and residues from peas for processing like leaves, stalks, and pea pods. Food potatoes are chosen due to having a high degree of disposal of 9.5 %. The potential as a biogas substrate can be quantified by the areal grown and the yield of the harvest per year together with the TS content and degree of disposal using. Similar to equation 5 but using the degree of disposal coefficient opposed to the straw to grain-ratio (Olsson *et al.*, 2022). In addition, the potential of potato tops and residue from peas for processing can be quantified by the cultivation area and a value for residue harvest in TS for one hectare and year, seen in equation 7. This is equal to 2.7 ton TS/ha year for potato tops and 5 ton TS/ha year for peas.

$$Crop\ residue \frac{ton\ TS}{year} = A\ ha\ \cdot R_{har} \frac{ton\ TS}{ha\ year} \qquad (7)$$

$Crop\ residue$, crop residue potential in ton TS per year

R_{har}, residue generated from harvest in ton TS per hectare and year

The energy potential for the crop residues can be calculated similar to equation 4 and using the methane potentials seen in Table 3.

Table 3. TS and methane potential of potato and pea residues

Type of residue	TS %	Methane potential m^3 CH_4/ton TS
Food potato	20	390
Potato tops	15	210
Peas for processing	15	296

3.3 Survey of biogas plants

Most of the information was collected via an interview study. Additional information was collected by contacting the Swedish Board of Agriculture and requesting the volume of manure digested each year from the biogas plants in RVG[2]. Specific substrates that were used at the farm-based biogas plants that were not covered in the interview study were taken from a project performed by Hushållningssällskapet, 2011-2014 (Eliasson, 2015).

[2] M. Johansson, Swedish Board of Agriculture, email correspondence on the 8th of February 2022.

3.3.1 Interview study

An interview study was performed in this thesis. The information from the interviews were used as a basis for the research questions asked in the project. The interview study was first conducted by finding suitable biogas plants through Biogas Väst, Swedish Board of Agriculture and the Swedish Gas Association. With focus on biogas plants in RVG. Two biogas plants outside were examined, one of interest for the RISE project and the other which a study visit was conducted together with Biogas Väst. WWTP biogas plants were excluded since the digestate is not suitable to be returned to the agricultural sector. The selection was also made to represent different biogas plant sizes seen in Table 4. To ensure that different perspectives of operating a biogas plant is taken into consideration.

Table 4. Biogas plant sizes presented in the thesis

Co-digestion plant		Farm-based plant	
Large	>50 GWh/year	Large	>3 GWh/year
Medium	20-50 GWh/year	Medium	0.5-2 GWh/year
Small	<20 GWh/year	Small	<0.5 GWh/year

Co-digestion and farm-based biogas plants were contacted via email or telephone. A questionnaire was drawn up (see Appendix B) to ensure that all the necessary information was collected and that a suitable time frame was maintained. The interview length was set to 30 min. The questions were both quantitative and qualitative to both survey the biogas plants capacity and the interest or thoughts on utilising agricultural residue streams. All the interviews were recorded and held via Teams or the phone depending on what suited the participants. The interviews were conducted in an ethical and transparent manner. By giving the participants an opportunity to read through the questionnaire beforehand, consent was given for recording and the answers were anonymized by replacing the name of the participant to the name of the biogas plant. Ten interviews were performed with seven co-digestion plants, one potentially upcoming co-digestion plant and four farm-based biogas plants seen in Table 5. The study visit was performed at Långhult biogas. Gasum Götene was interviewed since it will focus on agricultural residues and have the largest biogas production in RVG if/when it is built.

Table 5. List of interviews performed in the thesis

Type of facility	Company name	Size	Location
CD1	Gasum Lidköping	Large	RVG
CD2	Gasum Skövde	Medium	RVG
CD4	Falköping biogas	Small	RVG
CD5	Sobacken Borås	Medium	RVG
CD6	Vårgårda-Herreljunga (VH) biogas	Medium	RVG
CD8	Gasum Götene	Large	RVG (not in operation)
CD9	Gasum Katrineholm	Medium	Södermanland County
FB1	Götestorp	Medium	RVG
FB2	Häljeredsgård	Small	RVG
FB3	Långhult biogas	Medium	Region Jönköping County

Co-digestion (CD), farm-based (FB) biogas plants

The answers from the interviews were managed by transcribing the recorded interviews and categorising them into different themes. Both quantitative and qualitative information was collected. The quantitative answers were structured in Excel where the plant's existing capacity, substrate type and amount, and their future potential were recorded using tables and figures (see Appendix B and Table B.1-B.2). The amount and composition of the substrate in the potential expansion was based on the answers from the interviews. The biogas plants that were not included in the interview study are assumed to have the same potential as today. The energy potential was calculated using equation 4 and Table 2 for the non-fibrous substrates (slurry and poultry manure). The energy potential for the fibrous substrates (see Table 18) will include the implementation of mechanical pretreatment and is described in the following section, section 3.4.

The qualitative answers were analysed by organising the answers into four main themes. The first was the biogas plant design of digesting agricultural residues. Secondly, the interest of anaerobic digesting agricultural residues. Then the potential of expansion of the biogas production by implementing substrates from agriculture. Lastly, obstacles and limitations of that expansion. The individual experiences, key words, and common opinions were analysed. The quantitative answers from the interview study can give a good picture of the biogas production in RVG and important insights can be made. However, general arguments that claim that *this is the opinion of biogas plants in RVG* or that *X % believe this*, will not be made since only 10 interviews have been performed. A survey of the majority of the biogas plants has to be performed to make such claims.

3.4 Analysis of mechanical pretreatment

A hammer mill was chosen to represent the mechanical pretreatment due to having a moderate energy demand and utilised for large-scale operations. For small-scale operations like farm-based plants is a mixer wagon more suitable. Two scenarios will be included in the analysis. One where all the straw and ley silage can be assumed to be chopped when entering the biogas plant. The other scenarios assume that all the straw and ley silage consist of long stalks and have to be chopped at the plant. The two scenarios will therefore work as two extremes, with the chopped scenario having the lowest energy demand and the scenario with long stalks will have the highest. In practice both fractions will coincide. The sensitivity analysis performed will include an average of the two.

3.4.1 Energy analysis

An energy analysis was performed to examine how much energy is spent on mechanical disintegration relative to how much is obtained from an increased biogas yield. However, there are other parameters that are affected by mechanical pretreatment such as heating of the material, stirring, the rate of anaerobic digestion and performance in a wet digestion. These are excluded in these thesis and assumed to be constant regardless of particle size according to (Odhner *et al.*, 2015). The energy analysis will investigate the impact of mechanical pretreatment on the fibrous agricultural residues obtained from the potential expansion in RVG from the interviews.

The first step is to define what substrates that need mechanical pretreatment and their properties. The fibrous residues include solid manure from cattle and pig, deep litter manure from cattle, horse manure, ley silage and straw. They are chosen due to containing bedding material and/or lignocellulosic biomass with large particle sizes. The bedding material used in husbandry will affect these properties. Chopped straw, straw briquettes and wood shavings can be used. Straw briquettes do not need pretreatment and increase the methane yield. Wood shavings on the other hand decrease the methane yield (Edström *et al.*, 2012). Chopped straw was chosen to model the bedding material since it can be seen as a middle scenario of the bedding materials. The values are based on BMP analysis performed at RISE (Olsson *et al.*, 2022). A reasonable assumption of the increase in methane yield was 20 % for the agricultural residues (see Table 18).

The second step is the choice of mechanical pretreatment, a hammer mill was chosen as the main equipment for the model. Additional equipment is needed for the second scenario with long stalks such as a straw bale opener and shredder or chopping machine, examples of machines can be seen in (Cormall, no date). The energy demand of the different substrate is based on the literature review (see section 4.3.1 and Table 8) for an initial particle size of about 20-50 mm (up to 100 mm) to a final size of around 2-5 mm. The implementation of straw and silage with long stalks will generate additional energy demand since it needs coarser disintegration prior to the hammer mill. It is assumed that this step adds an additional energy demand of 10 kWh/ton ww. The initial particle size can be around 50 cm and the final size should be around 2-5 cm. The resulting energy demand varies depending on the substrate between 8-55 kWh/ton ww, where the solid manure has lower energy demand, and the lignocellulosic substrates has higher (see section 5.3.1 and Table 19). Sensitivity analyses of varying energy demand and methane yield will be performed, since both tend to fluctuate, using Python with the libraries NumPy and Matplotlib, the code can be seen in Appendix D.

The final step is to define the energy balance. The chosen method for this is the index energy return on investment (EROI) seen in equation 8. EROI is a way of measuring the quality of various fuels by calculating the ratio between the energy delivered and the energy invested to deliver it (Hall *et al.*, 2014). If EROI is equal or less than one is the energy source considered a net energy sink.

$$EROI = \frac{Energy\ Delivered}{Energy\ Required\ to\ Deliver\ that\ Energy} \tag{8}$$

EROI can be calculated by expressing the energy delivered as the energy gained by the surplus methane yield, seen in equation 9. The energy gained is expressed in kWh per year by taking the mass flow of the substrate (see Table 16), TS and VS content, the methane increase difference in kWh/ton VS (CH_4 9.67 kWh per Nm^3).

$$E_{gain}\frac{kWh}{year} = m_s\frac{ton\ ww}{year}\cdot TS\cdot VS\cdot (M_{treat} - M_{untreat})\frac{CH_4\ m^3}{ton\ VS}\cdot 9.97\frac{kWh}{CH_4\ m^3} \tag{9}$$

E_{gain}, energy delivered in kWh/year for respectively substrate

m_s, mass flow of substrate in ton ww per year

M_{treat}, methane yield of substrate with mechanical pretreatment in CH_4 m^3/ton VS

$M_{untreat}$, methane yield of untreated substrate in CH_4 m^3/ton VS

The energy required to deliver that energy can be expressed as the energy consumed of the mechanical pretreatment for the substrate in kWh per year, seen in equation 10. The consumed energy can be expressed as the mass flow of the substrate per year (see Table 16) and the energy demand of each substrate (see Table 19). The energy gained from the mechanical pretreatment can be compared with the energy consumed. To see how significant the energy spent is compared to the increased biogas production.

$$E_{consume} \frac{kWh}{year} = m_s \frac{ton\ ww}{year} \cdot E_d \frac{kWh}{ton\ ww} \tag{10}$$

$E_{consume}$, energy required to deliver the biogas in kWh/year for the substrate

E_d, energy demand of a certain substrate in kWh per ton ww

3.4.2 Economic analysis

An economic analysis was performed for the increased biogas income compared to the cost of electricity supplied. In order to evaluate the cost of the energy demand of the mechanical pretreatment. The analysis will display how the electricity price affects the biogas production and indicate the break-point, where the use of electricity exceeds the economic benefits of the added methane yield. The cost of maintenance is also important, but this was excluded, since it depends on the machine used and how it is being operated.

The value of the biogas and the cost of electricity in SEK/kWh must be estimated to assess the profitability of each substrate. The estimated revenue of selling produced methane was estimated to be 0.80 SEK/kWh. The electricity price used was a yearly average for zone 3 (RVG's zone) used since the price varies depending on the area in Sweden and the time of year. This was equal to 0.67 SEK/kWh 2021 (SCB, 2022). Due to large fluctuation in the electricity price for the past months, up to 1.3 SEK/kWh, a sensitivity analysis will be performed (SCB, 2022). The profitability of each substrate was expressed in SEK per ton ww and ton TS by diving. It was calculated using equation 11, by taking the difference in the energy gain and energy consumed (see 3.4.1), multiplied with the income of biogas and cost of electricity respectively and divided by the yearly mass flow. By diving with the TS content can it be expressed by SEK/ton TS.

$$P_{add} \frac{SEK}{ton\ ww} = {m_s}^{-1} \frac{year}{ton\ ww} \cdot (E_{gain} \frac{kWh}{year} \cdot I_{gas} \frac{SEK}{kWh} - E_{consume} \frac{kWh}{year} \cdot C_{el} \frac{SEK}{kWh}) \tag{11}$$

P_{add}, specific added profitability of respectively substrate in SEK per ton ww

I_{gas}, income of biogas SEK per kWh

C_{el}, cost of electricity SEK per kWh

Additionally, the total specific profit for a substrate that has undergone mechanical pretreatment per year was calculated. The energy for the treated substrate is given by the total methane yield, but this can be split up into the added methane yield and the untreated methane yield (see equation 9). The total specific profit can therefore be split up into the added profit seen in equation 11 (not diving with the mass flow) and added profit from the untreated material, see Appendix C for the derivation. The reason for this is to see the significance of the added specific profit compared to the untreated profit.

4 Theory of Agricultural residues

4.1 Agricultural residues in RVG

The following section will describe the properties of the most relevant biogas substrates coming from the agricultural sector and how they affect anaerobic digestion.

4.1.1 Manure

The livestock with the greatest biogas potential includes cattle, pigs, poultry and horses (Swedish Board of Agriculture, 2021b). Quantitative characteristics such as TS, VS and the C/N ratio are important to determine the biodegradability of manure (Nwokolo *et al.*, 2020). A summary is given in Table 6 for the different types of manure present in RVG. Another important aspect is the bedding material used and the particle size distribution (Edström *et al.*, 2012).

Table 6. Summary of the properties for different types of manure

Manure type	TS %	VS % (% of TS)	C/N	Methane potential m^3 CH_4/ton VS
Cattle, slurry [a c]	9	80	6-20	160-210
Cattle, solid [c]	20	80		150
Cattle, deep litter [c i]	25	80		135-180
Pig, slurry [a c]	8	80	5-15	200-268
Pig, solid [a f]	16-23	80	23	150-300
Poultry, slurry [i]	12	80		243
Poultry, solid [a e f]	35-44	67-76	3-10	247-312
Horse, deep litter [a b h j]	30-55	80-90	20-25	170-195

[a](Carlsson and Uldal, 2009), [b](Olsson *et al.*, 2014), [c] (Tufvesson *et al.*, 2013), [d](Nagy, 2012), [e](Jurgutis *et al.*, 2020), [f](Björnsson and Lantz, 2011), [g](Li *et al.*, 2020), [h](Melikoglu and Menekse, 2020), [i](Edström, 2022), [j](Schnürer and Jarvis, 2017)

4.1.1.1 Cattle manure

The availability of manure decreases during the grazing periods from May to October. But it also depends on the amount of pasture remaining in the later months and the management system of the livestock (Andersson *et al.*, 2017). Dairy cattle mostly generate slurry and a small fraction of solid manure. Whereas beef cattle, cattle for breeding and calves under 1 year generate around 40 % of slurry and deep litter manure and 17% solid manure (SCB, 2020). Manure from cattle has a lower biogas potential around 160 m_3 CH_4/ton VS compared to pig and poultry, since ruminant's manure is already partially anaerobically degraded (Carlsson and Uldal, 2009; Nasir *et al.*, 2012).

Cattle manure is beneficial at the start of fermentation and to co-digest with other substrates as it contributes to a good stability of the process, because the anaerobic degradation has been initiated and that methanogens are present (Tufaner and Avşar, 2016). The examples of co-digesting with cattle manure are numerous in the literature. One example is to co-digest it with wheat straw since it is already present as bedding material in animal farms which gives it economic advantages. Cattle manure enriched with wheat straw, 85:15 mixing ratio, was shown in one study to increase the BMP from

174 m_3CH_4/ton VS to 249 m_3CH_4/ton VS, using a residence time of 45 days (Kalamaras and Kotsopoulos, 2014). The drawback of using bedding materials is that they may contain rocks and other inert objects (Gunnarsson *et al.*, 2021).

4.1.1.2 Pig manure

Pig manure is generally available year round. The majority of the manure generated is slurry and about 3% is handled as solid manure (SCB, 2020). Slurry from pig has a TS content of 8% and differentiates from cattle slurry by having a higher biogas potential by not being as rich in fibres, see Table 6. Pig manure contains high amounts of minerals, that sediments and generates bottom deposits (Carlsson and Uldal, 2009). In addition, solid manure from pigs has a high methane yield of 300 m_3CH_4/ton VS, contains less water and a more balanced C/N ratio of 23. This makes solid manure an advantageous for biogas production since it has lower transportation cost and can provide an energy-rich substrate (Carlsson and Uldal, 2009). Problems with ammonia inhibition and low C/N ratio can be overcome by co-digesting pig manure with other substrates containing more carbohydrates such as cattle and horse manure or other agricultural residues (Schnürer and Jarvis, 2017). Synergistic effects and a more stable process was seen in a pilot experiment where pig slurry and grass silage with an average particle size of 50 mm were co-digested. The co-digestion resulted in a steady pH profile around 7.8, a methane yield increased from 154 m_3CH_4/ton VS to 254 m_3CH_4/ton VS by utilising a CSTR with HRT of 30 days (Xie *et al.*, 2017).

4.1.1.3 Poultry manure

Poultry manure is available year round similarly as pig manure. Most of the manure is collected from laying hens where 60 % is handled as solid manure and 40 % as slurry (SCB, 2020). Solid manure from poultry is characterised by being the most energy dense, having a high TS content and for being nutrient rich, see Table 6. The C/N ratio is relatively low between 3 to 10 and the total nitrogen is around 12-35 g N/kg (Edström *et al.*, 2018). Poultry manure is a valuable substrate but is more susceptible for ammonia inhibition compared to pig and cattle. The nitrogen composition has a high concentration of uric acid which is more prone to be converted to ammonia but also higher TS contents (Jadstrand and Lingmerth, 2017). A mesophilic condition is favoured since it is less susceptible to inhibition by sudden changes in ammonia concentrations compared to a thermophilic process. The reason is that a mesophilic process has a more diverse consortia of microorganisms (Jurgutis *et al.*, 2020). Additionally, the phosphor content is high due to high contents of it in the chicken feed which can be beneficial to enrich the digestate. Problems with sedimentation can arise due to a high content of egg shells, minerals and feathers floating on the surface (Carlsson and Uldal, 2009).

Problems with ammonium inhibition when mono-digesting poultry manure can be overcome by dilution or by being co-digested with carbon rich substrates such as lignocellulosic biomass (Edström *et al.*, 2018; Jurgutis *et al.*, 2020). One study investigated co-digesting a mixture containing 80 % of poultry solid manure, 14 % cattle and pig slurry and 4% cattle/pig deep litter manure. The conclusion was an increase in the BMP for the mixture with around 450 m_3CH_4/ton VS compared to mono-digestion of poultry, pig, and cattle manure with 380 m_3CH_4/ton VS, 325 m_3CH_4/ton VS and 170 m_3CH_4/ton VS respectively (Edström *et al.*, 2018).

4.1.1.4 Horse manure

Horses are often facilitated in urban areas making its manure difficult and expensive to dispose of. One solution can be to utilise it as a substrate in biogas plants. However, the limiting factor is that it requires facilities with at least 50 horses to make it economically viable (Olsson *et al.*, 2014). Horse manure is handled as deep litter manure. It is characterised by being dry, around 30-55 % TS and containing large amounts of bedding materials such as peat, sawdust, or straw (see Table 6). The nutritional content in the manure is influenced by the size of the horse, fodder and activity but it generally contains a source of potassium and phosphorus (Carlsson and Uldal, 2009). The bedding material can act as a carbon source, with the best option being straw pellets or finely chopped straw as this will increase the biodegradability of the substrate. The manure can be incorporated into a CSTR process by being mixed with water from the digestate or co-digester with other wet substrates such as slurry (Olsson *et al.*, 2014). Problems with horse manure in the process are sedimentation of stones and gravel, difficulties in pumping, agitation, and crust formation. To implement horse manure in biogas production, suitable bedding materials such as chopped straw or briquettes should be used. A stone separator and mechanical pretreatment can also be installed, depending on the condition and particle size of the manure (Mattsson *et al.*, 2015).

4.1.2 Crop residues

The agricultural residues with the most potential of being incorporated into biogas production in RVG will be investigated further. The most common crops grown in RVG are cereals and ley crops used as animal feed. Other crops that will be included in the biogas potential are food potatoes and peas for processing since the cultivation of these generate substantial amounts of residues and both are grown on 0.5 % of the arable land respectively (Swedish Board of Agriculture, 2021b). A summary of the most important aspects for anaerobic digestion of the crop residues in RVG can be seen in Table 7.

Table 7. Summary of properties for lignocellulosic biomass and crop residues

Biomass type	TS %	VS % (% of TS)	C/N	Methane potential m^3 CH_4/ton VS
Straw* [a e f]	70-78	79-91	50-90	120-200
Fresh ley crops [a b e f]	14-36	87-93	12-26	230-400
Ley silage [a c d e]	35-40	87-93	25	260-350
Potato [a e]	20-25	95	35-60	411
Potato tops [a e d]	15	80		263
Pea residues [d g]	15- 42	80-92		300-400

*Similar values for different types of straw, [a](Carlsson and Uldal, 2009), [b](Prade *et al.*, 2014), [c](Tsapekos *et al.*, 2015), [d](Edström, 2022), [e](Schnürer and Jarvis, 2017), [f](Ammenberg and Feiz, 2017), [g] (Almgren, 2011)

4.1.2.1 Straw

Straw accounts for the majority of the residue streams in agriculture and the most common in RVG is winter wheat, oat and winter rape. Other important sources of straw include spring wheat, rye, barley, triticale, and oil crops (Swedish Board of Agriculture, 2021b). A survey done concluded that the technical and economical available biogas potential for straw is estimated to 450 GWh/year in RVG (Börjesson, 2016). Straw is mainly harvested during a few weeks in late summer or early autumn. It can be stored and utilised year round if it is harvested dry with around a water content of 18 %. However, to minimise possible losses during storage it is preferable to utilise it during autumn and winter (Gunnarsson *et al.*, 2021).

Straw is an unconventional substrate in biogas production due to not being compatible with wet digestion in its untreated form. Therefore, mechanical pretreatment should be performed, due to large particle sizes and lignocellulosic content. However, the mechanical pretreatment depends on how the straw is supplied to the biogas plant (Andersen *et al.*, 2022). The harvested straw can either be chopped during harvest to a particle size up to 30 mm or pressed to round or rectangular bales consisting of long stalks. The chopped straw is bulky and has a low energy density making transportation more expensive and difficult. In comparison, bales are less costly to transport and easier to store. But the drawback is that the long stalks are often too coarse to be incorporated directly without causing issues in a mechanical pretreatment where fine particles are generated. A second pretreatment step is often needed, where the stalks are shredded and chopped to suitable size. Manual removal of plastic cover and net from the bales are also often needed. Another alternative is to use straw which is compressed into pellets or briquettes to facilitate the transportation and biodegradability but this is a more energy intensive and costly option (Gunnarsson *et al.*, 2021).

Straw is mainly a lignocellulosic biomass with the dry matter consisting of 30-40 % cellulose, 26-50 % hemicellulose and 8-21 % lignin. Straw has a high TS content and C/N ratio (see Table 7) (Ammenberg and Feiz, 2017). The fraction of lignin present in straw will decrease the VS since this will not contribute to the biogas production. Additionally, straw must be diluted prior to entering a CSTR digester. This can be done by co-digestion with a substrate with a low TS content such as slurry, recirculation of the water from the digestor or addition of water. Since straw mainly consists of carbon, nutrients must be added to meet the microorganism's demand. This also can be done by co-digestion of nitrogen rich substrates (Carlsson and Uldal, 2009).

Verbio Schwedt/Oder in Germany is an example of a biorefinery that uses straw along with distillery slop to produce biogas with a capacity of 136 GWh/year. The straw comes from different kinds of cereals and oilseed crops collected within a radius of 80 km and 40 000 tons of straw per year is used to produce biogas. The residence time is 30-150 days and the biofertilizer is returned to the farmers. The project is part of the EU programme NER300 and received 22.3 million EUR during 2014-2019 (Verbio, 2022).

4.1.2.2 Ley crops

As a substrate in the biogas production ley crops can either be used fresh or ensiled. Ley crops an unconventional substrate in today's biogas production, similarly as straw. Ley crops can be available as a substrate year round by being ensiled but also fresh where it can be utilised for the whole plant season, from early spring to last autumn (Prade *et al.*, 2014). One study (Lund *et al.*, 2018) concluded that the current largest potential to be incorporated in biogas production for ley crops is unutilised silage from fodder production consisting of surplus silage and discarded silage. However, ley crops can be cultivated with the purpose of being utilised as substrate for biogas production. This can be performed in RVG by incorporating it in the cereal crop rotation of six years by replacing winter wheat and oat cultivation for two of the years (Tidåker *et al.*, 2016). The potential of ley crops can also increase by intensifying the cultivation and increasing the yield. This can be done sustainably by optimising the date and the numbers of harvest, using high yield ley varieties and precision cultivation (Jørgensen *et al.*, 2020).

Fresh ley is not stable to store and should be digested close to the harvest time to avoid losses and heating of the material. This can be done by harvesting the ley daily or every other day and avoiding physical damage or cutting. The fresh ley can be supplied to the biogas plant by firstly being mowed and left on the field in swaths to then be collected by a forage wagon. Another option is to chop it with a direct cut forage wagon and directly transport it to the biogas plant. The advantage with fresh ley is that the cost of silage and storage is avoided. In addition, being pre-chopped where further fine disintegration can be performed. The forage wagon can also be equipped with a biogas drum for shorter cutting length, less than 1 cm, in that case can further pretreatment be avoided (Ljungberg *et al.*, 2013). On the contrary, ensiled ley can be used and stored during the whole year without losing its methane potential making it more accessible and easier to handle. The ensiled ley for biogas production can be harvested using the same technique as for animal production, most common is a mower followed by a self-propelled precision chopper. The major disadvantage of using discarded or excess ensiled ley for animal production is that it is composed of long stalks, having similar issues as baled straw (Gunnarsson and Lund, 2020). Too long straw lengths impede the anaerobic digestion and affect the mixing of the reactor, risk of clogging pumps and pipes and crust formation. The ley crops can undergo mechanical pretreatment to prevent this from occurring (Lund *et al.*, 2018).

Properties that affect the biogas production include composition of organic content, TS content, C/N ratio, harvesting time, number of harvests per year and storage (Nizami and Murphy, 2010). Ley crops can have a lignin content of 18% depending on type and age which will decrease the amount of biomass that can be converted to biogas (Ammenberg and Feiz, 2017). Fresh ley crops generally have a higher water content compared to ensiled ley, but can vary, (see Table 7). The methane yield is generally higher for clover based ley with yields between 350-480 m^3 CH_4/ton VS since they contain more protein. Grasses contain more lignocellulose and carbohydrates which yields slightly lower methane yield between 270-350 m^3 CH_4/ton VS. Ley crops also have a higher methane yield compared to straw since it contains less lignin (Ammenberg and Feiz, 2017). Additionally, methane yield decreases with age since the lignin content increases with time. To increase the methane yield, ley crops can be harvested twice or three times a year (Prade *et al.*, 2014). A study by (Prade *et al.*, 2014) found that fertilised commercial ley had an increase in methane yield by being harvested twice instead of once per year. With 300 m^3 CH_4/ton VS for the first harvest and 270 m^3 CH_4/ton VS for the second. Compared to the one time harvesting system which had 230-250 m^3 CH_4/ton VS.

Biowert is an example of a biorefinery founded 2000 in Germany. It is based on grass from permanent pastureland and produces different products and biogas. The facility utilises 8000 ton of grass per year and produces 5.2 GWh of biogas annually. The main products are grass fibre insulation, natural fibre reinforced plastic and bio-fertilizer from the liquid digestate. The grass is ensiled and processed with mechanical pretreatment. The fibres are isolated through pulping, drying, and pressing. Grass juice remaining from the mechanical pretreatment is co-digested together with local substrates like food waste and slurry. The success from the company comes from selling valuable and multifaceted products and by producing its own electricity. (Schwinn, 2019)

4.1.2.3 Vegetable residues

Other potential residue streams from crops grown in RVG that can be used as substrate for biogas production include discarded potatoes, potato tops and residues from peas. Potatoes are discarded due to rot infestation, wrong size, or other damage to the harvest (Olsson *et al.*, 2022). The crop residues are characterised by a low TS content (but can vary) and for being easily degradable with generally high methane yields, see Table 7. The main limitation of using potato tops is that they should be digested as soon as possible after harvest, due to the high water content during the harvest. Making the substrate difficult to store and less economically viable (Gunnarsson *et al.*, 2021). Residues from peas can be utilised both fresh and ensilaged making it beneficial to use as substrate for biogas plants (Almgren, 2011). Mechanical pretreatment is needed to utilise pea residues such as chopping, to avoid process related problems. Profitability of using the potato tops and the pea residues as substrate may pose a problem due to high machine cost for collecting the biomass and pretreatment but it could be an option for farm-based biogas plants that have it available (Almgren, 2011).

4.2 Methane yield

The methane yield for different substrates will be used to estimate the potential energy capacity of different agricultural residues. It is important to note when extracting such figures that there are different methods to determine the methane yield, see Figure 4. The choice depends on the available time and economics. There is a great amount of research on methane yield for different pretreatment technologies. The methane yield depends on to vary significantly for the same substrate and technique.

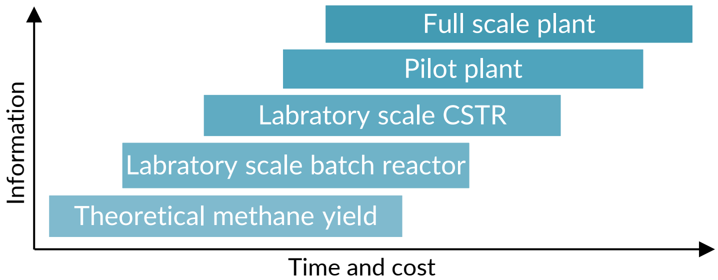

Figure 4. Levels of estimating methane yield with ascending time, cost, and information

The least expensive and fastest test is the theoretical methane yield. This is performed by chemical characterization techniques such as the chemical oxygen demand (COD) or elemental analysis and quantification of macromolecules which can determine the methane yield by stoichiometric relations (Nwokolo *et al.*, 2020). Overestimation of the methane yield is a drawback for these methods. However, the application can provide a maximum methane yield which assesses the reasonableness of other experimental values (Björnsson *et al.*, 2014). Laboratory batch reactors measure the BMP and are the most common method. The method consists of incubating a microbial inoculant with the substrate. Over time is the methane production plotted in a specific methane production curve (Koch *et al.*, 2019). The drawback is that there are no official guidelines deciding how the test should be performed causing large variation in results (Björnsson *et al.*, 2014; Koch *et al.*, 2019). The BMP can estimate the difference in methane yield for untreated and pre-treated substrates. The drawbacks include, it neglects the presence of inhibitors, the results cannot be applied to a continuous process and can be misleading when comparing different pretreatment techniques. However, the BMP test is simple and fast and can be applied to get a starting point (Björnsson *et al.*, 2014).

More accurate methane potentials can be given by CSTR in a laboratory scale which has a longer time scale compared to BMP. Substrates are added and digestate is removed continuously making it more similar to a full-scale operation. To get a reliable result, at least three HRTs should pass to ensure that no microbial inoculant added at the start will be present. The drawback is that the results can vary considerably as a result of feeding small amounts of the substrate. Consequently, the comparison between pre-treated and untreated substrates may not give statistically significant results. But it can be applied to validate BMP results in batch tests. (Björnsson *et al.*, 2014)

Pilot-scale biogas plants are able to better compare methane yield from pretreatments than laboratory methods since the equipment and procedure are similar to that in full-scale. Additionally, a pilot-scale plant provides information about physical parameters of the substrate such as pumping, mixing, heat integration, sedimentation and crust formation. The main application of pilot-scale plants is to provide dimensions for a full-scale process. Lastly, the final level of information is the full-scale operation which is the most accurate assessment of comparing the methane yield for different pretreatments in the long term. In addition to other parameters such as the energy demand and cost. However, the methane yield for a specific substrate is hard to obtain and the difference in the untreated and pre-treated state of it. It is therefore important to complement with other methods. (Björnsson *et al.*, 2014)

To conclude, there are different ways of estimating the methane yield for substrates, no method can provide with all the information needed to evaluate the efficiency of pretreatment and the methane potential of a substrate. However, it is important to note that evaluations done in laboratory scale will always be the starting point but may not be translated into reality. It is therefore important to compare them to the maximum theoretical value and other similar studies. Full-scale plants can showcase the true effects of a pretreatment technique however research and development stages are needed in order to compare different pretreatments with each other.

4.3 Mechanical pretreatment

For pretreatments at full-scale mechanical pretreatments are the most commonly used. The advantage over other pretreatments is that it is the most simple option in terms of process operation and design (Fernandez *et al.*, 2020; Andersen *et al.*, 2022). There are several aspects attributed, one of the most important is to facilitate and upgrade the digester feeding conditions to avoid crust formations and reduce the size of the materials. To subsequently improve mixing, pumping heat and mass transfer. In addition, it can increase the biodegradability and decrease the degradation time (Mönch-Tegeder *et al.*, 2014). The main drawback is the relatively high energy demand and that it can be damaged by inert materials in the substrate, like rocks or metal parts. This can be a cause for earlier maintenance and increased cost (Montgomery and Bochmann, 2014).

The main factor that is affected by mechanical pretreatment is the particle size distribution and shape. But other parameters that are affected include increased water retention capacity (WRC), fluidity and reduced viscosity (Mönch-Tegeder *et al.*, 2014; Fernandez *et al.*, 2020). Increased WRC and smaller particles affect the mixing, fluidity, surface area for heat and mass transfer and the flow behaviour of particles (Cai *et al.*, 2017). The increased specific surface area increases the possibility of enzymatic attacks, this is especially important for lignocellulosic biomass. The particle reduction reduces the viscosity as well which decreases the energy required for mixing. It also increases homogeneity and the formation of floating layers (Montgomery and Bochmann, 2014). Improved kinetics of the anaerobic digestion can be obtained, resulting in a shorter residence time and/or a higher OLR (Garuti *et al.*, 2022). Garuti et al. (2022) concluded that increase in R_{max} was related to the relative increase in Specific Surface Area (SSA) by using a hammer mill, knife mill and extruder. A reduced residence time leads to a smaller energy demand for agitation and pumps, smaller reactors and that more methane can be produced for the same time (Odhner *et al.*, 2015). The decrease of particle size prevents gradients of nutrients, suspended biomass, solids, temperature and pH. In addition to limiting sedimentation and crust formation (Fernandez *et al.*, 2020). All reductions of particle size are beneficial to the process, but a particle size of 1-4 mm provides an effective hydrolysis of lignocellulose (Montgomery and Bochmann, 2014)

Mechanical pretreatment can be performed with several different techniques such as shredders, ball mill, knife mill, hammer mill, wet disc mill, colloidal mill and extruder (Kratky and Jirout, 2011). The choice of technique depends on the substrate, wanted particle size and TS content. For dry materials with moisture content of up to 10-15% (wet basis) are knife and hammer mills the most commonly used. Knife mills generally have a lower energy demand. However, many industrial knife or hammer mills used for substrate are also used for wet materials with higher moisture levels (Montgomery and Bochmann, 2014). For wet materials with moisture content above 15-20 %, wet disc mills and extruders are the most commonly used (Taherzadeh and Karimi, 2008; Kratky and Jirout, 2011; Lund *et al.*, 2018; Fernandez *et al.*, 2020). Ball mill and vibratory ball mills are universal and can be used for both wet and dry materials (Taherzadeh and Karimi, 2008). Examples of machines from agriculture are mixer wagon, straw chopper and straw reaper machines (Lund *et al.*, 2018).

Hammer mill, knife mill and extruder have been chosen to be investigated further, due to being the most economically viable, easy to operate, most commonly used and works in large-scale operation. In addition, mixer wagons will be investigated for a small-scale operation option. The attributes that are considered for each technique include the energy demand, BMP for untreated and treated biomass and mechanical process. Most research on the effect of pretreatment on agricultural residues utilise lab-scale equipment and BMP tests. It is therefore important to consider that this does not translate directly to large-scale (Montgomery and Bochmann, 2014).

4.3.1 Hammer mill

A hammer mill breaks up biomass in a vigorous way by degrading the material through decreasing the particle size, affecting the shape and surface of the particles (Lund *et al.*, 2018). They are widely used due to their high size reduction ratio, easy adjustment of particle range, relatively cheap and easy to operate (Kratky and Jirout, 2011). The technique consists of a rotating main shaft with flails or hammers distributed on several hammer shafts inside a steel drum (Lund *et al.*, 2018). The principles of hammer mills are that they have a rotor with attached hammers which pushes materials against a breaker plate. The force of the hammer causes the material to be shredded and expelled through screens (Rodriguez *et al.*, 2017). The maintenance of the machines includes exchanging worn out hammers and is relatively seldom compared to other techniques if operated correctly, by removing rocks and gravel (Lund *et al.*, 2018). The most important aspects of using a hammer mill to digest agricultural residues can be seen in Table 8 and includes the energy demand and methane yield increase.

The energy demand is higher compared to other alternatives such as knife mills and is around 40 kWh/ton fresh matter (Kratky and Jirout, 2011; Andersen *et al.*, 2022). The energy demand depends on the initial and final particle sizes, moisture content, feeding rate, material properties and machine parameters like the hammer tip speed and screen size (Kratky and Jirout, 2011). Bigger initial particle size and smaller final particle size increase the energy demand, but also higher moisture contents. The energy demand is higher for straw compared to dried grass and even lower for solid manure (see Table 8).

The increase in methane yield is around 20 % depending on the final particle size and substrate can vary significantly according to Table 8 (see section 4.2). Andersen et al. (2022) conducted a literature study and found for six laboratory studies that a methane yield of 120-200 m^3 CH_4/ton VS for non-treated wheat straw can be expected. By applying a hammer mill and decreasing the average straw size to 2-5 mm can a methane yield of 240 m^3 CH_4/ton VS be obtained. Some studies showed an increase of 250-290 m^3 CH_4/ton VS by decreasing the particle size down to 2-0.5 mm (Andersen *et al.*, 2022). One study performed for solid cattle manure found no statistically significant increase in BMP for treated manure, but saw an increase of 20 % for the methane production rate and reduction of 85 % for the apparent viscosity (Fernandez *et al.*, 2020).

Table 8. Summary of important properties for hammer mill

Substrate	Initial size mm	Final size mm	TS %	Energy demand kWh/ton ww	BMP untreated m^3 CH_4/ton VS	BMP treated m^3 CH_4/ton VS
Wheat straw [a]	200	1	70	43	120-200	240
Wheat straw [b]	21	2.4	95	31	-	-
Wheat straw [b]	7.7	1.9	90	36	-	-
Rye straw [b]	21	1.6	91	47	-	-
Dried grass *Miscanthus* [c]	125	10	90	16	-	-
Wheat straw [d]	50	1	90	-	237	269
Mixture with solid manure*[e]	0.1-5	<0.1	43	6	280	309

[a](Andersen *et al.*, 2022), [b](Kratky and Jirout, 2011) , [c](Moiceanu *et al.*, 2019), [d](Victorin *et al.*, 2020), [e](Garuti *et al.*, 2022), *Solid manure from chicken, cattle manure, maize silage, corn meal

An impact crusher, a type of hammer mill from the recycling/waste sector, has been identified as the most suitable for agricultural residues (Gunnarsson *et al.*, 2021). Examples of impact crushers can be seen from Lindner called the Limator and BioG called the Bio-crusher (Lindner, no date; BioG, no date). For example Linder's impact crusher, Limator L 1200, has an energy demand of 13-90 kWh/ton ww depending on the substrate (Lindner, no date). Examples of hammer mills are the Roto Grind 760 and I-Grind (Roto Grind, no date; I-Grind, no date).

4.3.2 Knife mill

Knife mills or shredders are often used for dry lignocellulosic biomass with a moisture content up to 15%, such as grasses, straw and other fodder crop waste (Kratky and Jirout, 2011). The technique consists of knives that cut the biomass in several different directions depending on the shape of the knives and the setting (Lund *et al.*, 2018). The cutting process occurs by rotary equipment equipped with several knives mounted on a spinning steel rotor. The feedstock is continuously cut until it can pass through a drum screen (Rodriguez *et al.*, 2017). The final particle size distribution varies with the feeding velocity, rotational speed of the rotor and the type of drums screen. The most important aspects of using a knife mill to digest agricultural residues can be seen in Table 9 and includes the energy demand and methane yield increase.

The energy requirement depends on the rotational speed, final particle size, the longitudinal angle that the knife is mounted and the bevel angle of the knife (Kratky and Jirout, 2011). The energy demand increases with higher moisture content, larger initial particle size and smaller final particle size (Montgomery and Bochmann, 2014). Knife mills generally have a lower energy demand for dry biomass compared to other mills such as hammer mills, around 10 kWh/ton fresh matter. But this can vary significantly, mostly due to smaller particle sizes (see Table 9). Knife mills are not suited for substrates containing stones or metal that can dull the knife blades (Montgomery and Bochmann, 2014). Maintenance of knife mills is needed after a few months by exchanging the knife blades when handled correctly (Lund *et al.*, 2018).

The methane yield for the untreated and pre-treated vary according to Table 9, with increases from 10 % up to 80 %, similar to the hammer mill. One study performed on wheat straw in a mesophilic batch process using a two-stage knife mill with a particle size distribution of 1.2 mm to 0.3 mm particle size, gave a 49% increase in methane yield with 251 m^3 CH_4/ton VS compared to 168 m^3 CH_4/ton VS for untreated straw with particle size of 30 mm. In addition, the methane production of the pre-treated straw was faster compared to the non-treated straw (Dell'Omo and La Froscia, 2018). Examples of commercial knife mills used for fibrous substrates are the RS Cut Master from Rasspe (Group Schumacher, 2016) with 15 kWh/ton ww (Lund *et al.*, 2018).

Table 9. Summary of important properties for knife mill

Substrate	Initial size mm	Final size mm	TS %	Energy demand kWh/ton ww	BMP untreated m^3 CH_4/ton VS	BMP treated m^3 CH_4/ton VS
Wheat straw [a]	30	0.3-1.2	93	67	168	246-265
Wheat straw [b]	70	2	87	-	182	334
Barley straw [b]	70	5	91	-	240	370
Wheat straw [c]	21	2-8.7	96	4.4-4.8	-	-
Wheat straw [d]	50	13	91	13	-	-
Switchgrass [d]	50	13	91	10	-	-
Mixture with solid manure*[e]	>5-1	1-0.1	88	34	266	300

[a](Dell'Omo and La Froscia, 2018), [b](Menardo *et al.*, 2012), [c](Kratky and Jirout, 2011), [d](Bitra *et al.*, 2009), [e](Garuti *et al.*, 2022), *Solid chicken manure, olive seeds and pomace, maize & triticale straw, by-products dairy industry cheese and milk

4.3.3 Bio-extrusion

Extruders are typically applied to manufacture objects with a fixed cross-sectional profile, but the technique has been proven to work efficiently to disintegrate lignocellulosic substrates (Ljungberg *et al.*, 2013). Bio-extrusion is mainly applied to wet substrates. Examples of agricultural residues included fresh ley and vegetable residues. The advantage of extrusion is that it is a continuous treatment and can easily be used in large-scale biogas production (Kratky and Jirout, 2011). Substrates are mechanically crushed and finely disintegrated. Frictional heat occurs in the process which opens up the lignocellulosic structures (Odhner *et al.*, 2015). The extruder technique consists of a feeding zone, transition and compression zone and a metering zone (Kratky and Jirout, 2011). In the feeding zone the material is fed in a tube by a screw, where it is exposed to high pressure, temperature, and shear forces. Around 2 bar and 160-180°C. The material exits through a matrix with a sudden pressure drop similar to that in steam explosion. This causes the particle size to decrease and the substrate to be partly degraded. Both which can increase the methane yield (Montgomery and Bochmann, 2014).

A summary of the energy demand and methane yields from literature sources can be seen in Table 10. The energy demand is higher for bio-extruder compared to the other alternatives but can vary significantly depending on the substrate from 4-86 kWh/ton fresh matter, see Table 10. But the energy demand can be increased to around 100-200 kWh/ton of fresh matter (Kratky and Jirout, 2011; Odhner *et al.*, 2015). Expensive maintenance is the major drawback to extrusion. The screws have to be changed after a few months and are sensitive to stones and metallic materials (Montgomery and Bochmann, 2014). The yearly maintenance cost can be up to 60 % of the investment of the extruder (Odhner *et al.*, 2015). In order to decrease the wear on the extruder wet materials are better to use, when using dry materials such as straw and silage it can be beneficial to soak it beforehand (Odhner *et al.*, 2015).

The methane yield increase of bio-extrusion has the potential to be higher compared to the hammer and knife mill since thermal degradation of the material is also performed (Odhner *et al.*, 2015). There are examples of BMP tests that achieve high methane yields, with increases around 70 %. But there are also examples where smaller or no increases were achieved (see Table 10). Odhner et al. (2015) made a thorough investigation of using bio-extrusion in biogas production using wheat straw and ley crops. It was concluded that the methane yield of grasses and straw could increase by 30 % by using an extruder with an energy demand of 86 kWh/ton ww and 30 days residence time. Another study (Hjorth *et al.*, 2011) investigated the methane yield for barley straw, fresh grass, solid manure from cattle and pigs and deep litter manure from cattle. The methane yield was 18-70 % higher for the substrates after 28 days but decreased to 9-28% after 90 days by using an extruder that consumed around 4-10 kWh/ton ww. Consequently, the main benefit of the extruder was to speed up the anaerobic digestion and not increase the overall methane yield (Hjorth *et al.*, 2011).

Examples of bio-extruders can be found from Lehmann GmbH. For example, the MSZB model which has an average energy consumption of 10 kWh/ton for grass silage, solid manure, and green waste and around 50 kWh/ton for straw. The reported increased methane yield is 35% for straw, 36% for solid cattle manure and 24% for grass silage (Lehmann, 2019). Another company is Promeco which has a model called Bioextruder© for organics (Promeco, no date).

Table 10. Summary of important properties for bio-extrusion

Substrate	Initial size mm	Final size mm	TS %	Energy demand kWh/ton ww	BMP untreated m^3 CH_4/ton VS	BMP treated m^3 CH_4/ton VS
Wheat straw [a]	-	-	90	86	253	298
Reed canary grass silage/baled [a]	-	-	64 /49	61/47	160/160	175/275
Szarvasi baled [a]	-	-	54	51	240	320
Wheat straw [b]	50	2	90	-	237	237
Barley straw 28/90 days [c]	50	5	91	-	160/320	272/353
Deep litter cattle 28/90 d. [c]	-	-	30	4-12	160/225	255/290
Maize silage, solid manure*[d]	5-0.1	0.1	38	4.3	309	318

[a](Odhner *et al.*, 2015), [b](Victorin *et al.*, 2020), [c](Hjorth *et al.*, 2011), [d](Garuti *et al.*, 2022), *Maize silage, potatoes skins, solid chicken and cattle manure, cattle slurry

4.3.4 Mixer wagon

Fodder wagon/mixer or mixer wagon is more suitable for farm-based and small-scale facilities. The fodder wagon is used as a feeding system to solid substrates where it is also disintegrated (Lund *et al.*, 2018). The machine is most commonly used batch wise to mix and chop fodder in the form of cereal straw, hay, or silage. It is usually equipped with rotating knives attached to screws which can be lying or standing. The substrate is removed from the machine by a screw or a moving tray. Fodder wagons are mainly used as a first rough disintegration of the substrate. They are often combined with a second step such as chopper pumps or a macerator for small-scale application or knife/hammer mill for large-scale operations (Gunnarsson *et al.*, 2014). Examples of fodder wagons are BvL V-mix agilo or plus depending on the size (BvL, no date) or Haybuster®'s CMF vertical mixers (Haybuster, no date).

5 Results

5.1 Potential of agricultural residues in RVG

5.1.1 Manure potential

The yearly manure potential in RVG can be seen in Figure 5 which is based on the number of livestock present in the area (see Appendix A and Table A.1). The manure production is the greatest for cattle and pig slurry and thereafter horse manure. Figure 5 illustrates the dry weight containing the organic matter used for anaerobic digestion and the water weight. Water is the dominating part of the manure production, especially for the cattle and pig slurry. This enables wet digestion by providing sufficient liquid to the process but also makes transportation expensive. Hence, there is a trade-off between a more energy dense substrate and process water that can be provided directly by the substrate.

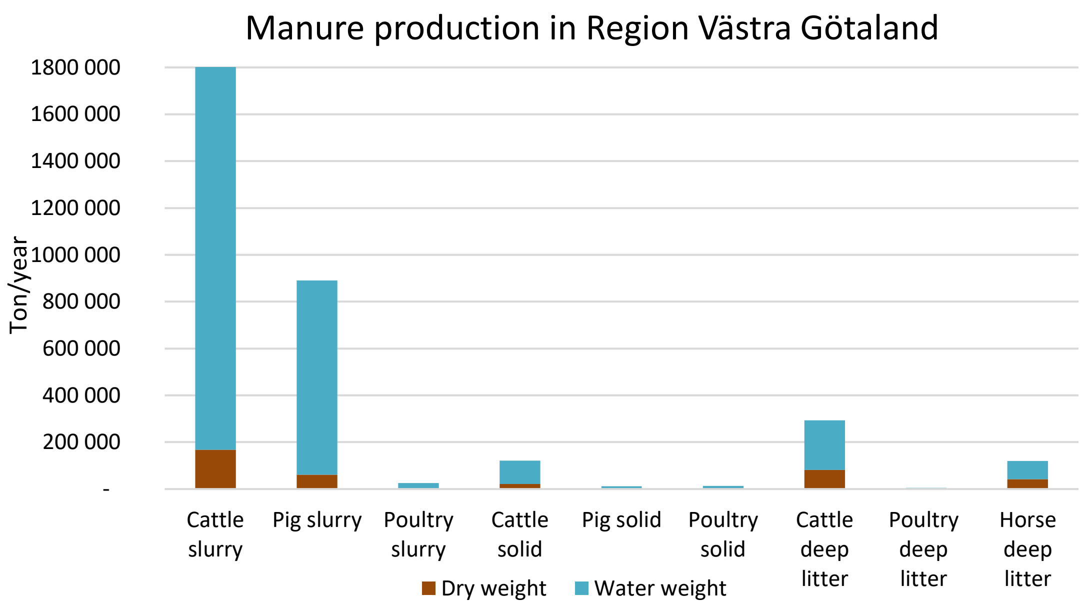

Figure 5. Manure production, ton per year in RVG with water weight and TS separated

The yearly energy potential of each manure type in RVG can be seen in Figure 6. These numbers are based on the amount of TS generated each year, the density and the methane potential of each substrate (see Appendix A). Cattle slurry has the dominating energy potential with 244 GWh generated each year and thereafter pig slurry with 122 GWh/year. Other manure types in RVG with great energy potential included solid and deep litter manure from cattle and horses. However, the choice of substrates is mostly dictated by nearby farms to the biogas plant and what equipment is available to receive solid fractions such as solid and deep litter manure.

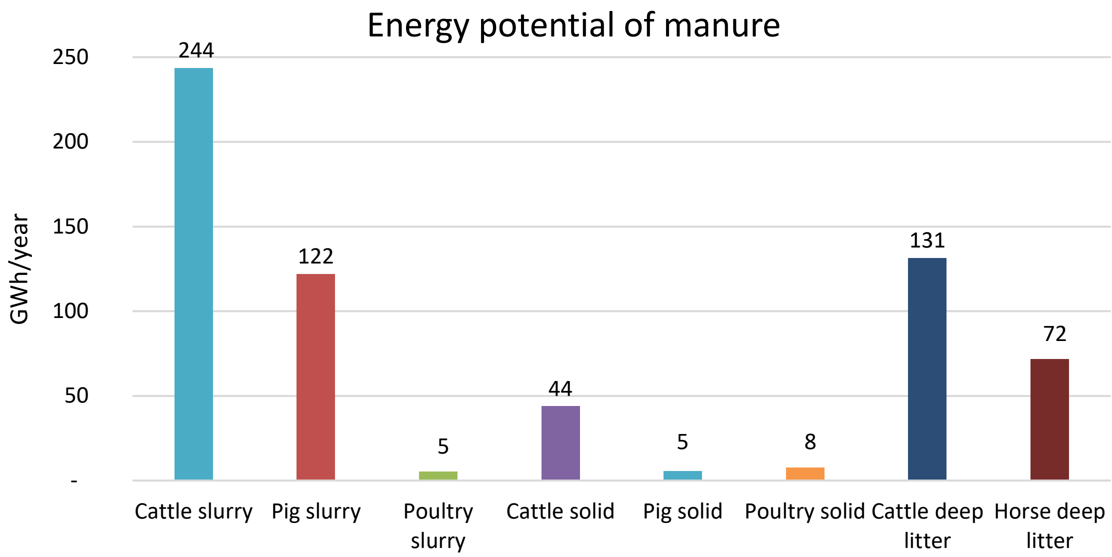

Figure 6. Energy potential in GWh for the TS content of respectively manure type each year

5.1.2 Crop residue potential

A summary of the yearly TS potential of each crop residue that can be incorporated in the biogas production is shown in Table 11. The crop residue in RVG with the greatest potential is straw, specifically winter wheat. The other straw with the potential includes winter rape, rye, winter triticale and oat straw. Straw from winter rape has a large potential due to not being used in husbandry and for having a large straw-to-grain potential (see Table A.6). Oat and spring barley are cultivated almost to the same degree as winter wheat (see Table A.5), but the TS potential is lower since more is used as animal bedding. The potential of excess and discarded ley silage with 1 % disposal is similar to that of rye straw. Whereas the 5 % and 10 % disposal of ley silage have higher TS potential, more similar to winter wheat straw. Out of the vegetable residues, peas have the greatest potential, but it is relatively small compared to the other crop residues.

Table 11. TS potential for crop residues in RVG per year

Crop residue	Ton TS/year
Winter wheat straw	157 100
Rye straw	14 200
Winter barley straw	4040
Winter triticale straw	8640
Spring wheat straw	1230
Spring barley straw	3660
Oat straw	6590
Mixed cereals straw	338
Winter rape straw	29 830
Ley silage 1 % disposal	15 990
Ley silage 5 % disposal	79 940
Ley silage 10 % disposal	159 900
Discarded food potatoes	1440
Food potato tops	5640
Residues from peas for processing	11 690

The following will include the energy potentials in GWh per year of the crop residues seen in Table 11, starting with straw. The total energy potential for straw is 445 GWh/year, it is dominated by winter wheat straw with 80 % of the potential in RVG, see Figure 7. Winter rape, rye and winter triticale also demonstrates significant potential and could be a viable substrate for facilities where they are grown in the near vicinity. The other straw types are less abundant and are not as accessible for biogas production.

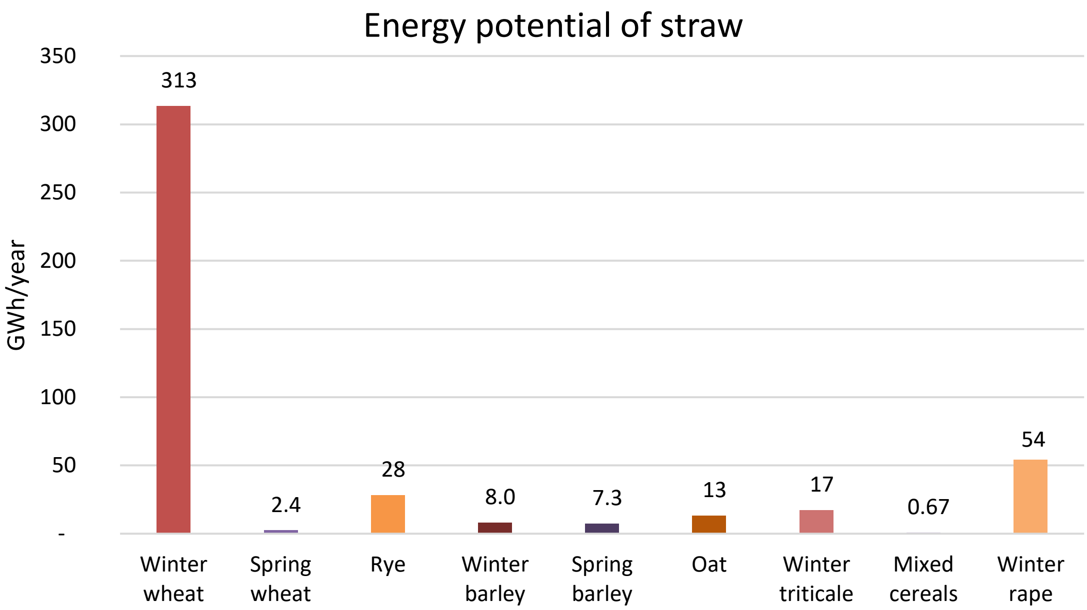

Figure 7. Energy potential in GWh for the TS content of respectively straw type each year

The energy potential of the other crop residues is included in Figure 8 which included the discarded and excess ley silage and residues from peas and potatoes. The energy potential of the ensiled ley varies from 38 to 377 GWh/year depending on the disposal degrees of either 1 %, 5 % or 10 % (see Figure 8). The energy potential of residues from peas is 35 GWh/year, for food potato tops 12 GWh/year and 6 GWh/year for discarded food potatoes.

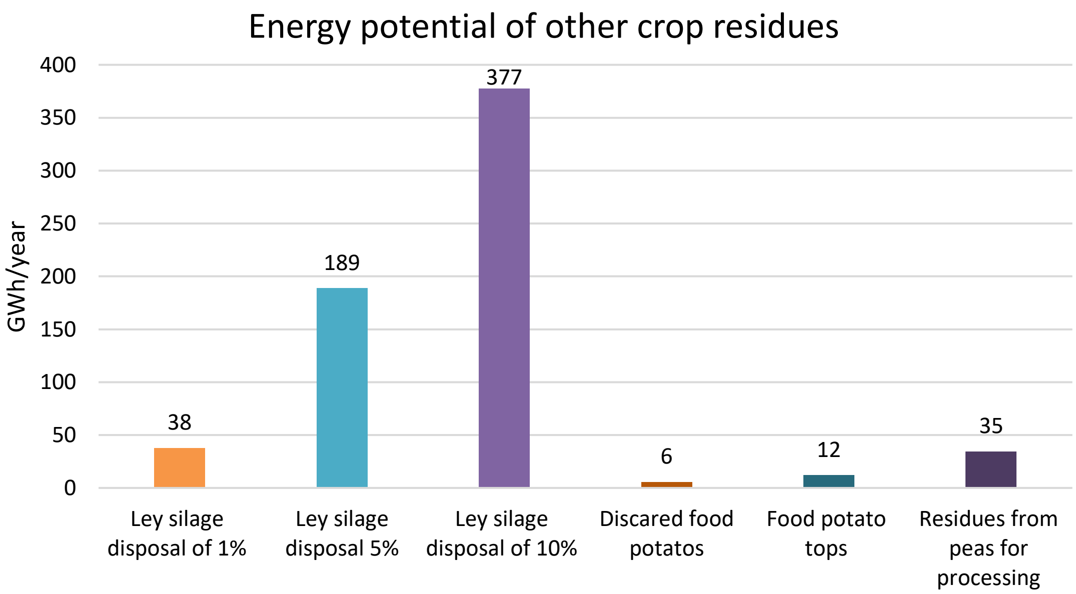

Figure 8. Energy potential of other crop residues including discarded and excess silage for three different disposals 1 %, 5 % and 10 % as well as pea and potato residues all in GWh/year

5.2 Survey of biogas plants

5.2.1 Existing capacity in RVG

A summary of the biogas production is shown in Table 12 for co-digestion and farm-based biogas plants in RVG. There are 7 co-digestion (CD) and 12 farm-based (FB) biogas plants in RVG. Table 12 illustrates that the energy produced is dominated by the co-digestion plants with 97% of the energy produced. The biogas facilities that took part of the interview study from RVG includes CD1, CD2, CD4-CD6 and from the FB biogas plants, Götestorp and Häljeredsgård (See section 3.3.1).

Table 12. Summary of existing capacity of biogas production in RVG 2020

Co-digestion (CD)[1]	GWh/year	Farm-based (FB)[1, 2]	GWh/year
Gasum Lidköping (CD1)	65	Gajan biogas	1.6
Gasum Skövde (CD2)	23	Qvantenburgs säteri	3.0
RenaHav (CD3)	10	Grinsta gård	3.7
Falköping biogas (CD4)	4.0	Sylves lantbruk	3.7
Sobacken Borås (CD5)	30	Brunsbo lantbruk AB	0.70
VH biogas (CD6)	23	Svenstorp	0.30
Vadsbo biogas (CD7)	18	Högebo gård	0.84
Sum	173	Häljeredsgård	0.07
		Götestorp	0.80
		Horshaga lantbruk	0.07
		Nygårdens BiHjogas	0.08
		Sötåsen	0.50
		Sum	15.4

[1](Biogas Väst, 2020), [2](Eliasson, 2015)

The composition of the substrate digested by co-digestion and farm-based biogas plants in RVG is depicted in Figure 9. In total 658 500 ton fresh matter is digested per year. The most common substrates are manure with 44 % of the total fresh matter digested and industrial food waste with 42 %, thereafter municipal food waste. All biogas plants in RVG use wet digestion to produce biogas, thus the TS content is around 5-10 % for the substrate composition and the rest is mainly water. The farm-based biogas plants and Vadsbo biogas (CD7) utilise manure exclusively. Whereas the co-digestion plants differentiate in their utilisation of substrates. Gasum Lidköping (CD1), RenaHav (CD3) and Sobacken Borås (CD5) are the facilities that do not digest manure. However, only a small fraction of manure is digested at Gasum Skövde (CD2) and Falköping biogas (CD4). It can be seen that crop residues from agriculture are not used to a large extent with 2 % of the total amount and is only digested at Gasum Lidköping

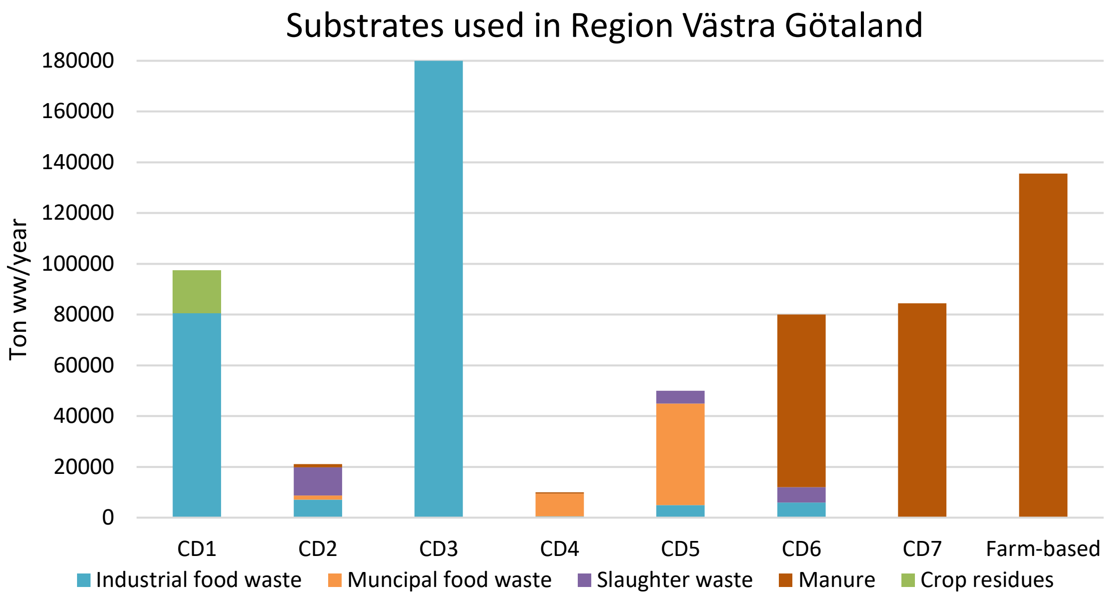

Figure 9. Substrate composition of biogas plants in RVG 2022 in ton ww/year, co-digestion (CD)

The agricultural residues that are utilised in RVG each year can be seen in Table 13. The dominating agricultural residue used in biogas plants in RVG is cattle and pig slurry, however 90 % of this is water weight. Other manure types that are utilised to a high degree includes solid manure from poultry and pigs. Residues from cereal cultivation is the most used crop residue. Ley is not used to a high extent in today's biogas production. Previously, Vadsbo biogas had a substrate mixture consisting of 10 % ley. But this was too expensive, and the concept was abandoned according to correspondence with the company[3]. Additionally, Table 13 displays today's utilisation of agricultural residues related to the total potential seen in section 5.1. It can be seen that even though cattle and pig slurry is dominating, there is still a lot of potential to digest more. Solid manure from pig and poultry are the ones where the potential is utilised the most. Because the total potential is much less compared to slurry. The other agricultural residues still have a large potential to be incorporated into the biogas production but require some kind of pretreatment step and a process that is adapted to handle fibrous solid substrates.

Table 13. Agricultural residues used in RVG biogas production in 2022 and the utilisation degree

Manure type	**Ton ww/year**	**GWh/year**	**Utilised of total potential %**
Cattle and pig slurry	279 500	38	10
Cattle solid manure	908	0.3	0.7
Pig solid manure	4 220	1.9	35
Poultry solid manure	3 350	1.9	24
Cattle deep litter manure	908	0.4	0.3
Sum	288 900	42	9.6
Crop residue			
Discarded cereals and straw	15 030	26	6.6
Ley silage (5 % disposal rate)	1 670	1.4	0.7
Sum	16 700	27	3.6

[3] Vadsbo biogas, telephone call on the 20th of Mars 2022.

5.2.2 Commercial biogas process

This section will include how a process can be designed to handle agricultural residues that need pretreatment. Based on biogas plants with experiences of this and a study visit. All the questioned biogas plants preferred a stationary pretreatment solution.

5.2.2.1 Co-digestion biogas plants

Of the investigated biogas plants two co-digestion plants stated that they had adapted the process of handling fibrous crop residues, one biogas plant in RVG, Gasum Lidköping and Gasum Katrineholm (CD9) located in Södermanland county. The substrate includes cereal residues consisting of discarded grain and straw and discarded silage. However, the facilities do not use long stalks of the cereal straw. They prefer chopped straw which then is finely milled. Gasum Lidköping has had trials with long stalks. Floating layers will form when it is not chopped enough. Pumps and other equipment can also get clogged. Both plants have a wet and mesophilic digestion. They utilise a hammer mill to disintegrate straw and ley silage is added directly to the mixing well. Gasum Lidköping states that they have not had problems with crust formation from floating silage and this is due to having a lot of liquid residues from industries which homogenise the mixture. A stone separator is used prior to the hammer mill to remove inert objects. Other Gasum facilities use a magnet separator to remove metal objects. The facilities have positive experiences digesting fibrous residues. The main difference in digesting these kinds of substrates is an increased residence time of about two weeks. Gasum Lidköping states that an understanding of the complete process is needed to introduce fibrous substrates. Like how the microorganism will adjust to the change in substrate and OLR.

The other investigated co-digestion facilities do not have a process that are able to digest fibrous residues from agriculture. In addition, these plants have not investigated how they can adapt their process or what equipment that would be suitable. Falköping biogas (CD4) and VH biogas (CD6) experienced problems with including fibrous substrates. Because their facilities were not being adapted to handling more fibrous and dry substrates. Falköping biogas attempted to add horse manure to the process by disintegrating it with a mill which crush municipal solid food waste. This was not successful, because the manure got stuck prior to reaching the mill in the feeding system. Which consist of screws and a gripping claw and is designed for liquid substrate. However, they are still unsure if the mill can handle fibrous substrate. The idea was abandoned since the facility was not equipped to handle the substrate. In comparison, VH biogas has a solid feeding system where they add discarded animal feed for cats and dogs. Previously ensiled ley was added here, but this caused problems in the process. The silage would rise to the top and create a crust which was hard to break down with the agitators. However, the plant incorporates solid manure from pigs and poultry in their process. This is added directly to the mixing well using a wheel loader. If too much is loaded into the reactor clumps can start to build up and in the worst case a crust can form. Stopping the biogas from being released.

5.2.2.2 Farm-based biogas plants

There are two examples of farm-based biogas plants handling more fibrous substrates in the form of manure containing straw in the interview study. One cattle farm, Götestorp (FB1) uses slurry, solid and deep litter manure from cattle. This is disintegrated using a mixer wagon and homogenised with slurry using a macerator, Rotacut from Vogelsang (Vogelsang, no date). The macerator is a vital part to produce a mixture with appropriate TS content that can be pumped into the reactor, by diluting deep litter manure (50-60 % TS) with slurry and liquid digestate. The experiences of handling more fibrous substrates are overall positive even though it makes the process more complex. In return can all the manure be incorporated. The generated biofertilizer is more effective and much easier to spread out onto the field compared to the solid manure fractions. Another benefit is that the iron slurry which is added to decrease the hydrogen sulphide levels is better to mix with the solid/deep litter manure. It tends to sink to the bottom otherwise when mixed with the slurry and form clumps.

A study visit was performed for a farm-based biogas plant, Rånghult biogas (FB3) in Jönköping County, in an area adjacent to RVG. The plant digests slurry and deep litter manure from cattle using the process shown in Figure 10. The final storage of the biofertilizer after leaving the post-digester lacks a roof and the addition of deep-stable manure is therefore vital for the process. Because this generates a crust which prevents nutrient leakage. Rånghult biogas can also utilise the heat generated from the process by heating a neighbouring green-house year round that produces organic tomatoes. The deep litter manure is firstly disintegrated using a mixer wagon, BvL V-mix Agilo (BvL, no date) and then mixed with slurry which lets heavy particles to sediment like stones. The mixture is then homogenised with a chopping pump, which disintegrates the mixture further, and pumped through a matrix that has a size of 2 cm. This ensures that inert objects that did not sediment do not enter into the reactor. The substrate is fed to the reactor and simultaneously preheated with 5-10°C by being heat exchanged with the digestate leaving the reactor. After the anaerobic digestion the digestate is pumped to a post-digester and then used as a biofertilizer. The heated biogas is used to heat water, which is used for heating the green-house prior to entering the gas engine, a Chevrolet V8. The mechanical work from the engine is transferred to the generator which produces electricity. The waste heat from this energy conversion can be up to 65% and is also used to heat the district heating for the green-house.

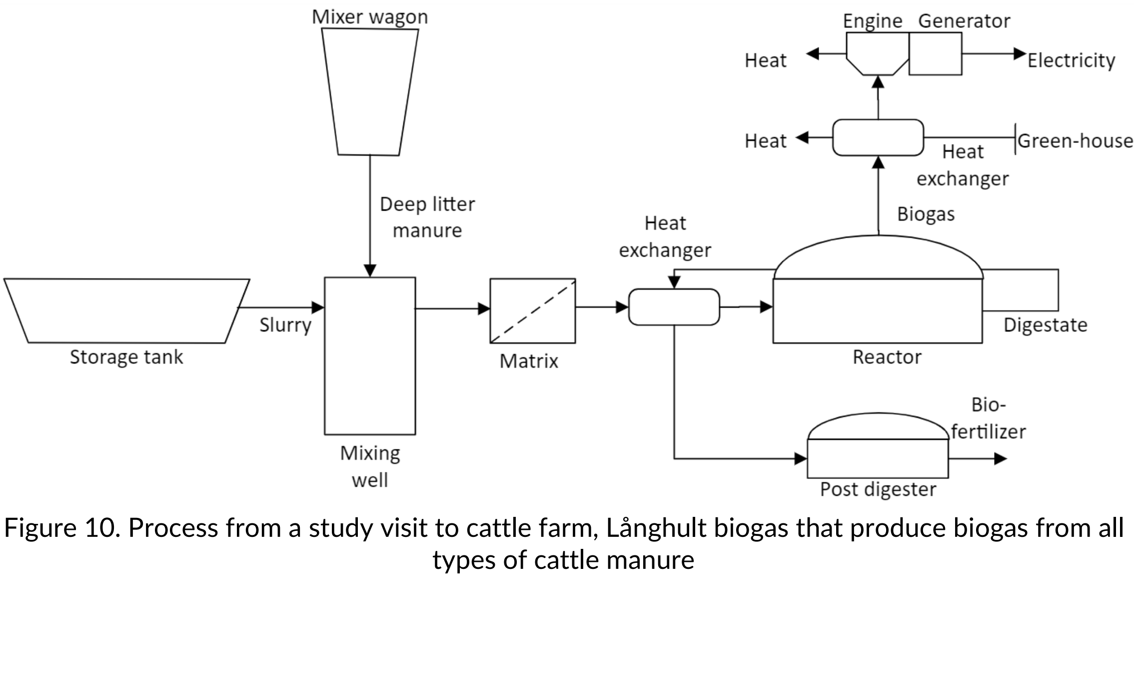

Figure 10. Process from a study visit to cattle farm, Rånghult biogas that produce biogas from all types of cattle manure

5.2.3 Interest of including agricultural residues

A summary of which types that are of interest for the questioned biogas plants is given in Table 14. Almost all facilities are interested in utilising agricultural residues in their process, the interest is mainly for digesting manure. Only one facility stated that they had no interest, Sobacken Borås (CD5), since it is not located in an agricultural area which makes transportation expensive.

The farm-based biogas plants were mainly interested in the manure from the livestock on the farm but not in any crop residues. Häljeredsgård (FB2) was only interested in cattle slurry since it is a convenient and reliable substrate. Götestorp (FB1) and Långhult (FB3) biogas are interesting in all fractions of manure that is produced on the farm, since the generated biofertilizer is easier to handle. The farm-based plants stated that they were not interested in any other residues on the farm such as discarded ley silage or left over fodder. Since sufficiently large quantities are not produced on the farm and that dirt and other inert objects accumulate when stored at the farm.

The main interest from the co-digestion plants was on slurry from cattle and pigs. The main contributor to this is that the manure-gas aid provides more economical stability and is easily anaerobically digested. Advantages of adding slurry that was stated includes a more stable process, including more methanogens and replacing the need of adding fresh water. The facilities that only were interested in slurry said that it was the only substrate that was suitable to add to their process. There was also focus on digesting more solid manure from pig and poultry from biogas plants (see Table 14) since this contains more energy and less water, making transportation less expensive. Deep litter and straw-rich manure was of less interest since it requires a more complex process. The potential biogas plant Gasum Götene (CD8) stated that they were interested in adding deep litter manure into the process. Gasum Lidköping (CD1) showed some interest, but they are currently lacking environmental permits to digest manure.

When it came to fibrous crop residues the interest was low. Most of the biogas plants are not adapted to handle these substrates and cannot see that there will be incitement for it in the near future. The only interest came from Gasum Lidköping and Gasum Katrineholm (CD9) but also from the prospective biogas plant Gasum Götene. Gasum Lidköping is located nearby a large factory making spirits from locally produced winter wheat. Which is the reason that they are interesting and digest a relatively large fraction of cereal residues. Gasum Götene was mostly interested in discarded silage and leftover fodder from the farm that they will get manure from. These three facilities were also the only ones that would be interested to make adaptations and changes to their facilities in the near future. If that was needed for them to expand their substrate composition.

Table 14. Summary of agricultural residues of interests for biogas plants in RVG

Agriculture residue	Interested biogas facility
All types of manure	CD1, CD8, CD9, FB1, FB3
Slurry and solid manure	CD6
Only slurry	CD2, CD4, FB2
Fibrous crop residues	CD1, CD8, CD9
No interest	CD5

Co-digestion (CD), farm-based (FB) biogas plants

5.2.4 Obstacles of including agricultural residues

A summary of the obstacles stated by the biogas plants can be seen in Table 15. The most common was TS content, process related problems, having to invest in new equipment and adapt the facility.

Firstly, the obstacle mentioned by all the interviewees to introduce fibrous agricultural residues in their process is the TS content in the reactor. All facilities use wet digestion which sets a limit of 6-8% TS. Consequently, there must be a balance between the liquid and the dry substrates to ensure that the mixture can be pumped and mixed. Sobacken Borås (CD5) states that the trade-off of handling drier substrates is a lower cost of transport but a cost of adding process water and diluting the substrate. An extreme case is Gasum Skövde (CD2) which is limited to having a TS content of 1 % in the reactor. This requires that only liquid substrates are digested and limits the use of dry and fibrous substrates from being used.

Thereafter is the main obstacle to invest in adapting the wet digestion process to accept more fibrous and dry substrates. Mechanical pretreatment is needed to decrease the particle size to ensure that the substrate can be efficiently digested, pumped, and homogenised with the rest of the substrate. However, investing in a pretreatment step may not be sufficient since the process cannot handle dry and fibrous substrates despite being disintegrated. Other equipment is needed such as top mounted agitators, more powerful pumps, a separate solid feeding system, stone and gravel separation and magnetic separator. For example, Falköping biogas (CD4) struggled to add horse manure due to its feeding system, before reaching the mechanical pretreatment. VH biogas (CD6) mentioned that their main obstacle is that the plant is not adapted to receive dry and fibre-rich substrates. They would need some kind of mechanical pretreatment, but they have not looked at what type. The general picture by the facilities that do not have any fibrous substrates today (CD4, CD5, CD6 and FB2) is that the investment needed is too expensive and not worth the energy that will be produced. In addition, Falköping biogas and Sobacken Borås states that it would be better to introduce slurry since this is simpler and that they would be compensated by the manure-gas aid. The larger biogas plants at Gasum did not see adapting their facility further as an obstacle.

Additionally, the interviewees mentioned several problems that could occur in the process associated with agricultural residues. The greatest concerns were clogged pumps, inert objects such as stone, gravel or metal parts, crust formation, heavy sediments and that the substrate would get tangled with the equipment. Häljeredsgård (FB2) mentioned that they have deep litter manure and left over animal feed left but are not interested in digesting it. Due not having the correct equipment and that it would make the process too complex and prone to failure.

Other obstacles were experienced by a few biogas plants (see Table 15). One is transport distances, and this was mentioned by facilities located in medium sized cities, Gasum Lidköping (CD1) and Sobacken Borås. Gasum Götene stated that today’s limit is 25 km. Low nitrogen levels were a concern for Gasum Lidköping. Sobacken Borås mentioned several factors that would affect their process, including longer residence time, contamination of the biofertilizer and difficulties in adapting the thermophilic microbial community to new substrates.

Table 15. Summary of mentioned obstacles from the biogas plants of including fibrous resides

Obstacles	Biogas facility
TS content	All the questioned
Facility not adapted	CD2, CD4, CD5, CD6, FB2
Problems in the process	CD2, CD4, CD5, CD6, FB1, FB2
Invest in mechanical pretreatment	CD4, CD5, CD6, FB2
No economic incitement	CD4, CD5, CD6 FB2
Transport	CD1, CD5
Nitrogen levels	CD1
Longer residence time, adaptation of microorganisms and contaminate biofertilizer	CD5

Co-digestion (CD), farm-based (FB) biogas plants

5.2.5 Potential expansion in RVG

The potential expansion stated by the biogas plants in the interview will be described in the following section and the limitations. The expansion consists of the possibility of implementing more agricultural residues to increase the biogas production at the existing facilities. The intended biogas plant, Gasum Götene, will be presented, and its capacity will be included in the potential expansion scenario.

5.2.5.1 Possible substrate expansion

Gasum Lidköping has ambitions to expand the biogas production with 40 000 tons/year by using other substrates such as manure or MSFW. But are waiting to get a new environmental permit approved. Gasum Skövde has an environmental permit to handle more substrates, about 60 000 tons more per year. Falköping biogas could double their substrate intake to 20 000 ton/year, by expanding their upgrading facility or selling the raw gas to a district heating plant. Likewise, VH biogas could expand the production with 50 %, 160 000 ton substrate per year if they expand the upgrading facility. Sobacken Borås is operating at its maximum capacity. This is connected to the fact that they recently invested in a new pretreatment technique and larger post digestion chamber. Gasum Götene is designed to produce 120 GWh/year and handle solid and deep litter manure as well as fibrous crop residues such as discarded silage. They will do this by mechanical disintegration by milling or chopping. The TS content will be balanced by mixing in slurry which has 5-6 % TS with the drier material and end up with a total process with 10 % TS content. To reach this may other types of liquids be added such as water, whey, or diluted water from a dairy industry nearby.

Based on these interview results and the substrate composition of the investigated plants can a potential substrate expansion in RVG be seen in Figure 11. The data from the interviews can be seen in Appendix B. The biogas plants that were not included in the interview study are assumed to have the same potential as today (see Figure 9). By introducing the expansion from the biogas plant and the addition of Gasum Götene increases the total substrates digested with 64%. The amount of manure digested increases with 70 % and the crop residues with 78 % compared to the current potential (in ton ww/year). Compared to the current potential, manure will play an even more important role in the biogas production in RVG and crop residues will be utilised more.

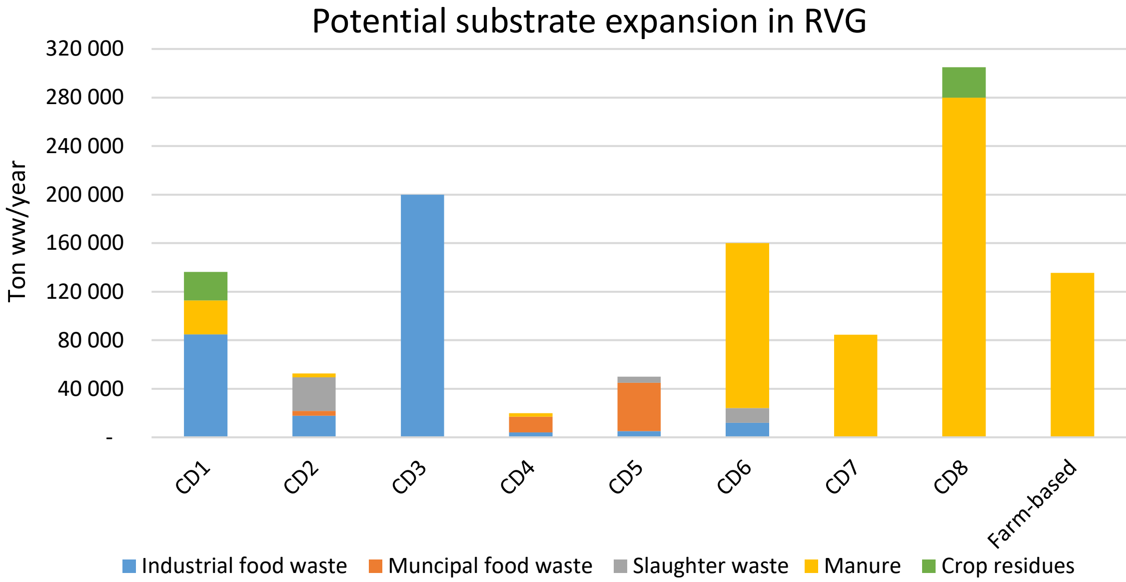

Figure 11. Potential future expansion of the biogas production in RVG, co-digestion (CD)

A summary of the agricultural residues and which types of the potential expansion can be seen in Table 16. The energy produced from manure can increase to 115 GWh/year and 69 GWh/year for crop residues. The dominating substrate is still pig and cattle slurry (see Table 13) and this will have the biggest increase, in addition will poultry slurry also be utilised. The use of solid and deep litter manure will also increase substantially compared to the current biogas production. Furthermore, the utilisation of ley and silage will increase to a large extent while the increase of straw and cereals will be less predominant. The utilisation of manure increased from 10 % to 22 % and from 4 % to 13 % for crop residues. The substrates that are utilised to the highest degree include the solid manure from pig and poultry. The substrate with highest potential of further increase of utilisation includes cattle solid manure/deep litter, straw, horse manure, ley and silage and slurry from cattle and pigs.

Table 16. Potential expansion of agricultural residues in RVG and the utilisation degree

Manure type	Ton ww/year	GWh/year*	Utilised of total potential %
Cattle and pig slurry	589 400	80	22
Poultry slurry	11 080	2.3	44
Cattle solid manure	5 108	1.8	4
Pig solid manure	8 420	3.8	70
Poultry solid manure	9 000	5.0	66
Cattle deep litter manure	32 470	14	11
Horse manure	14 840	8.6	12
Sum	670 350	115	22
Crop residue			
Cereals and straw	24 790	41	11
Ley silage (5 % disposal rate)	32 900	28	14
Sum	57 690	69	13

*Energy consumed of mechanical pretreatment is included for fibrous residues (see Table 18)

5.2.5.2 Limitations to expanding the biogas production

A summary of the limitation can be seen in Table 17. The biggest limitation for the large Gasum biogas plants (CD1, CD8 and CD9) is to get new environmental permits. That allows them to expand both their biogas production and the selection of substrates. Gasum Lidköping (CD1) has ambitions to expand the biogas production by using other substrates but are limited to their current environmental permit and are waiting for a new one to be approved. Gasum Götene (CD8) states that it is unclear how long it takes for the government agency to make a decision and handle appeals. It has overall been a lengthy process and it is still not certain if they can construct the facility.

For the farm-based biogas plants was one limitation available substrate on the estate. Häljeredsgård (FB2) mentions that their generator of 11 kW runs at its maximum capacity. Their farm is too small for large investments to expand their production. They have about 70 cows and state that over 100 animals would be more economically viable since more fibrous residues would be available. FB2 is also limited to their area of arable land where they can produce animal feed, due they are located near a larger city. However, the farm does not wish to produce more than they consume due to having to pay more tax. Furthermore, Götestorp (FB1) has no plans to expand the biogas production since this requires another digester. One option could be to have a thermophilic process since this would decrease the residence time or alternatively add a post digester. Långhult biogas (FB3) is part of a pilot for small-scale LBG production and would therefore like to expand their biogas production. The farm is limited to both the substrate available on the farm and its new environmental permit. The farm has ambitions to expand beyond 3 GWh/year by building a second reactor and also accepting other substrates such as manure from other farms or charcuterie waste.

Both Falköping biogas (CD4) and VH biogas (CD6) have the reactor volume and environmental permit to expand their biogas production. Their limitation is the upgrading facility which currently runs at its maximum capacity. Sobacken Borås (CD5) is currently producing at its maximum capacity and has talked about doubling their production but that can only be realised if there is a demand for it.

Table 17. Summary of the limitations for a potential expansion of the biogas plants

Limitations	Biogas facility
Environmental permits	CD1, CD8, CD9, FB3
Substrate availability	FB1, FB2, FB3
Upgrading facility	CD4, CD6
Reactor volume	CD5, FB1
Generator	FB2
Demand/interest of biogas	CD5

Co-digestion (CD), farm-based (FB) biogas plants

5.3 Analysis of mechanical pretreatment

The following sections will include an analysis of the fibrous agricultural residues that can be included from the potential expansion of the biogas production in RVG. Two scenarios will be considered, one where the straw and ley silage can be assumed to be chopped and one where it contains long stalks. Sensitivity analysis will be performed for parameters that exhibit fluctuations in their values.

5.3.1 Energy analysis

The following section will consider the energy balance of using a hammer mill to disintegrate fibrous agricultural residues for the expansion seen in Table 16. The increase of the methane yield for the substrates is set to 20%, seen in Table 18. The ley silage and solid manure have the highest methane yield. Substrates containing more lignocellulose, like horse and deep litter manure along with straw has lower methane yields.

Table 18. TS, VS, and methane yield increase after the mechanical pretreatment

Substrate	TS %	VS%	Untreated m^3 CH_4/ton VS	Pre-treated m^3 CH_4/ton VS
Cattle solid manure	18	80	208	250
Pig solid manure	24	80	200	240
Cattle deep litter manure	28	80	167	200
Horse manure	35	80	178	214
Straw	86	90	185	222
Ley silage	38	90	220	264

The energy demand of operating the hammer mill seen in Table 19 and is given by kWh to process one ton of fresh substrate. The energy demand ranges from 8-50 kWh/ton ww for the fibrous substrates. It is highest for long-straw crop residues since these require extra processing and lowest for the solid manure since it has smaller particle size and less bedding material is present. EROI seen in Table 19 has a range of 3.7 to 9.6 and illustrates the ratio of the energy gained by performing the mechanical treatment against the energy demand of that operation. A higher value indicates that more energy is gained by the pretreatment, less electricity has to be added for a certain methane yield. EROI is highest for the solid pig manure with a value of 9.6 and thereafter cattle solid manure and chopped straw. The lowest values were given by deep litter manure and long-straw ley silage. In addition, Table 19 displays the ratio of the energy consumed by the mechanical pretreatment and the energy gained, where a smaller value of this indicates a more efficient energy gain. The energy consumed of the energy gain varies from 10 % for solid manure from pigs to 27 % for long-straw ley silage.

Table 19. Energy demand, EROI and ratio of energy consumed of energy gained

Substrate	Energy demand kWh/ton ww	EROI	Energy consumed of energy gain in %
Cattle solid manure	10	6.0	17
Pig solid manure	8	9.6	10
Cattle deep litter manure	20	3.7	27
Horse manure	20	5.0	20
Straw chopped	45	6.3	16
Ley silage chopped	30	5.0	20
Straw long-straws	55	5.2	19
Ley silage long-straws	40	3.8	27

The ratio between the energy gained and the energy consumed by performing mechanical pretreatment in GWh/year is illustrated in Figure 12. With the purpose of illustrating the energy consumed to the energy gained for each fibrous agricultural residue seen in Table 19. The proportion is quite similar for the fibrous residues but not the magnitude. The total energy is highest for straw and ley silage since more is digested in the potential expansion (see Table 16). Another factor is also the TS content seen in Table 18 since the water present in the substrate will not yield methane.

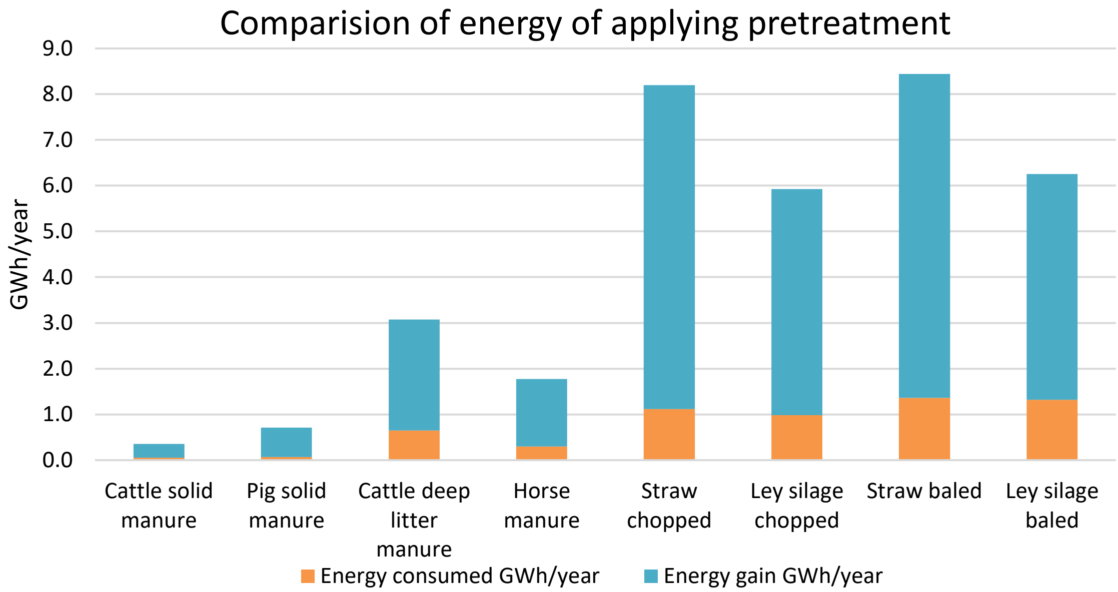

Figure 12. Comparison of the energy gained by using a hammer mill (blue bars) and the energy required (orange bars) for fibrous agricultural residue in GWh/year

A sensitivity analysis was performed for the energy demand of the hammer mill shown in Figure 13. This is susceptible to vary depending on aspects such as quality of the substrate, machine type and how it is operated. The axes of Figure 13 are in logarithmic scale to showcase the differences between the substrates clearer. The energy demand was set to vary between 1 to 300 kWh and was compared to the EROI index. To see if the substrates instead of being an energy source becomes an energy sink (when EROI is equal or less than one). EROI varies from 290-0.4 for this range. It can be seen that straw obtains the highest EROI values for different energy demands and cattle solid manure has the lowest. The first break-point occurs at 60 kWh/ton ww for solid cattle manure, 80 kWh/ton ww for pig and deep litter manure, 100 for horse manure and 150 kWh/ton ww for ley silage. Lastly, straw showcased a break-point at 290 kWh/ton ww. However, it is important to note that straw and ley silage are much more likely to reach energy demands above 100 kWh/ton ww compared to manure.

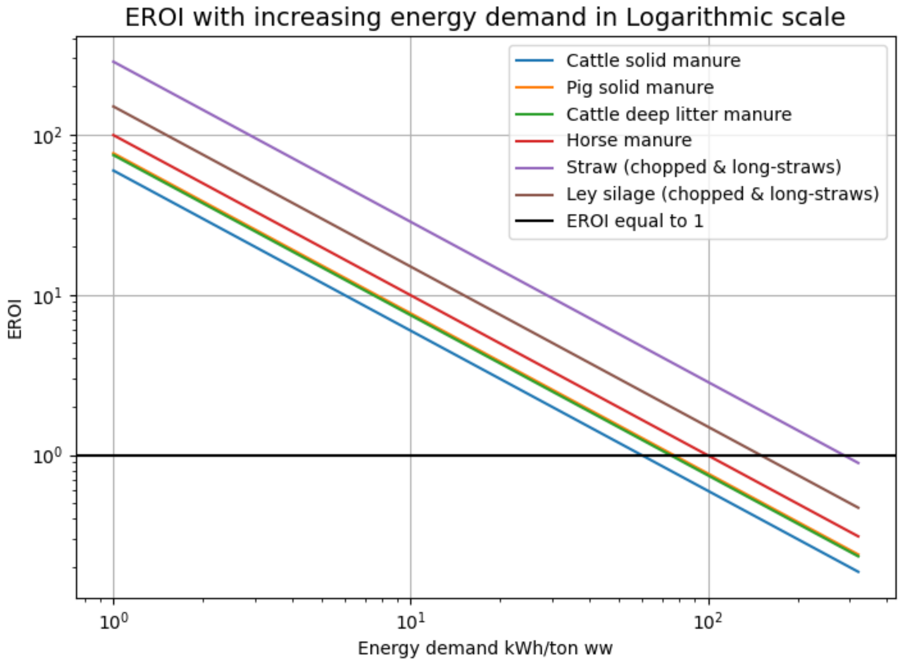

Figure 13. The EROI with varying energy demand by utilising a hammer mill in Log-scale

A similar sensitivity analysis seen in Figure 14 was also conducted for the methane yield gain of performing mechanical pretreatment since this parameter tends to vary as well. The methane yield gain ranges from no gain, equal to 1 and an increase with 40 % given by 1.4. It is however most likely that it will be between 10-30 %. Over this range the EROI varies from 0-19. For no gain in methane yield, to a 40 % increase in methane yield for solid pig manure. It can be seen that the breakpoint for the residues is around 5 % or less. EROI for solid manure from pigs increase the most with an increased methane yield and the rest of the residues have more similar values with solid manure from cattle having a higher EROI values and deep litter manure having the lowest.

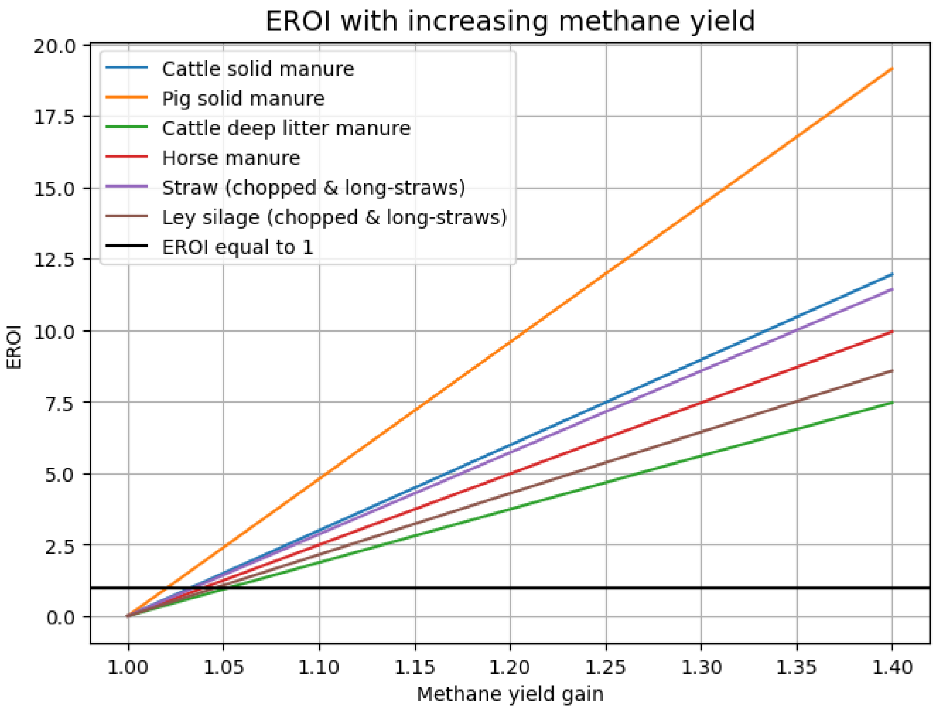

Figure 14. The EROI with varying methane yields gain obtained by utilising a hammer mill

5.3.2 Economic analysis

By comparing the income of the energy gain as a result of using a hammer mill and the cost of that energy for the fibrous residues can the specific profit be calculated, seen in Table 20. The specific added profit illustrates the economic gain of performing the mechanical pretreatment instead of the energy. It can be seen in Table 20 that straw has the highest specific added profit ranging from 192-198 SEK/ton ww, thereafter is the ley silage with 93-100 SEK/ton ww and the manure fractions is between 41-66 SEK/ton ww. When the specific profit is related to the dry matter of the substrate the difference between the fibrous residues is less and is between 165-263 SEK/ton TS. With the chopped ley having the highest specific profit. In addition, Table 20 displays how the specific added profit relates to the value of the untreated substrate. To compare what can be gained if a hammer mill is utilised. It can be seen that the fraction of the specific fraction is similar for all fibrous residues, around 16-18% of the untreated profit.

Table 20. Specific cost difference in SEK/ton ww and SEK/ton TS, how that relates to the profit of not using mechanical pretreatment and the total profit in million SEK/year

Substrate	Specific added profit SEK/ton ww	Specific profit SEK/ton TS	Specific added profit of untreated substrate in %
Cattle solid manure	41	228	17
Pig solid manure	56	233	18
Cattle deep litter manure	46	165	16
Horse manure	66	189	17
Straw chopped	198	231	17
Ley silage chopped	100	263	17
Straw long-straws	192	223	17
Ley silage long-straws	93	245	16

The magnitude of the profitability of introducing the fibrous agricultural residues from the potential expansion in RVG, shown in Figure 15. The blue bars represent the specific added profit of performing the mechanical pretreatment and the orange is the untreated profit which also can be considered the residual income. The total profitability is highest for straw and ley silage with 33 and 23 million SEK/year, respectively. In addition, it can be seen that the difference of the profitability between chopped and long-straws is not large. For the manure fractions the potential profitability is lower since less is available to anaerobically digest and therefore can less be incorporated into the biogas production.

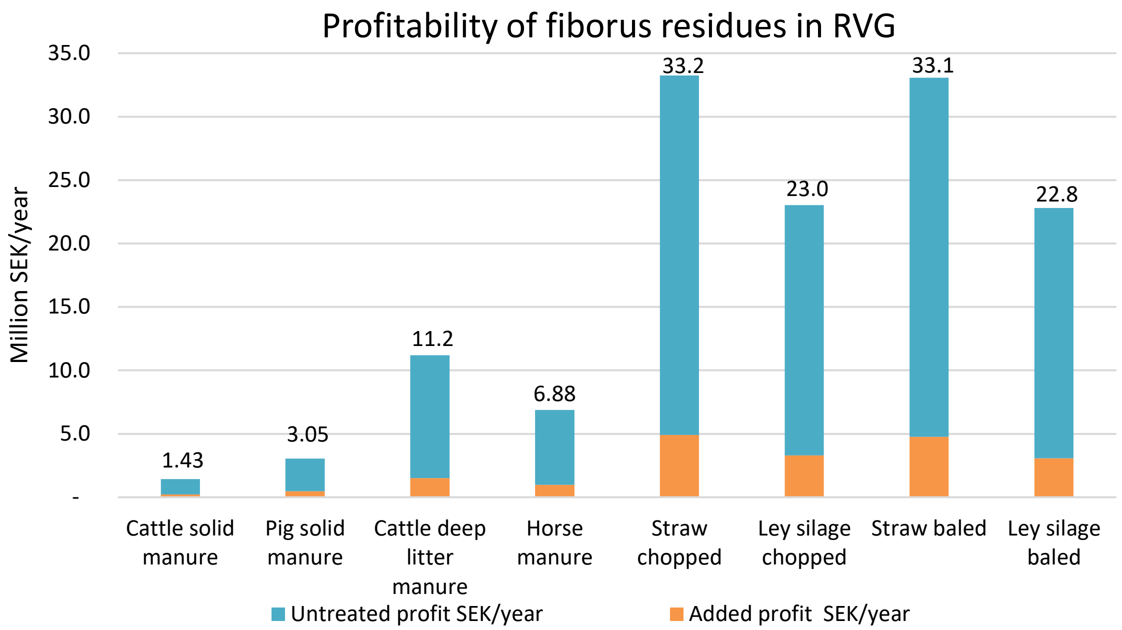

Figure 15. Profitability of fibrous residues is represented by the whole bar in million SEK/year with the specific added profit (blue bar) and specific untreated profit (orange bar)

A sensitivity analysis was conducted for the specific cost of the fibrous substrates by varying the electricity price, seen in Figure 16. This is of importance due to large fluctuations of the electricity price during the past months. The obvious trend is that the specific profitability of the substrate decreases with increasing electricity prices. It can be seen that straw is less sensitive towards this, due to having a higher initial profit. The substrates with the lower energy demand are also less impacted like solid manure compared to deep litter manure and ley silage.

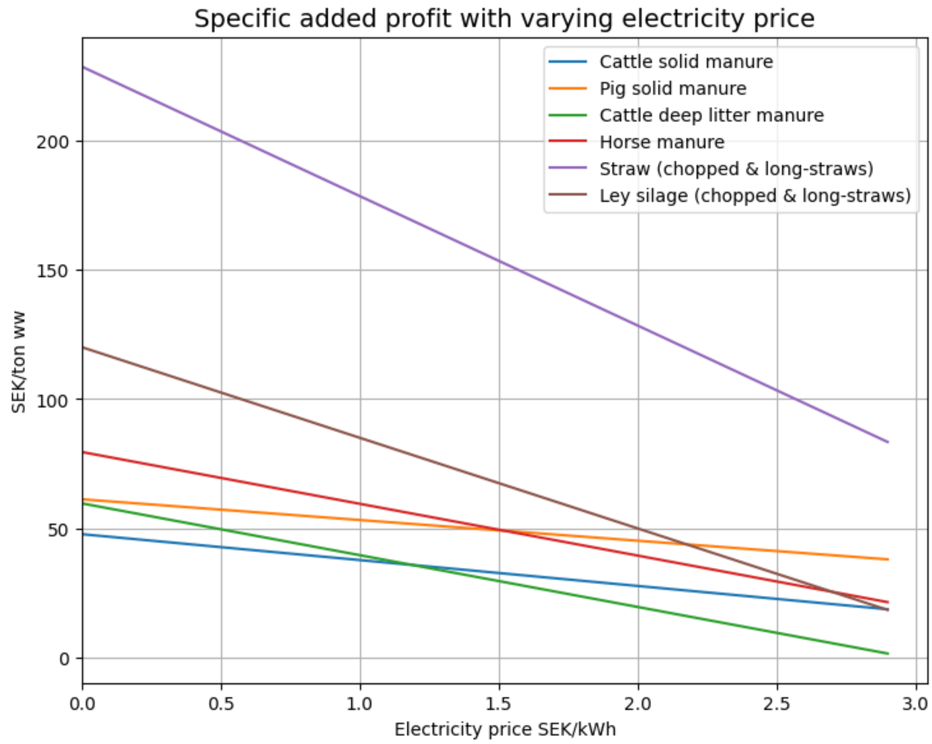

Figure 16. The specific added profit with varying electricity price in SEK/ton ww

6 Discussion

6.1 Residual agriculture streams in RVG

RVG is a region with great potential for the production of biogas from waste and residues, where agricultural residues represent a great potential. Manure is today the largest residual stream from agriculture that is digested, accounting for 42 % of the total substrate digested by co-digestion and farm-based plants. Slurry from cattle and pig is the most common manure type digested. Mainly due to being compatible with wet digestion and for receiving the manure-gas aid.

The total theoretical potential of agricultural residues in RVG according to this study is 1.31 TWh/year, with 5 % disposal rate of ley silage. The potential from manure is 621 GWh/year and 480-819 GWh/year for crop residues, for varying disposal rate of ley silage. In comparison, the total agricultural potential found in Broberg et al. (2022) for RVG is 1.41 TWh/year. The higher value can be explained by that the report included ley grown on fallow land. The manure potential found in Broberg et al. (2022) was 411 GWh/year, meaning the manure potential found in this thesis may be overestimated. Another comparison can be done with the straw potential in RVG from (Börjesson, 2016) which was assessed to 450 GWh/year. The potential found in this thesis was 445 GWh/year, which corresponds to the value found in Börjesson (2016).

The biogas production in RVG can increase from today's 300 GWh/year to the goal of 1.2 TWh/year by introducing more agricultural residues and adapting facilities to handle fibrous substrate, like installing mechanical pretreatment. The agricultural residual stream with the most potential include slurry from cattle and pig slurry and winter wheat straw, with the energy potentials of 366 GWh/year and 313 GWh/year respectively. The fibrous manure fractions are also a major source, where solid and deep litter manure from cattle and horse manure together corresponds to 236 GWh/year. The energy potential of discarded and excess ley silage can also be important but can vary significantly, around 38-377 GWh/year.

The other agricultural residues include solid manure from pigs and poultry. These are more energy dense but have an overall lower energy potential of per year, as they are not produced to a great extent. Likewise with vegetable residues, the TS potential is small compared to the other crop residues, but the energy potential is still relatively large, 53 GWh/year. Due to the high methane from being easily degradable and containing less lignocellulose. Straw from winter rape is another interesting substrate with an energy potential of 54 GWh/ year, since this is not utilised as animal bedding. Hence more can be incorporated as substrate. The combined energy potential of the other cereal straws has a lower energy potential of 76 GWh/year compared to winter wheat, since more is being used as animal bedding but also for being grown less. Ley crops that are cultivated with the purpose of being a substrate can be of importance in the future. Such as incorporating ley crops in the crop rotation, using it as a catch crop and collecting from municipal areas. This is of significance since it can enable the extraction of straw by maintaining the soil fertility from the cultivation of nitrogen-fixing ley crops such as clover. The limitation today is that it is too expensive compared to the biogas produced.

Manure is prioritised over crop residues but the main limitation of using manure is expensive transportation, due to the high water content. It is less expensive for solid or deep litter manure but less is available compared to slurry. However, the environmental benefits of the cultivation of ley crops can be equated with manure thus creating an incentive of introducing a ley-gas aid. Still, relying on aid could pose problems for the biogas production sector. The interest of digesting more fibrous residues can also occur if a HTL facility is built in RVG since the solid fraction of the digestate can be used as a feedstock in the process to produce bio-oil and char. Additionally, the focus should be on creating a more profitable sector and increasing the value chain. One future possibility can be a symbiotic relationship between local biogas plants and a regional biorefinery.

6.2 Commercial biogas process for agricultural residues

For the choice of pretreatment, the literature review and interview study concluded that mechanical pretreatment was the best choice for a commercial process even if other techniques such as chemical and thermal increase the methane yield more. The main reason for this is that it provides a cost effective, robust and less complex process. The other alternatives cannot provide this. Because some disintegration is still needed to be compatible with the wet digestion, effluent streams are generated that have to be treated and inhibitory products can form. However, there is an opportunity of heat integration which can increase the energy efficiency compared to mechanical pretreatment

The mechanical pretreatment to incorporate agricultural residues were both investigated by current processes at biogas plants in RVG and theoretically. For the large-scale was hammer mills utilised and for small-scale was mixer wagons used. Successful biogas processes of digesting fibrous residues from agriculture were found at four biogas plants in the interview study with some key aspects to consider. The first is to have some kind of mechanical pretreatment where the material is chopped sufficiently small to not cause problems in the process. Demonstrated examples include hammer and knife mill, extruder and mixer wagon. If long straws are used, two steps are usually required, in the form of shredders or choppers. Secondly, the dry substrate must be homogenised to create a pumpable slurry that can be added to the reactor. This can be achieved with adding liquid substrate or recycled digestate. Equipment used for this included a macerator and mixing well with a chopping pump. The removal of inert objects is also vital not to damage the equipment including the mechanical pretreatment. This can be done with various measures, such as sedimentation wells, matrix or stone/magnet separators. However, at the farm-based plants was the separation performed after the mechanical pretreatment step. The reason is that the mixer wagon does not perform a fine disintegration and is therefore less impacted compared to a hammer mill. Moreover, other essential adaptations include a solid feeding system, stronger agitators and pumps.

The hammer mill was chosen to investigate further due to being commonly used and having a moderate energy demand. Additional equipment was also needed to incorporate long-straws. The EROI index indicated that the energy required for the mechanical pretreatment was less than the energy delivered in the form of added biogas production, with values from 3.7 to 9.6 for the fibrous residues. The highest EROI value was given by the solid pig manure and the lower for lignocellulosic substrates. However, straw had a relatively high EROI value despite having the highest energy demand, due to having a higher TS content. The energy consumed of the energy gain for the different agricultural residues was not major, with values between 10- 27 %. The difference between chopped and long-straws was also relatively small with 3 % and 6 % difference. It was higher for ley due to a larger water content. The energy gain that can be obtained from the expansion in RVG is greatest for straw and excess ley silage since more is digested and available but also that manure contains more water.

The sensitivity analysis performed for EROI with a varying energy demand showcased that solid and deep litter manure from cattle is the most sensitive. These became energy sinks at 60-80 kWh/ton ww. Straw and ley silage were the least sensitive, with being an energy sink at 150 kWh/ton ww for ley silage and 290 kWh/ton ww for straw. But it is more realistic that the energy demand for straw and ley could exceed 100 kWh/ton ww than manure which requires less disintegration. A different behaviour was seen for the EROI with increasing methane yield since the specific energy demand is used. Resulting in the highest EROI increase for the substrates with the lowest energy demand, like pig solid manure. Ley silage and cattle deep litter manure increased the least with added methane yields due to having relatively high energy demands and low TS contents. A methane yield increase of 5 % is needed for the fibrous substrates to be an energy source. Meaning that the biodegradability does not have to increase much for it to still pay off.

The positive energy balance for implementing mechanical pretreatment found in this study could shift, as the useful work that biomethane and electricity can deliver for the same kWh differ. However, this is dependent on the end application of the energy. With the current energy production and high electricity prices is this highly relevant. In doing so must the environmental and economical values of producing biomethane be considered. For example, that the produced digestate that can replace mineral fertilisers or that the dewatered digestate be a possible feedstock in a biorefinery in the future.

The added profit of the increased biogas production left from the electricity consumed when using mechanical pretreatment showed that the substrates with the highest energy demands gave the highest specific profit per fresh ton, such as straw and ley. The reason for this is that the income of biogas is higher than the electricity price. Resulting in that the TS content and not the energy demand will be a key parameter. This was clearly illustrated between the two scenarios, where the difference in the added profit for straw and ley of chopped and long-straws was almost zero. However, the addition of process water is also associated with an added cost. When looking at the added profit per ton TS is the difference between the substrates less significant, where the manure fractions exhibit similar profits as straw. Similarly, the added profit is around 17% of the total profit for all fibrous residues. As expected, substrates with high energy demands were more sensitive towards increasing electricity prices but an important conclusion is that high electricity prices are needed, above 3 SEK/kWh for the added profit not to pay off.

6.3 Existing capacity, potential expansion and interest for biogas plant in RVG

The responses from the interviews have provided key insights of the current capacity and how it can be expanded. It should be noted that not all biogas plants, especially the farm-based, participated in the study. Consequently, the interview study may not cover all activities happening in the biogas sector in RVG. Co-digestion is the most important actor, standing for 56 % of RVG's total biogas production and has the greatest potential of expanding its biogas production by incorporating more agricultural residues. The expansion of the biogas production by the interviewed biogas plants of incorporating agricultural residues in RVG is 184 GWh/year, presuming that Gasum Götene will be built. This is feasible and about 14 % of the total theoretical agricultural residue potential. The main limitation of the expansion was difficulties of receiving an environmental permit, meaning that there are strong reasons for making the process more efficient.

Manure was the substrate that most biogas plants were interested in due to being compatible with their process and receiving the manure-gas aid. For example, Gasum Götene chooses fibrous manure over crop residues since they will get aid for it. Fibrous residues which have the largest unrealized potential were only of interest for the biogas plants that already digest them. The other biogas plants were not interested due to not having the suitable equipment and no future plans of making adaptations to the facility. Another important aspect that determined the interest of a substrate was the closeness to the biogas plant. The farm-based biogas plants stated that the only substrate available in enough quantities were manure. Crop residues were not generated enough and contained objects that could damage the equipment.

The most significant obstacle of introducing fibrous residues from agriculture is that it would entail a more complex process which is more prone to failure. Suggesting that the knowledge and techniques in this field must increase and be more widely spread. The most important aspect is the TS content is higher for fibrous substrates, which requires a more careful review of the water content in the reactor. A dry digestion process would be more suitable, but further development and knowledge is needed for it to be chosen. This is important since rapid developments are made for other renewable technologies such as hydrogen and electrification. Similar efforts should be made for the biogas sector, as it provides a circular solution and has less impact on the use of critical metals.

Process related problems stated by biogas facilities lacking mechanical pretreatment were crust formation, sedimentation, tangles and more. Meaning that the plants must be adapted, the main being to install mechanical pretreatment. This was seen as an obstacle due to the increased cost and complexity. The biogas plants belonging to the company Gasum were the only ones that had interest in adapting its process to receive other types of substrates. The general opinion was that it would be better to build facilities adapted from the start that could digest fibrous residues, like Gasum Götene. Obstacles concerning an increased energy demand or methane yield were not raised by the biogas plants, but were the main concerns emphasised by research and literature.

Overall, there is little incentive to introduce fibrous crop residues in the process even if there is a great energy potential. Slurry is still abundant, require no pretreatment or adaptations and the manure-gas aid creates an economic reason, although it contains mostly water. The biogas facilities that can benefit from digesting more dry substrates are those that do not have slurry in the near vicinity but want to expand their production. Consequently, the usage of fibrous residues and especially crop residues will not increase dramatically unless there is a need of or demand of increasing the biogas production. However, due to the current events and a need to replace fossil fuels from Russia, the interest of expanding the biogas production in Sweden has grown. This may be a turning point for an increased utilisation of fibrous residues coming from agriculture.

6.4 Further studies

Further studies can investigate the potential expansion of farm-based biogas plants and examine the interest and potential of cultivation of ley crops as a biogas substrate. It would also be preferable to perform a complete economic and energy analysis of implementing mechanical pretreatment. A life cycle analysis on the usage of electricity to produce biomethane to include environmental benefits is another research area. The useful work of electricity and biomethane for different applications can also be analysed.

7 Conclusions

It was concluded that the total energy potential from agriculture residues in RVG is 1.31 TWh/year, where the fibrous residues account for around 68 %. Hence, the goal of anaerobically digesting 1.2 TWh/year in RVG can be realised if the biogas plants are able to handle dry and fibrous substrates. The interview study concluded that the operating biogas facilities in RVG can increase its production with 184 GWh/year by incorporating agricultural residues. The main limitation for this is receiving environmental permits. The potential to include more is still great, as 78 % of the manure potential and 87 % of the straw and excess/discarded ley silage potential remain unutilised after the expansion.

Manure was of highest interest for being compatible with wet digestion and given economic incentive. It was concluded that implementation of fibrous residues requires adaptations to the operating biogas plants, such as adding mechanical pretreatment. This was only feasible for large or a network of biogas plants or by designing a facility from the start. The important conclusion is that the implementation of fibrous crop residues must become more profitable to be of interest and compete with manure. Options presented include, ley-aid, a symbiotic relationship with a regional biorefinery and an increased demand of biomethane.

It was concluded that the most suitable pretreatment for biogas production is mechanical pretreatment. The most suitable for large-scale operations is a hammer-mill and a mixer wagon for small-scale. The study concluded that an increase of 5 % of the methane yield is needed for the mechanical pretreatment to pay off. The energy gained will exceed the energy invested when the energy demand is below 60 kWh/ton ww for manure, 150 kWh/ton ww for ensiled ley and 290 kWh/ton ww for straw. Similarly, an electricity price below 3 SEK/kWh is needed for it to be profitable.

Conclusions from the thesis is that higher TS content gives a higher energy density, less transportation cost and is more profitable. At the same time, high TS contents is the main limitation for biogas plants. It was concluded in the energy and economic analyses that the difference between long-straws and chopped substrates is not large. Meanwhile, the operating biogas plants concluded that both are unfavourable for the process.

The conclusion from the literature review is that the increase of methane yield and energy demand of pretreatments is of great importance. The most important feature for operating biogas plants is a robust and efficient design. They concluded that fibrous residues are too dry, cause problems and result in a complex process. In conclusion, research should focus on developing a trustworthy process and equipment that can handle dry and fibrous substrates in a wet digestion process.

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Appendix A: Agricultural potential calculations

Table A.1 Types and number of livestock in RVG 2020

Type of livestock	Number of animals
Dairy cattle	53 393
Cattle for breeding of calves	34 913
Beef cattle	87 595
Calves, <1 year	82 165
Sheep, rams and ewes	38 098
Lambs	36 157
Sow for breeding	25 316
Pigs for meat >20 kg	169 141
Pigs for meat <20 kg	60 747
Laying hens	634 421
Laying chicken	56 603
Broilers	1 321 929
Horses*	56 400

*Statistics from 2016

Table A.2 TS content in % for different types of animals and manure type

Type of livestock	TS content %		
	Slurry	Solid manure	Deep litter manure
Dairy cattle	9	18	28
Cattle for breeding of calves	10	18	28
Beef cattle	10	18	28
Calves, <1 year	10	18	28
Sow for breeding	8	24	-
Slaughter pig >20 kg	6	24	-
Slaughter pig <20 kg	6	24	-
Laying hens	12	30	-
Broilers	-	-	30
Horses	-	-	35

Table A.3 Total manure production dry weight for each type of animal and manure

Type of livestock	Slurry TS m^3/year	Solid manure TS m^3/year	Deep litter manure TS m^3/year
Dairy cattle	118 624	7 175	5 044
Cattle for breeding of calves	8 700	4 050	26 951
Beef cattle	26 034	11 463	86 939
Calves, <1 year	15 105	6 598	45 759
Sow for breeding	30 641	2 965	-
Slaughter pig >20 kg	30 477	888	-
Laying hens	3 015	4 568	-
Broilers	-	-	2 776
Horses	-	-	83 895

Table A.4 Methane and energy potential for each type of manure

Manure type	CH_4 m³/year	Energy potential GWh/year	Energy potential %
Cattle slurry	24 427 140	244	39
Pig slurry	12 223 660	122	20
Poultry slurry	503 466	5	1
Cattle solid	3 294 566	33	5
Pig solid	520 191	5	1
Poultry solid	756 433	8	1
Cattle deep litter	13 175 486	131	21
Horse manure	7 173 023	72	12

Table A.5 Crop areal per year in RVG average over period 2016-2020

Type of crop	Areal of crop ha/year	Percentage of arable land
Winter wheat	67 774	14.7
Spring wheat	9 782	2.1
Rye	5 781	1.3
Winter barley	2 206	0.5
Spring barley	44 298	9.6
Oat	62 757	13.6
Winter triticale	4 281	0.9
Spring triticale	358	0.1
Mixed cereals	5 029	1.1
Winter rape	11 897	2.6
Spring rape	686	0.1
Cook-fodder peas	12 559	2.7
Peas for processing	2 338	0.5
Brown beans	3	0.0
Maize	762	0.2
Mowing- grazed pasture lands	177 642	38.6
Ley for seeds	4 555	1.0
Food potato	2 089	0.5
Potato for starch	92	0.0
Flax	416	0.1
Garden plants	734	0.2
Other crops	1 050	0.2
Energy forest	760	0.2
Fallow	33 825	7.3
Unspecified land	1 873	0.4
Total arable land	460 401	100

Table A.6 Properties of straw and harvest in RVG

Cereal type	Norm harvest kg ww/ha year	Salvage coefficients	Straw to grain ratio	Straw kg ww/ha	Straw ton ww/year
Winter wheat	6 860	0.93	0.6	3 828	259 431
Spring wheat	4 058	0.76	0.66	2 035	19 911
Rye	5 590	0.93	0.78	4 055	23 442
Winter barley	5 700	0.93	0.57	3 022	6 664
Spring barley	5 108	0.71	0.37	1 342	59 442
Oat	4 618	0.71	0.52	1 705	106 999
Winter triticale	5 514	0.93	0.65	3 333	14 269
Mixed cereals	3 452	0.71	0.445	1 091	5 485
Winter rapeseed	3178	0.90	1.02	2755	32 779

Table A.7 Straw potential for biogas production

Cereal straw	Residual straw ton ww/year	Residual straw ton TS/year	CH_4 m^3/year	Energy potential GWh/year
Winter wheat	182 710	157 131	31 426 171	313
Rye	16 509	14 198	2 839 590	28.3
Winter Barley	4 693	4 036	807 277	8.05
Winter triticale	10 049	8 642	1 728 420	17.2
Spring wheat	1 425	1 226	245 161	2.44
Spring barley	4 255	3 659	731 899	7.30
Oat	7 660	6 587	1 317 459	13.1
Mixed cereals	393	338	67 534	0.67
Winter rape	32 779	29 829	5 428 883	54

Table A.8 Potential of discarded and leftover ley silage in RVG per year

Hectare harvest ton TS/ ha year	9		
TS%	35%		
Total ley silage ton TS/year	1 598 776		
Degree of disposal silage %	1	5	10
Residual ley silage ton TS/year	15 988	79 939	159 878
Residual ley silage ton ww/year	45 679	228 397	456 793

Table A.9 Potential and properties of crop residues

Type of residue	Food potato	Food potato tops	Peas for processing
Norm harvest kg ww/ha year	36 313	-	-
Residues ton TS/year	1 441	5 639	11 691

Appendix B: Interview survey

Interview questionnaire in Swedish:

1. **Biogasprocessen**
   1.1. Ungefär hur mycket biogas producerar ni per år (GWh/år), ligger ni då på maxkapacitet av anläggningens potential eller ert tillstånd?
   1.2. Hur är fördelningen av ert substrat, rötas fiberrika substrat, om ja, hur hanteras dessa, erfarenheter-lätt/svårt, behövs särskilt teknisk kompetens?
   1.3. Används några förbehandlingssteg på er produktionsanläggning?
   1.4. Hur hanteras rötresten?
2. **Reströmmar i jordbruket**
   2.1. Finns det ett intresse hos er att använda fiberrika reströmmar från jordbruket så som halm, fastgödsel, kasserat ensilage, vall, spannmål som substrat och vad beror intresset på?
   2.2. Kan ni med er befintliga anläggning ta emot den här typen av substrat och i så fall hur mycket?
   2.3. Anser ni att det finns hinder för att inkludera den här typen av substrat och i så fall vilka? (få tag i materialet, teknikkompetens saknas, behöver köpa in ny utrustning)
   2.4. *Gårdsanläggning:* Hur ser ni på att använda halm och vall från er egen växtodling som substrat i er biogasproduktion?
3. **Hantering**
   3.1. Hur ser ni på att använda er av fiberrika substrat, till vilken grad kan ni tänka er att anpassa verksamheten så som att lägga till ett förbehandlingssteg eller köpa in ett sönderdelat substrat?
   3.2. Om ni skulle tänka er att lägga till mekanisk sönderdelning, hade ni då föredragit en mobil eller stationär lösning och vad beror det på?

Table B.1 Data from interviews with substrate used for biogas production in RVG 2022

	Industrial food waste	Municipal food waste	Slaughter waste	Manure	Crop residues
CD1	80 600	-	-	-	16 700
CD2	7 120	1600	11080	1 332	-
CD3	180 000	-	-	-	-
CD4	500	9000	-	500	-
CD5	5 000	40000	5000	-	-
CD6	6 000	-	6000	66 998	-
CD7	-	-	-	84 500	-
Farm-based	-	-	-	135 521	-

Table B.2 Data from interviews with substrate for potential expansion biogas production in RVG

	Industrial food waste	Municipal food waste	Slaughter waste	Manure	Crop residues
CD1	84 840	-	-	28 000	23 380
CD2	17 800	4 000	27 700	3 100	-
CD3	200 000				
CD4	4 000	13 000	-	3 000	-
CD5	5 000	40 000	5 000	-	-
CD6	12 000	-	12 000	136 000	-
CD7	-	-	-	84 500	9 300
CD8	-	-	-	279 990	25 010
Farm-based	-	-	-	135 521	-

Appendix C: Analysis of mechanical pretreatment

Table C.1 Data for the substrate's energy when untreated, treated, the difference of them (gain, energy consumed) and the difference between gain and consumed (net energy)

Substrate	Energy untreated kWh/year	Energy treated kWh/year	Energy gain kWh/year	Energy consumed kWh/year	Net energy GWh/year
Cattle solid manure	1 525 210	1830 250	305 040	51 080	1.78
Pig solid manure	3 223 580	3 868 300	644 720	67 360	3.80
Cattle deep litter manure	12 108 630	14 530 360	2 421 730	649 330	13.9
Horse manure	7 373 820	8 848 580	1 474 760	296 790	8.55
Straw chopped	35 395 310	42 474 370	7 079 060	1 115 710	41.4
Ley silage chopped	24 677 070	29 612 490	4 935 420	986 900	28.6
Straw long-straws	35 395 310	42 474 370	7 079 060	1 363 640	41.1
Ley silage long-straws	24 677 070	29 612 490	4 935 420	1 315 860	28.3

Derivation of the total profit (see equation 11)

$$P_{total}\frac{SEK}{year} = E_{total} \cdot \frac{kWh}{year} \cdot I_{gas}\frac{SEK}{kWh} - E_{consume}\frac{kWh}{year} \cdot C_{el}\frac{SEK}{kWh} \tag{12}$$

The methane yield can be expressed as: $M_{treated} = M_{gain} + M_{untreated}$

$$E_{total}\frac{kWh}{year} = m_s \cdot TS \cdot VS \cdot M_{treated} \cdot 9.97 = E_{gain} + E_{untreated} \tag{13}$$

$$P_{total} = E_{total} \cdot I_{gas} \cdot (E_{gain} + E_{untreated}) - E_{consume} \cdot C_{el} = P_{untreated} + P_{treated} \tag{14}$$

Table C.2 Data for the specific untreated profit, income of the energy gain and cost of the energy consumed

Substrate	Untreated profit SEK/ton ww	Income of energy gain SEK/year	Cost of energy consumed SEK/year
Cattle solid manure	239	244 033	34 220
Pig solid manure	306	515 772	45 131
Cattle deep litter manure	298	1 937 381	435 051
Horse manure	398	1 179 811	198 849
Straw chopped	1 142	5 663 249	747 524
Ley silage chopped	600	3 948 330	661 220
Straw long-straws	1 142	5 663 249	913 640
Ley silage long-straws	600	3 948 331	881 626

Appendix D: Sensitivity analysis code

Python code for energy balance with varying methane yield

```
import matplotlib.pyplot as plt
import numpy as np
#Mass flow for each substrate
A=np.array([5107.5, 8420.0, 32466.5, 14839.5, 24793.5,32896.5])
TS=np.array([0.18, 0.24, 0.28,0.35,0.86,0.38])
VS=np.array([0.8, 0.8, 0.8, 0.8, 0.9,0.9])
#Untreated methane yield for each substrate
UnCH=np.array([208,200,167,178,185,220])
#Energy demand for each substrate
Ereq=np.array([10,8,20,20,50,35])
k1=A*TS*VS*UnCH*9.97
k2=A*Ereq
#Varying methane yield of mechanical pretreatment
x = np.arange(1,1.45,0.1)
labels= []
for i in range(len(k1)):
    plt.plot(x, ((k1[i]*(x-1))/k2[i]))
    labels.append("Cattle solid manure")
    labels.append("Pig solid manure")
    labels.append("Cattle deep litter manure")
    labels.append("Horse manure")
    labels.append("Straw (chopped & long-straws)")
    labels.append("Ley silage (chopped & long-straws)")
    labels.append("EROI equal to 1")
plt.axhline(y=1, color='black', linestyle='-')
plt.title('EROI with increasing methane yield', fontsize=14)
plt.ylabel('EROI')
plt.xlabel('Methane yield gain')
plt.grid()
plt.legend(labels)
plt.show()
```

Python code for energy balance with varying energy demand

```
import matplotlib.pyplot as plt
import numpy as np
#Mass flow for each substrate
A=np.array([5107.5, 8420.0, 32466.5, 14839.5, 24793.5,32896.5])
TS=np.array([0.18, 0.24, 0.28,0.35,0.86,0.38])
VS=np.array([0.8, 0.8, 0.8, 0.8, 0.9,0.9])
#Untreated methane yield for each substrate
UnCH=np.array([208,200,167,178,185,220])
k1=A*TS*VS*UnCH*9.97
k2=A
#Varying energy demand of mechanical pretreatment
x = np.arange(1,300,0.1)
labels= []
for i in range(len(k1)):
    plt.plot(x, (k1[i]*(1.2-1))/(k2[i]*x))
    labels.append("Cattle solid manure")
    labels.append("Pig solid manure")
    labels.append("Cattle deep litter manure")
    labels.append("Horse manure")
    labels.append("Straw (chopped & long-straws)")
    labels.append("Ley silage (chopped & long-straws)")
    labels.append("EROI equal to 1")
plt.axhline(y=1, color='black', linestyle='-')
plt.title('EROI with increasing energy demand in log scale', fontsize=14)
plt.yscale("log")
plt.xscale("log")
plt.ylabel('EROI')
plt.xlabel('Energy demand kWh/ton ww')
plt.grid()
plt.legend(labels)
plt.show()
```

Python code for economic analysis with varying electricity price

```
import matplotlib.pyplot as plt
import numpy as np
#Energy gain and consumption in kWh/ton ww
Eg=np.array([59.724288, 76.5696, 74.591552, 99.4, 285.52086, 150.02856])
Ec=np.array([10,8,20,20,50,35])
#Varying electricity price
C=np.arange(0,3,0.1)
#Income from biogas SEK/kWh
I=0.80
labels= []
for i in range(len(Eg)):
    plt.plot(C, Eg[i]*I - Ec[i]*C)
    labels.append("Cattle solid manure")
    labels.append("Pig solid manure")
    labels.append("Cattle deep litter manure")
    labels.append("Horse manure")
    labels.append("Straw (chopped & long-straws)")
    labels.append("Ley silage (chopped & long-straws)")
plt.title('Specific added profit with varying electricity price SEK per ton ww',
fontsize=14)
plt.ylabel('SEK/ton ww')
plt.xlim(xmin=0)
plt.xlabel('Electricity price SEK/kWh')
plt.grid()
plt.legend(labels)
plt.show()
```