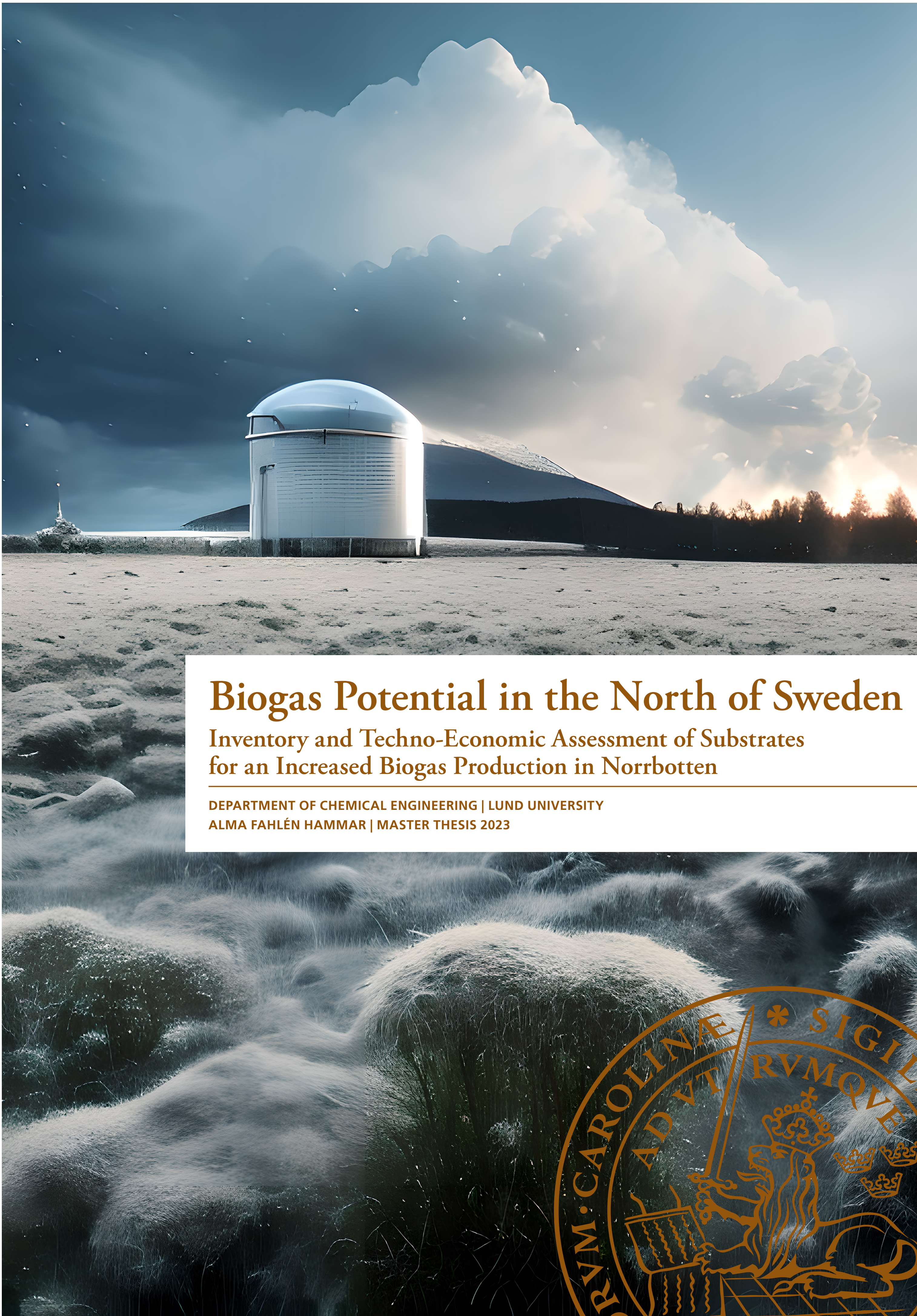

Biogas Potential in the North of Sweden

Inventory and Techno-Economic Assessment of Substrates for an Increased Biogas Production in Norrbotten

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Biogas Potential in the North of Sweden – Inventory and Techno-Economic Assessment of Substrates for an Increased Biogas Production in Norrbotten

by

Alma Fahlén Hammar

Department of Chemical Engineering
Lund University

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Supervisor: Mats Galbe
Co-supervisor: Björn Larsson (Lumire)
Examiner: Åsa Davidsson

Picture on front page: "A Sparkly, Glittery, Anaerobic Digestion Plant In The North Of Sweden, Surrounded By Fields Of High Grass And With Snowy Mountains And Forest In The Background And A Snow Storm With Thunder Rolling In" generated using Starryai

Postal address
P.O. Box 124
SE-221 00 Lund, Sweden
Web address
www.chemeng.lth.se

Visiting address
Getingevägen 60

Telephone
+46 46-222 82 85
+46 46-222 00 00
Telefax
+46 46-222 45 26

Förord

Från februari till juni 2023 hade jag ynnesten att få bosätta mig i Luleå för att genomföra detta arbete. Jag vill börja med att tacka min handledare på Lumire, Björn, som gav mig möjligheten att förkovra mig i detta intressanta ämne med stor självständighet och som ju ledde till öppnandet av fler dörrar! Ett stort tack också till handledare Mats för allt stöd och uppmuntran – jag har verkligen haft ett handledar-dream team och ert engagemang och entusiasm har varit ovärderlig. Tack till examinator Åsa som tipsade om Mats som handledare och som nappade på ämnet från första början.

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Jag längtar alltid efter er.

Alma Fahlén Hammar

Luleå, 30 oktober 2023

Populärvetenskaplig sammanfattning:
Tillgång och Effektfrågan – Biogasens Roll i det Gröna Norrbotten

Allt fler nyfikna ögon riktas mot Norrland i takt med att den nordligaste landsänden ångar på framåt i utvecklingen mot fossilfria industrier; kommande år planeras miljardinvesteringar i fossilfria tekniker i region Norrbotten, en satsning som kallas den *gröna omställningen.* Men för att kunna förse etableringarna och samhället med ren energi, och i förlängningen nå det gemensamma målet satt av Europeiska unionen om en koldioxidneutral union till 2050, måste produktionen av alternativa energikällor trappas upp. Biogas är ett förnyelsebart energislag som utöver som fordonsgas skulle kunna nyttjas i fossilfri ståltillverkning eller som en källa till vätgas. Det finns alltså nästan ingen hejd på efterfrågan, men hur kan produktionen öka?

Biogas är en gasblandning av koldioxid och metan som bildas när ett ekosystem av olika mikroorganismer bryter ned organiskt material i en syrefri, eller anaerob, miljö. I naturen kan anaerob nedbrytning ske i sumpmarker och i idisslares magar men människan har lärt sig att tillämpa processen i reaktorer genom att mata kulturen med lämpligt material, kallade substrat, och hålla lämpliga processförhållanden. Substrat utgörs vanligen av restströmmar och måste vara smältbart för mikroorganismerna. Mycket av det som är dåligt för oss i för höga doser – såsom tungmetaller, läkemedel och för högt eller lågt pH – är också skadligt för mikroberna. Hushåll, reningsverk, matindustrier och jordbruk är viktiga källor till substrat och genererar till exempel matavfall, avloppsslam, gödsel, grödrester och energigrödor. Ett sätt att öka produktionen av biogas är att öka mängden substrat, genom att finna fler.

Den kartläggning av substrat som utförts, i anslutning till Luleå och i samarbete med den kommunala biogasproducenten Lumire (Luleå Miljöresurs AB), visade att det inte finns mycket organiskt material tillgängligt *idag* eftersom de restströmmar som uppstår redan används för biogasproduktion av andra aktörer eller som djurfoder. Dessutom är jordbruket begränsat, delvis på grund av klimatet, delvis för att andelen produktiv jordbruksmark länge minskat. Men av samma anledning kan en del jordbruksmark finnas tillgänglig för produktion av energigrödor. Dock finns det samtidigt projekt som syftar till att öka självförsörjningsgraden i Norrbotten och en intensifiering av jordbruket kan ge större restströmmar. Medan lejonparten av regionens slaktavfall redan nyttjas för biogasproduktion genereras varje vecka 11–16 m^3 blod från lokala slakterier som transporteras till Skellefteå för biogasproduktion.

Biogasproduktionen i Norrbotten är således en dragkamp om resurser, där flera biogasproducenter kan tävla om samma material för samma ändamål. I fallet med det ”exporterade” blodet kan hemhämtning innebära minskad dieselkonsumtion vid transport och minskade kostnader för köttproducenten men gör att biogasanläggningen i Luleå behöver ändra sitt driftsätt och investera i utrustning som krävs enligt lagen om animaliska biprodukter, något som riskerar att bli dyrt sett till att volymen blod är relativt liten. En annan fråga är vilka resurser som måste mobiliseras, om rester som för nuvarande används som djurfoder i stället blir till biogas? Och om nya substrat i stället ska skapas, bör outnyttjad jordbruksmark då användas för produktion av energigrödor när regionen är starkt beroende av matimport eller bör fokus ligga på matförsörjning som *kan* alstra mer substrat? Säkert är att mer ren energi behövs, om Sverige ska bli fossilfritt på riktigt.

Abstract

Great investments are planned in the north of Sweden the coming years, not the least in the county of Norrbotten where the projects collectively are referred to as the *green transition* due to the focus on fossil-free techniques. But to be able to secure a sustainable energy supply and reach the goal set by the member states of the European Union of a carbon dioxide neutral union in 2050 the production of alternative energy sources needs to intensify. The continuous phaseout of fossil energy and increased electrification, of society as well as industry, place heavy demands on the energy supply, meaning that all non-fossil energy sources become important and should increase its production to meet the ever-increasing effect need. One energy source that is produced from renewable sources and can be directly interchanged with natural gas is the methane fraction of biogas. Biomethane is currently mostly used as a vehicle fuel in Sweden but that can be subjected to change and for example become an important source of hydrogen or be used for fossil-free steel production in the north of Sweden.

This thesis explored the availability of potential local substrates for biogas production in the county of Norrbotten, with certain focus on Luleå municipality. The work was performed in collaboration with Lumire (Luleå Miljöresurs AB), a municipal company that mostly produces biogas from wastewater treatment sludge and is responsible for water and sewage, as well as waste collection and recycling within Luleå. An inventory was compiled, and potential substrates evaluated in order to select two specific substrates for a techno-economic analysis with the purpose to assess energy inputs and connected costs related to the implementation of new substrates along with the potential biogas production. The energy balances included the potential energy yield, the energy consumption from the generation of the substrate, transport to the biogas plant, and pretreatment and was calculated for different scenarios. The effect that a biogas loss of 9.5% had was also included. Alongside the costs for the energy consuming activities, the investment cost of a pretreatment equipment was also estimated.

The inventory of substrates showed that there is suitable organic material, such as manure and food industry waste, in the region but that a small amount could be considered available today as much is currently used, if not for biogas but as animal fodder and for ethanol production. The share of productive farmland has decreased in Norrbotten over time and the disused or unutilised arable land revealed a potential source of biogas substrates. The most common crop today is ley which is grown to be used for husbandry. Meat and dairy are important industries in the north and the inventory showed that 11–16 m^3 of blood from local slaughterhouses are generated each week and sent out of the county and to Skellefteå to be turned into biogas. Due to the "export" of a local substrate and the existing unused farmland, ley crops and slaughterhouse blood was chosen as model substrates.

The techno-economic analysis showed that the production of ley crops accounted for the main cost and energy input compared to transport and pretreatment. In total, the activities could amount to 25–46% of the potential energy yield. The cost to be covered was around 10 SEK/kg of fuel gas under the used assumptions. The estimated cost of the investment of an extruder was just over one million SEK compared to 790 000 SEK in 2015.

The evaluation of slaughterhouse blood excluded the generation of the blood and focused on the transport and pretreatment. The result showed that the suggested pretreatment technique of pasteurisation stood for the main share of the cost, no matter the transport distance, but that the energy input of the transport accounted for 60% of the total energy input at a transport distance

of 140 km, which is the current transport distance. Combined, the activities could consume 45-60% of the total potential energy yield from the biomethane production. Costs to be covered varied between 9 SEK/kg fuel gas in the most energy-demanding scenario down to 2 SEK/kg fuel gas in the least costly scenario. The investment in a pasteurisation facility using district heating as the heating medium was estimated to 4.8 million SEK when dimensioned after a dilution of the highest blood delivery. Furthermore, the surface of heat exchangers as an alternative to pasteurisation tanks were estimated, showing that the required surfaces were small, around 1 m^3. The conclusion was drawn that a pasteurisation facility risks becoming equipment intensive seen to the amount of substrates.

Generally, the results show that there are energy winnings from both substrates but that it is dependent on the activities in the value chain of the substrates. Implementation of ley crops demand that a business model is developed in collaboration with current landowners and that the position and amount of available farmland is mapped. The local usage of slaughterhouse blood would decrease the diesel consumption of the transport but risk becoming equipment-heavy seen to the relatively limited amount of substrate.

Sammanfattning

Stora industriella investeringar planeras i norra Sverige de kommande åren, inte minst i region Norrbotten där satsningarna gemensamt benämns som en *grön omställning* eftersom de innefattar fossilfria tekniker. Men för att säkra nog med ren, förnyelsebar energi och nå det gemensamma målet satt av Europeiska unionen om en koldioxidneutral union till 2050 måste produktionen av alternativa energikällor öka. Den kontinuerliga utfasningen av fossila energikällor och ökande elektrifieringen av såväl samhälle som industri ställer höga krav på energiförsörjningen och innebär att alla icke-fossila energikällor blir viktiga och bör utöka produktionen för att möta det ständigt tilltagande effektbehovet. En energikälla som produceras av förnyelsebart material och som är direkt utbytbar mot naturgas är metanfraktionen av biogas. Biometan används i dag huvudsakligen som fordonsgas i Sverige men kan komma att nyttjas annorlunda i framtiden och till exempel bli en viktig källa till vätgas samt användas för fossilfri ståltillverkning i norra Sverige.

I detta arbete undersöktes tillgången på potentiella lokala substrat för biogasproduktion i region Norrbotten, med särskilt fokus på Luleå kommun. Arbetet utfördes i samarbete med Lumire (Luleå Miljöresurs AB), ett kommunalt företag som främst producerar biogas utav avloppsslam och som är ansvarigt för vatten och avlopp samt avfallsinsamling och återvinning i Luleå. En inventering sammanställdes och potentiella substrat utvärderades med syfte att välja ut två för en tekno-ekonomisk analys som menade att utreda ett urval av de energiinsatser och kopplade kostnader som substraten kan medföra vid en implementering, samt den potentiella biogasproduktionen. Energibalansen inkluderade den potentiella energiproduktionen samt energikonsumtionen för generering av substrat, transport till biogasanläggningen och förbehandling och beräknades för olika scenarier. Effekten som en biogaspotentialförlust på 9.5% hade på dessa scenarier inkluderades också. Utöver kostnaderna för de energikonsumerande aktiviteterna uppskattades också investeringskostnaden för förbehandlingsutrustning.

Inventeringen av substrat pekade på att det fanns lämpligt organiskt material i regionen såsom gödsel och matindustriavfall men att en liten andel kunde anses tillgängliga idag då mycket redan användes, om inte för biogas så för syften såsom djurfoder och etanolproduktion. Andelen produktiv jordbruksmark har minskat över tid i Norrbotten och denna nedlagda eller eftersatta mark visade sig vara en potentiell källa för biogassubstrat. Den vanligaste grödan är idag vall, som odlas för att nyttjas i djurhållningen. Just animaliebaserade industrier såsom kött- och mejeriproduktion är viktigt i norr. Av inventeringen framkom att det idag genereras 11–16 m^3 blod varje vecka från lokala slakterier som inte nyttjas för biogasproduktion inom regionen, utan i stället transporteras till Skellefteå för att behandlas där. På grund av ”exporten” av substrat samt tillgången på åkermark valdes vall som modellsubstrat tillsammans med slakteriblodet.

Den tekno-ekonomiska analysen visade att produktionen av vall stod för den största kostnaden och energiinsatsen jämfört med transport och förbehandling. Totalt kunde aktiviteterna stå för 25–46% av den potentiella energiproduktionen. Kostnaden som skulle täckas för motsvarade cirka 10 SEK/kg fordonsgas under de aktuella antagandena. Uppskattningen av investeringskostnaden för förbehandlingsutrustning gjordes utifrån en extruder och visade att den skulle kosta strax över en miljon kronor jämfört med 790 000 SEK år 2015.

Utredningen av slakteriblod uteslöt substratgenereringen och fokuserade enbart på transport och förbehandling. Resultatet visade att den föreslagna förbehandlingstekniken pastörisering

stod för den huvudsakliga kostnaden, oavsett transportsträcka, men att energiinsatsen för transport stod för 60% av den totala energiinsatsen vid en transport på 140 km, vilket är den ungefärliga transportsträckan idag. Tillsammans visades att aktiviteterna kunde konsumera 45–60% av den potentiella energin från biometanproduktionen. Kostnaderna att täcka motsvarade runt 9 SEK/kg fordonsgas i det mest kostsamma scenariot eller 2 SEK/kg fordonsgas i scenariot med lägst energiinsats och kostnader. Investeringen av en pastöriseringsanläggning som använder fjärrvärme som värmemedium uppskattades till 4.8 miljoner SEK dimensionerad för en spädning av den högsta blodleveransen. Dessutom uppskattades värmeväxlarytorna för ett scenario där pastöriseringstankar inte används och beräkningarna visade att dessa skulle bli små, runt 1 m^2. Slutsatsen drogs att en pastöriseringsanläggning riskerar att bli utrustningsintensiv sett till mängden substrat.

Översiktligt visar resultaten att det finns energivinster med båda substraten men att den är beroende av aktiviteterna i värdekedjan. Implementeringen av vall kräver att en affärsmodell utvecklas i samråd med dagens jordägare och att positionen för och andelen tillgänglig jordbruksmark kartläggs. Användandet av slakteriblod lokalt skulle minska dieselkonsumtionen vid transport men riskerar att vara mycket utrustningskrävande sett till den relativt begränsade mängden substrat.

Table of Contents

1 Introduction 1
1.1 Aim 1
1.2 Scope 2
2 Background 3
2.1 Biogas Production by Controlled Anaerobic Digestion 3
2.2 The Microbial Process of Anaerobic Digestion 6
2.3 Operating Conditions 7
2.3.1 Temperature 7
2.3.2 Substrates 8
2.3.3 Organic Loading Rate and Hydraulic Retention Time 9
2.4 Pretreatment of Substrates 10
2.4.1 Lignocellulosic Material 10
2.4.2 Animal Byproducts 10
2.5 Uddebo Wastewater Treatment Plant 11
3 Methodology 13
3.1 Techno-Economic Analysis 13
3.1.1 Energy Analysis 14
3.1.2 Economic Assessment 16
4 Results 19
4.1 Inventory of Substrates in Norrbotten 19
4.1.1 Regional Biogas Production 19
4.1.2 Overview of Regional Substrates 20
4.1.3 Agriculture 20
4.1.3.1 Ley Crops 21
4.1.3.2 Grain 21
4.1.3.3 Potato 21
4.1.3.4 Food Crops 22
4.1.3.5 Manure 22
4.1.4 Energy Crops 23
4.1.5 Food Industry 24
4.1.5.1 Bakery 24
4.1.5.2 Eggs 24
4.1.5.3 Dairy 24
4.1.5.4 Fishery 24
4.1.5.5 Meat 24
4.1.6 Other Industries 25

4.1.6.1 Paper and Pulp Mills 25
4.1.6.2 Aircraft Deicing Liquid 25
4.2 Substrate Evaluation and Selection 26
4.2.1 Agriculture 26
4.2.2 Energy Crops 27
4.2.3 Food Industry 27
4.2.4 Other Industries 28
4.2.5 Selection 28
4.3 Ley Crops 29
4.3.1 Value Chain 29
4.3.2 Evaluation of Pretreatment Techniques 32
4.4 Slaughterhouse Blood 33
4.4.1 Current Value Chain 34
4.4.2 Evaluation of Pretreatment Techniques 35
4.4.2.1 Sanitising Techniques 35
4.4.2.2 Suggested Pretreatment Design 37
4.5 Techno-Economic Assessment 38
4.5.1 Techno-Economic Assessment of Ley Crops 38
4.5.1.1 Model 38
4.5.1.2 General Parameters 41
4.5.1.3 Energy Potential 41
4.5.1.4 Production 42
4.5.1.5 Pretreatment 42
4.5.1.6 Transport 42
4.5.1.7 Energy Analysis 43
4.5.1.8 Economic Assessment 45
4.5.2 Techno-Economic Assessment of Slaughterhouse Blood 47
4.5.2.1 Model 48
4.5.2.2 General Parameters 49
4.5.2.3 Energy Analysis 49
4.5.2.4 Economic Assessment 52
5 Discussion and Conclusions 55
5.1 Discussion 55
5.1.1 Inventory of Substrates in Norrbotten 55
5.1.2 Techno-Economic Assessment of Ley Crops 55
5.1.3 Techno-Economic Assessment of Slaughterhouse Blood 57
5.2 Conclusions 57

5.3 Suggested Future Research 57
6 References 59
6.1 Personal Communication 72
Appendix A: Energy Conversion Parameters and Primary data from Uddebo WWTP73
Appendix B: Ley Crops – Energy Calculations 75
Appendix C: Ley Crops – Economic Calculations 81
Appendix D: Blood – Energy Calculations 83
Appendix E: Blood – Economic Calculations 89
Appendix F: Summary of Substrate Inventory 91

1 Introduction

In November 2019 the parliament of the European Union (EU) acknowledged the ongoing climate crisis, calling it an emergency. By adopting the European Climate Law in 2021, the union members have committed themselves to reduce greenhouse gas emissions by 55% by 2030 (compared to the year of 1990) through the legislation package called *Fit for 55*. The purpose is to ultimately fulfil the main goal of the policy and strategy bundle called the European Green Deal which was initiated in December 2019 and aims for a climate neutral EU by 2050. (European Parliament, 2023a) After the Russian full-scale invasion of Ukraine on the 24th of Februrary 2022 the EU questioned its dependency on Russian natural gas and launched REPowerEU, a plan which led to a reduced energy usage in the Union and the replacing of 80% of the gas imported through Russian pipelines, within 8 months. (European Commission, 2023)

Natural gas has in Sweden been advised to be called fossil gas due to the misguiding inclusion of the word “natural” in a gas that is non-renewable and easily confused with biogas (Isof, 2023). While biogas is often produced from organic residual material and waste as a part of the current carbon cycle, fossil gas releases carbon that has been captured during a long time (Naturskyddsföreningen, 2023). Both gases contain methane and can be used for the same purposes; commonly electricity, heating, or as a fuel - the latter being the dominating intended usage of biogas in Sweden (Naturskyddsföreningen, 2023; Energigas Sverige, 2022). Biomethane, the methane purified from biogas, has been pointed out as a part of the energy system strived towards by the EU (European Commission, 2022). Fossil gas has no future in a fossil-free world, but biogas is still relevant even if the future of biomethane as a vehicle fuel is uncertain after the EU banning the sale of carbon dioxide emitting cars by 2035 (European Parliament, 2023b). An important application of biogas could therefore be subject to change.

Parallel to this, an industrial boom is seen in the northern parts of Sweden as great investments are made into fossil-free techniques for what is called a *green transition*. An estimated 700 billion SEK (or around 65 billion €) is to be invested in green technology in the county of Norrbotten by 2040 to improve the mining industry, to make the steel industry fossil-free, and into building hydrogen reserves (Länsstyrelsen Norrbotten, no date). Biogas is currently being assessed as a potential source of hydrogen for the public transport system in Luleå, and could become an essential part of fossil-free steel production (IVL, 2023; Energigas Sverige, 2020)

Electrification and the continuous disuse of fossil resources are happening at the same time, leading to a demand for more and alternative energy sources. The Swedish Energy Agency writes that the transition from fossil energy sources requires massive investments for electricity production; therefore, every non-fossil energy source is important (Energimyndigheten, 2023). This thesis explores the potential to increase the biogas production in Luleå, Norrbotten, by compiling an inventory over potential regional biogas substrates and by evaluating alternatives from a technical and economic viewpoint.

1.1 Aim

This master thesis was performed in collaboration with the municipal company Lumire (Luleå Miljöresurs AB) which is responsible for the waste and water management in Luleå municipality. The purpose was to investigate what local substrates are suitable for biogas production and which of these that could be available to the company and what that could mean for the existing production plant in terms of energy production and in equipment investments in relation to the potential increase in biogas yield. The result consists of two parts: an inventory and a techno-economic analysis. In the inventory, substrates were assessed based on published and unpublished material as well as through contact with companies and experts, and by study visits. The purpose of the inventory was to provide an overview of potential substrate sources based on the circumstances that are special to the region. Out of the gathered information, two substrates were chosen for the analysis. These were evaluated with the focal point on substrate generation and activities upstream of the anaerobic bioreactor responsible for the biogas production, together with the potential biogas yield from the reactor. The evaluation of upstream activities included assessing pretreatment methods and suggesting a suitable process design as well as brief energetic and economic analyses coupled to the design through mass flows and the required resources and equipment. The expected outcome was to provide Lumire with material that can be used when making decisions about the future of their biogas production.

1.2 Scope

Source-sorted municipal organic waste (food waste from households) is not assessed in this thesis and residual streams from forestry are also excluded. The background is meant to provide information about the complete life cycle of biogas (and biomethane), but the focus of the investigatory sections lies on evaluating the processes upstream from the anaerobic digestion chamber and not on how downstream processes, such as digestate generation or upgrading, are affected by the implementation of a certain substrate, or how processes can be optimised. However, the *capacity* of the plant to take in new substrates must be briefly estimated. The mode of operation of the anaerobic digestion reactor is not investigated but briefly discussed when overlapping with pretreatment techniques. Potential biomethane yield is an important parameter in the techno-economic analysis but is not estimated or investigated related to the mode of operation, or the mix of substrates being digested. Pretreatment in this thesis refers to the processes performed before feeding into the reactor but after storing of the substrate material. The scope is illustrated in *figure 1*, below.

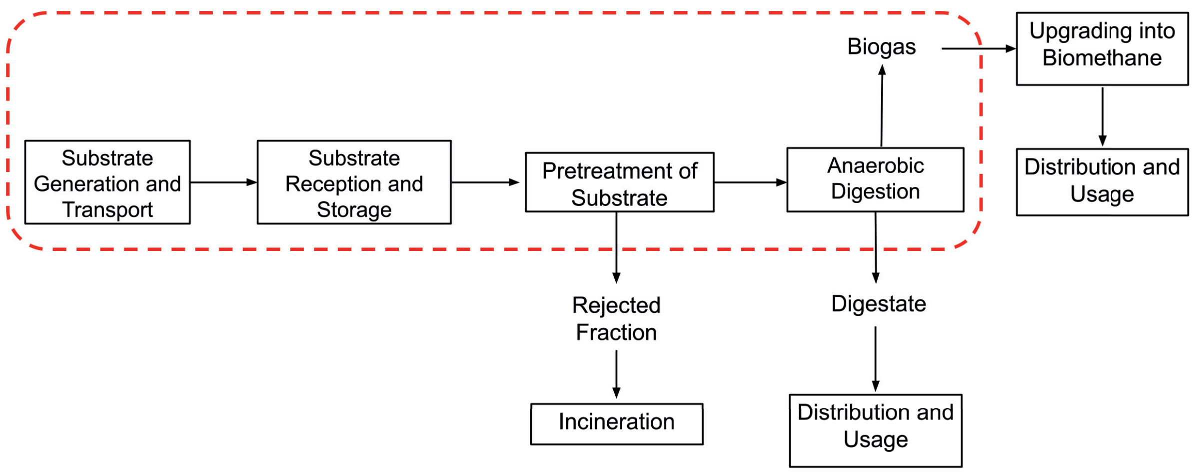

Figure 1. Simplified flow scheme of activities and material flows included in the life cycle of biogas. The scope of the thesis is enclosed in red.

2 Background

In an oxygen-free environment, such as in wetlands and at the bottom of lakes, organic matter can be microbially converted into a gas consisting of mostly methane and carbon dioxide, or what is called biogas (Agency for Renewable Resources, 2012; Jarvis and Schnürer, 2009). This biochemical process can be referred to as anaerobic digestion (AD) and is indicated to have been known to man for over 2000, perhaps nearly 3000 years (Deublein and Steinhauser, 2011; Wellinger et al., 2013). The earliest studies of methane-producing AD in the Western world can be said to have begun during the 17th century and is related to the understanding about and classification of methane. More than a hundred years later the septic tank was developed, and AD used to handle sewage water. It was also around this time that the biogas began being used for power, heating, and lighting instead of emitted (Deublein and Steinhauser, 2011; PennState Extension, 2023).

The AD method kept its relevance in microbially stabilising and reducing the volume of wastewater sludge, which was complemented by other waste streams in the 1970s, and energy crops in the 1990s; Austria and Germany being pioneers (Biogödsel, no date; Wellinger et al., 2013). Stabilising a sludge biologically means that the nutrients are degraded and converted in a controlled way and used for microbial energy and growth purposes. (Wesley Eckenfelder, 2006). Aerobic stabilisation is also possible and is a process associated with a faster cell growth and significant heat generation, in contrast to AD, and end products such as carbon dioxide, water and organic acids and alcohols. (Schnürer and Jarvis, 2017; Wesley Eckenfelder, 2006)

2.1 Biogas Production by Controlled Anaerobic Digestion

The digester, or reactor, is the heart of the commercialised anaerobic process (illustrated in *figure 1*). Feeding of organic material into the digester is controlled and a microbial process is still responsible for converting the complex structures into biogas. Biogas plants can be located at farms, industries, landfills or at wastewater treatment plants (WWTPs). The reactors are often fed with matter from the activities related to the location of the biogas plant. Substrates fed into the digester can be, e.g., manure and crops, industry waste, leachate from landfills and WWTP sludge. The most common type of biogas plant in Sweden in 2021 was the co-digestion plant, accounting for 53% of the registered plants. (Energigas Sverige, 2022) A co-digestion plant can be defined as a plant that treats different kinds of organic matter but not WWTP sludge (Biogödsel, no date). Examples of substrate mixtures in a co-digestion plant can be food waste, manure, and slaughterhouse waste.

A residual called digestate, a water-rich sludge that contains a mixture of cells and undigested substrate material, is generated by the AD process. The digestate can be marketed and used as a biofertiliser if it has a high purity and excludes WWTP sludge fractions. (Biogödsel, no date) Usage of digestate as a fertiliser is possible because nutrients (such as nitrogen, phosphorus, and potassium) needed for fertilisation remain in the digestate, while much of the carbon-containing material has been converted into gas. In other instances, the digestate can be dewatered and for example used as cover soil, i.e., for covering landfills or for construction purposes. (Nyns, Nikolausz and Liebetrau, 2014; Holmgren et al., 2020) WWTP sludge can contain significant amounts of heavy metals, drug residues and other potentially harmful substances (such as flame retardants and polyfluorinated substances) but is purer in Sweden compared to other European countries (Finnson, 2019; Holmgren et al., 2020). It is allowed to be spread on farmland as a fertiliser if heavy metal concentrations are kept below the limit concentrations, but no restrictions are applied when using WWTP sludge as cover soil (Jordbruksverket, 2021; Holmgren et al., 2020). The same restrictions regarding heavy metals must also be met by what is to become biofertiliser (Jordbruksverket, 2022a). WWTP sludge can be certified by RISE (Research Institutes of Sweden) according to the system *Revaq*, which is meant to show that the WWTP sludge meets certain standards and that it is suitable for spreading on farmland (Finnson, 2023).

Several reactor alternatives are available for an AD process, for example the plug-flow reactor, but more commonly used are stirred tank reactors. Reactors are built in concrete and/or steel that can withstand the corrosive nature of the biological process. (Agency for Renewable Resources, 2012) The reactors can be either fed batch-wise or continuously and be run in single or with several reactors in series (Wellinger et al., 2013).

Other characteristics of an AD process are related to the amount of dry matter (or total solids, TS) in the reactor, which will affect nutrient and water concentration and consequently transport phenomena (Agency for Renewable Resources, 2012). Wet digestion usually refers to processes with TS contents of less than 15% and is the most used. Carrier materials can be used in wet digestion to efficiently retain the microbes in the process. (Jarvis and Schnürer, 2009) TS contents exceeding 35-40% can stop a digestion process completely (Agency for Renewable Resources, 2012; Jarvis and Schnürer, 2009).

Main activities upstream from the reactor are reception and storage of substrates, pretreatment of substrates and possibly intermittent storage before digestion (Agency for Renewable Resources, 2012). The purpose of pretreating a substrate can for example be to improve the conditions for feeding the substrate into the reactor, to remove impurities and to increase the degradability (Carlsson, 2015). It can also be performed due to being required by law, such as when treating potentially contagious material. An example is the pretreatment of animal by-products which is performed to reduce the occurrence of pathogens (Jordbruksverket, 2016). During the pretreatment which can be physical, chemical, or biological processing, a refuse fraction can be formed if, for example, the substrate contains non-degradable, wrongly sorted material and/or stones (Wellinger et al., 2013; Agency for Renewable Resources, 2012). Expected reject fractions can be generated from packaged foods ground to release the organic material. It can be sent for incineration, supplying heat and power (Bohn et al., 2011).

Biogas is formed continuously in a balanced AD process and the eventual treatment of the gas is found downstream from the digestion. Besides mainly consisting of methane and 25-50 volume percentage of carbon dioxide, raw biogas contains water vapour (1-5 vol%), nitrogen (0-5 vol%), hydrogen sulphide (0-0.5 vol%), ammonia, siloxanes, and possibly solid particles. Raw biogas is purified because utilising a less pure gas in machinery could potentially be damaging to equipment and change the gas properties by resulting in a lower energy content and causing emissions other than carbon dioxide. Several impurities can be removed by using activated charcoal in the treatment of the gas. (Deublein and Steinhauser, 2011)

Raw biogas is referred to as being upgraded when it is purified into concentrated biomethane to be used as vehicle fuel or injected into the gas grid. It commonly consists of 97% methane and 3% carbon dioxide and nitrogen after upgrading. Two thirds of the produced biogas was upgraded in Sweden in 2021 and examples of upgrading techniques used include water scrubbing, pressure swing adsorption (PSA) and membrane technology. (Energigas Sverige, 2022)
Water scrubbers work by utilising the differing chemical properties of carbon dioxide and methane for absorption. When biogas with a pressure of around ten times the atmospheric pressure

is percolated in a column with packing material and water, the carbon dioxide can be absorbed in the water, with which it interacts more favourably compared to methane. Carbon dioxide can then be released from the water by being transported to a column of atmospheric pressure. A methane content of up to 98% is achievable depending on the qualities of the water, the temperature and the pressure. (Deublein and Steinhauser, 2011).

PSA works by utilising several, often four, columns filled with adsorbing surface-active packing material, for instance activated carbon. The raw biogas is first compressed to 10-12 bar and then cooled, which provides means for water removal by condensation before the gas is led to a first column for adsorption of carbon dioxide under pressure. The biomethane passes out of the column and the carbon dioxide is released from it by pressure release, followed by regeneration of the column by pressurisation. The process of adsorption, desorption and restoring of columns is thus repeated, using different columns as adsorption chambers. (Deublein and Steinhauser, 2011; Benjaminsson, 2006)

Purification using membrane technology works by allowing the biogas to pass along membranes that retain methane but allows for compounds like carbon dioxide, water, and oxygen to pass through. Working pressures could be 6-10 bars. (Benjaminsson, 2006)

After upgrading the biomethane, it is compressed or liquified and used as vehicle fuel or injected into the gas grid. Apart from the gas being upgraded and used as vehicle fuel in 2021, 18% was used for direct heat generation, 9% was combusted by torching and 2% used for electricity production (Energigas Sverige, 2022). Establishing a biogas plant includes contact with and permission from authorities as such plants generate explosive and fire hazardous components (MSB, 2013). Torches are found at biogas plants as a safety measure to be able to combust excess gas and one demand for granting permission for the establishing of a biogas plant can be to dimension the torch so that it is possible to torch off all gas produced if necessary (Länsstyrelsen Dalarnas Län, 2022). The torch has also been described as an important installation to minimise methane emissions as methane is a greenhouse gas that is several times more potent than carbon dioxide (Jansson, 2006).

Methane leakage and emissions, also referred to as *methane slips*, can originate from different parts of a biogas plant, either downstream, in connection to, or upstream of the AD reactor. Sources could be the substrate storage and pretreatment, both which can lead to premature biogas production and leakage because of microbial activity; possible to occur during digestate handling as well. Other potential points for methane slips could be pressure safety valves tied to the reactor that opens at the wrong pressure, loose couplings in the upgrading facility or that some methane is lost when emitting the residual gas. (Hjort et al., 2015) Two examples of terms to be met when establishing a biogas plant has included a maximum methane leakage from the upgrading facilities of 0.2% of the incoming amount of methane (Länsstyrelsen Dalarnas Län, 2022; Länsstyrelsen Halland, 2020).

The energy balance of an AD reactor has been described by Svahn (2006). Energy is added from stirring, heating of the reactor and inflow of substrate while energy leaves the reactor through effluent sludge, gas and through heat emission from the reactor surface (Svahn, 2006). The total energy usage for the operation of a biogas plant have been estimated by Berglund and Börjesson (2003) which suggested that the energy usage of a central (i.e., non-farm based) biogas plant could amount to 20-40% of the produced biogas energy content. The assessment included activities such as pumping and pretreatment. The heating requirement was estimated to generally vary between 6-17% of the energy content of the created biomethane and the electricity 8-17.5%. It was assumed that heat was produced from burning of biogas and that the electricity was provided by the burning of fossil gas. Making other assumptions about the sources of energy would yield other results. (Berglund and Börjesson, 2003) Liljestam Cerruto (2011) found, under the same assumptions, that the heat and the electricity requirements of the biogas plant Svensk Växtkraft in Västerås used 16.6% for heat and 19.4% of the energy content of the produced biogas for electricity. The plant digested sorted organic household waste, separated grease and ley (Liljestam Cerruto, 2011).

2.2 The Microbial Process of Anaerobic Digestion

A microbial network in a sensitive equilibrium is the prerequisite for biogas production. Different organisms are generally responsible for different stages of the production of biogas and the biological processes occur simultaneously when nutrients are made available; as soon as an intermittent product is formed, it can be used as a substrate for another process stage. (Gerardi, 2003) This microbial process can be divided into four main stages, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis, as illustrated in *figure 2*. During hydrolysis, complex nutrients consisting of proteins, polysaccharides and fats are cleaved into their building blocks of amino acids, sugars and fatty acids by enzymes excreted by different bacteria. (Wellinger et al., 2013)

The next stage, acidogenesis (also called the fermentative stage), gives rise to organic acids such as acetate, along with alcohols, carbon dioxide and hydrogen through the conversion of the mono- and oligomers formed during the hydrolysis. The smaller organic products are then used in acetogenesis, which is an oxidative process forming more acetate, hydrogen, and carbon dioxide. These three compounds are utilised by archaeal methanogens to form methane, either through an acetic acid pathway or through a hydrogen and carbon dioxide pathway. (Jarvis and Schnürer, 2009)

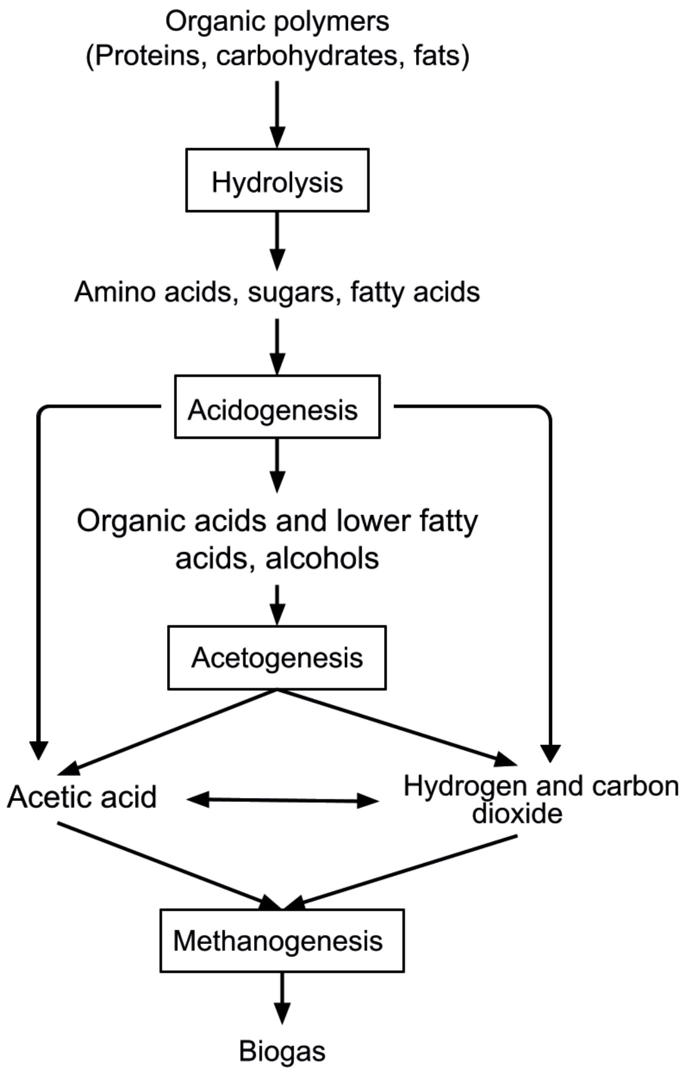

Figure 2. The microbial process of anaerobic digestion of organic material into biogas. Illustration based on the work of Jarvis and Schnürer (2009) and Agency for Renewable Resources (2012).

2.3 Operating Conditions

The sensitive nature of the microbial community of an AD process puts certain demands on the operating conditions and changes in the process mean that the community must readapt. Several operating parameters need to be monitored to create a stable process and will influence the final biogas and biomethane yield. Generally, the process is affected negatively by the presence of oxygen and other compounds toxic to the microbes, such as antibiotics, heavy metals and high concentrations of salt. The pH can be around 5-10, but is most commonly maintained around 8, to suit methanogens. (Jarvis and Schnürer, 2009)

2.3.1 Temperature

Swift temperature changes in the AD process are unwanted because it creates disturbances in the microbial processes, leading to unproductiveness before a possible restabilisation (Gerardi, 2003). A commercial biogas process is run either under mesophilic conditions (around 35-40°C) or at thermophilic conditions (around 50-55°C) (Nyns, Nikolausz and Liebetrau, 2014).

Methanogens are among the slowest growing microbes in the process and are generally favoured by temperatures around 35-37°C. Below this, their activity is halted enough to lead to accumulation of intermittent fatty acids and alcohols, leading to pH drops of fully inhibiting levels. At thermophilic conditions methanogens that are resilient to higher temperatures are naturally selected, forming a less varied culture. (Jarvis and Schnürer, 2009) The higher temperature of a thermophilic operation mode increases reaction speeds and changes substrate characteristics such as viscosity and might on one hand have a positive effect on pathogen reduction. On the other hand, it can require a larger input of heat (Nyns, Nikolausz and Liebetrau, 2014) and potentially be more sensitive to operational changes if there is a less diverse microbial community. (Jarvis and Schnürer, 2009)

2.3.2 Substrates

The material converted into biogas often comes from residual streams from different parts of society, the common denominator being its biodegradability. According to statistics from The Swedish Gas Association the substrates estimated to have produced the most biogas in Sweden in 2021 were, in order of declining importance: WWTP sludge, sorted food waste, manure, other substrates (including agricultural residues, whey and glycerol), waste from the food industry, slaughterhouse waste, landfill leachate, industrial wastewater and energy crops. (Energigas Sverige, 2022)

A compound can be defined as consisting of a water fraction and a dry matter fraction commonly called total solids (TS). (Schnürer and Jarvis, 2017) The total weight of water and TS is referred to as the wet weight (WW). The TS is decided by drying the material at 105 °C and comparing the weight of the dried material with the WW. The TS, in turn, can also be defined as consisting of two fractions: volatile solids (VS) and ash. The VS is decided by burning the dried material at 550 °C and comparing the weight of the ash against the TS weight. The loss after the combustion is the VS, the organic fraction of the material. (Agency for Renewable Resources, 2012). VS is often referred to in its percentage fraction out of the TS.

Biomethane potential (BMP) can be referred to in relation to the VS content and can be calculated theoretically using a method that links the potential to the amounts of carbon, hydrogen, oxygen and nitrogen found in a compound. It is called the Buswell formula. However, the empirical biomethane production might not be the same as the theoretical, for many reasons. For example, parts of the nutrients are used as building blocks for cell growth, instead of becoming gas, and the gas yield (including methane yield) is also determined by the composition and degradability of the substrate. BMP is also affected by the operation of the digester. An empirical way of determining the BMP is through digestion trials that test the total gas production over a certain amount of time and measures the methane content. BMP is often referred to as the production of methane in Nm^3 (normal cubic metres), which is the methane volume at zero degrees Celsius and atmospheric pressure. The BMP is commonly reported in Nm^3/kg VS. (Schnürer and Jarvis, 2017)

Balance in the anaerobic digester is dependent on the composition and evenness regarding feeding of substrate. Injected material should consist of structures of carbon, oxygen, nitrogen, and hydrogen, as well as trace elements and vitamins. Substrates have different BMPs and are converted differently depending on the composition. (Deublein and Steinhauser, 2011) Smaller molecules such as sugars, volatile fatty acids and alcohols are degraded within hours, while proteins, fat and hemicellulose require days. Cellulose requires weeks and lignin can be considered to pass the digestion process unaffected due to the rigid structure (Wellinger et al., 2013).

Using great amounts of complex substrate leads to a low methane production, while excessive amounts of easily degradable substrates create an imbalance due to the accumulation of fatty acids which can lower the pH and inhibit further processes. During degradation of complex carbohydrates hydrolysis becomes the rate-limiting step. (Gerardi, 2003) Pretreatment to increase the attack surface or partially break the structure is a way of improving the conversion rate of carbohydrates (Jarvis and Schnürer, 2009). Another intermediate compound that will affect the process is hydrogen. If not consumed at enough rate by the methanogens, or if the production is too high, acetogens will bring the production to a standstill, inhibiting the hydrogen-methane pathway (Deublein and Steinhauser, 2011).

High concentrations of nitrogen in the substrate can lead to the formation of ammonia in the process. Proteins release ammonia (in equilibrium with ammonium) during the digestion, and it becomes toxic for the cells at a given concentration. A way of measuring the suitability of a substrate is to determine the C/N (carbon to nitrogen amount) ratio of the substrate. An AD process is often recommended to be kept around a ratio of 15-25 and can be adjusted by adding carbon or nitrogen rich material. It is also known that a substrate consisting of a mixture of different kinds of matter will give a more diverse microbial community and can provide greater gas productions than what digesting the materials separately would (Jarvis and Schnürer, 2009)

2.3.3 Organic Loading Rate and Hydraulic Retention Time

Even if a suitable substrate is added to an AD process, too much at a time can create imbalances and burden the process. The organic loading rate (OLR) gives information about approximately how much degradable material is added to the digester. (Gautam et al., 2022) It can be defined using the amount of added volatile solids (VS, the combustible fraction of the total solids) in the added substrate that is added per day, divided by the active reactor volume. (Agency for Renewable Resources, 2012) A suitable OLR for a mesophilic process is around 2-3 kg of VS per day and m^3 of the digester (Jarvis and Schnürer, 2009). The OLR (kg VS per m^3 of reactor volume and day) can be defined according to *equation 1*.

$$OLR = \frac{VS}{V_{reactor} \cdot day} \quad (1)$$

Another important parameter is the hydraulic retention time (HRT), or the theoretical residence time in the reactor. It determines the theoretical time that the same material (i.e., microbes and substrate) is kept in the digester, or how long it takes to “exchange” all the material in the reactor (*equation 2* adapted after Davis, 2019). A short retention time can mean that the substrate might not be used to its full potential before it leaves the reactor and that microbes risk being washed out because of the short time allowed for cell growth (Gerardi, 2003) It is not uncommon that AD processes have an HRT of 10-25 days (Jarvis and Schnürer, 2009).

$$HRT = \frac{V_{reactor}}{Q_{in}} \quad (2)$$

HRT is the time in days, $V_{reactor}$ is the active volume of the reactor (m^3) and Q_{in} is the volumetric flow rate of liquid into the reactor per day (m^3/day).

2.4 Pretreatment of Substrates

The purpose of pretreatment can be to remove impurities that can disturb the AD process, to adjust the substrate characteristics for injection or to make a substrate more susceptible to microbial activity. It can be performed physically, chemically, biologically or using a combination of processes (Wellinger et al., 2013). The following section provides an overview of two common substrate kinds.

2.4.1 Lignocellulosic Material

Plants are made to last and while starch (the energy storage polymer) is readily converted in an AD process, cellulose, hemicellulose, and lignin are meant to provide structure and resilience. Treating plant material is performed to release more of the carbohydrate polymers from the complex structures (Wellinger et al., 2013) and to decrease the needed retention time in the reactor. (Björnsson et al., 2014) Decreasing the risk of formation of a floating layer in the reactor is another aspect that needs to be considered when using plant material as substrate (Björnsson et al., 2014). Commercially applicable pretreatment techniques have previously excluded methods using ultrasonication, microwave or gamma ray exposure and the usage of ionic liquids (Björnsson et al., 2014).

Mechanical pretreatment of lignocellulosic biomass means decreasing the particle size which increases the surface area available for enzymatic attack. Different techniques use grinding, chopping, or crushing. Knife, hammer and roll mills, shredders, macerators, deflakers, dispersers and extruders have been used to pretreat materials rich in lignocellulosics, in different trials (Gunnarsson et al., 2014). The correct equipment needs to be chosen based on the substrate but overall, the desired outcome is that particle size is reduced to 1-2 mm for optimal hydrolysis. Disadvantages of using these types of equipment are the potentially high energy demand and sensitivity to foreign objects, such as stones. (Kratky and Jirout, 2011)

Plant materials can also be pretreated using thermal techniques that include hot water or steam and pressure changes, which distorts the structures, making more carbohydrates available (Wellinger et al., 2013). Chemicals can be used for the same purposes and strong bases will partially degrade hemicellulose and lignin (Wellinger et al., 2013). Biological pretreatments include addition of enzymes or conducting the hydrolysis and possibly acidogenesis separate from the rest of the digestion process by using several reactors with environments optimised for each individual stage (Wellinger et al., 2013).

2.4.2 Animal Byproducts

Just like lignocellulosic biomass, food and other bulky material undergoes size reduction and impurity removal before the reaction chamber (Avfall Sverige, 2013). There are also legal requirements by European and Swedish law that need to be fulfilled to get permission to anaerobically treat foods and other material that contain animal residues. The law about animal byproducts (ABP) classifies the waste into three different classes after contamination and health concerns. Category 1 is considered the most potentially unsafe waste and includes, for example, whole bodies from animals, brains, bone marrow and eyes (Avfall Sverige, 2022a). This category is not used for biogas production in Sweden at present (Avfall Sverige, 2022b). Category 2 includes manure and animals that contain pharmacological residues after veterinary treatments and animal embryos and foetuses (Jordbruksverket, 2015). Category 3 deals with slaughterhouse waste, sorted organic household waste and food waste from stores (Avfall Sverige, 2022a). There is a sharp distinction between food waste from kitchens (of all kinds, including households, restaurants, and café kitchens), and industry-generated food waste which is from stores and the food industry. The two types have different legal requirements, for example concerning documentation and transport. (Avfall Sverige, 2022b)

Category 3 is always allowed to be digested after approval by the Swedish Board of Agriculture. The general demand is that the material to be used has a particle size below 12 mm and pretreated by being heated to 70°C and kept so for 1 hour. This process is commonly referred to as *pasteurisation* and another method that can be approved is *internal thermophilic digestion* that keeps the reactor temperature above 52°C for 10 hours and has an HRT of at least 7 days. In some instances, category 2 and 3 materials (for example some milk products) can be excepted from the pretreatment demands after being approved by the Swedish Board of Agriculture. (Jordbruksverket, 2016)

2.5 Uddebo Wastewater Treatment Plant

Lumire's biogas plant is located in connection to the municipal wastewater treatment plant (WWTP) Uddebo and is the basis for the thesis analyses. The WWTP is dimensioned for 120 000 person equivalents (pe) and today receives wastewater from 66 000 pe through the sewage network, from smaller treatment plants, and collection from private septic tanks. The total amount of raw WWTP sludge that is fed into the wet anaerobic digestion chamber sums up to around 144 m^3 per day and the plant is operated 7 days a week. The WWTP sludge is digested together with approximately 45 m^3 liquid waste of a lower TS (around 1-2%) provided by a liquid from the dairy industry Norrmejerier in Luleå along with separated grease from restaurants. A majority share of the biogas produced is upgraded to fuel quality using membrane technology and distributed to be used for buses in the public transport system Luleå Lokaltrafik (LLT).

Cleaning of the incoming WW is performed through initial mechanical processes such as screening and chemical processes using flocculation before and after the aerated biological treatment in moving bed biofilm reactors. Raw WWTP sludge is collected from pre- and after sedimentation. The wastewater collected from outside of the municipal sewage network is treated in a parallel line before the external WWTP sludge formed is mixed with that of the main treatment line and kept in a tank before dewatering. Polymers are added to facilitate screw dewatering, which thickens the sludge from having a TS of below 2.5% to a yearly average around 4.5%. Next, the raw sludge is pumped into the digestion chamber but before so, it can be preheated by exchanging with the outflowing digester sludge.

Anaerobic digestion at Uddebo WWTP follows a mesophilic temperature profile, at 38°C. The AD process consists of two equally large digestion chambers of 3 500 m^3 each, of which one is currently in use, but the plant is designed so that digestion in series or parallel is possible when both are active.

Raw WWTP sludge is pumped into the centre of the reactor which is stirred frequently to avoid flotation layers and to get a homogeneous mixture. The hydraulic retention time (HRT) is at present 20 days with 11 days being the lowest operative HRT possible. The current organic loading rate (OLR) is around 1.7 kg VS/m^3d and the maximum OLR capacity 3.2 kg VS/m^3d.

The temperature in the reactor is controlled by recirculation of sludge that exits at the bottom of the chamber and heat exchanges with district heating having a temperature of around 80 °C during summertime and 100 °C during winter. Each of the two reactors has its own sludge/district heating exchanger but shares the preheating one that exchanges heat between raw WWTP sludge and digester sludge. An illustration of the influent and effluent flows related to anaerobic digestion can be seen in *figure 3*.

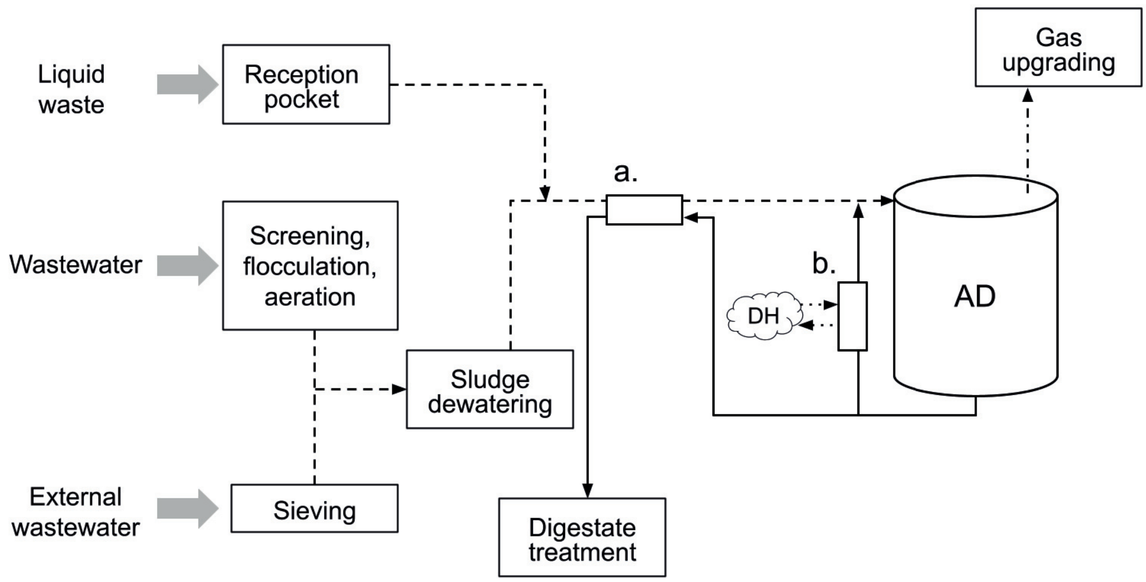

Figure 3. Overview of activities and flows at Uddebo WWTP. Raw WWTP sludge flows are represented by the arrows with broken lines (-), digester sludge is represented by the whole lines and raw biogas is the arrow including dots and broken lines (-.). a. is the preheating heat exchanger (HEX) that exchanges digester sludge and raw WWTP sludge and is also connected to the other digestion chamber. b. is the HEX used for digester sludge recycling and heating, used to control the temperature in the reactor and heated by using district heating (DH).

The digester sludge leaving the reactor for downstream processing has a TS percentage of around 1.8-2.3% and is dewatered to a TS of 20% using screw dewatering. The separated water is led back into the wastewater treatment line while the digestate is transferred to a cement plate for storage during one year before it can be distributed as "cover soil". Almost 12 800 tonnes of digestate are generated per year.

Biogas that is collected from the digestion process is stored in a dome with an inner and an outer membrane and a storing capacity of 430 m^3. A flow of around 100 m^3 of raw biogas per hour consisting of 66% methane and 25% carbon dioxide reaches the upgrading facility, using membrane treatment, where purification to 96% methane is obtained. The upgrading also includes usage of activated carbon to remove impurities and a methane slip of up to 0.5% has been reported for the upgrading facility. In 2022, the yield from the upgrading of biogas represented an energy content of around 4.3 GWh. Parameters associated with the operation of Uddebo WWTP are found in *Appendix A*.

3 Methodology

The result section of the thesis consists of an investigatory section divided into four main parts: an inventory of regional substrates, a general evaluation of substrates followed by selection of two substrates of specific interest, a more thorough assessment of the chosen substrates, and finally a basic techno-economic analysis of the two substrates.

The inventory will provide an overview of the current regional biogas production but also on the different sources of organic material related to the local industry and conditions. Research has included literature studies, especially focusing on previously published inventories from the region, but also study visits and contact with experts.

A general evaluation of the inventory is meant to assess the availability of potential substrates, putting emphasis on factors such as location, amount, and suitability. It will determine what substrate truly is or could be available currently or in the future and to make the decision about which substrates are to be evaluated more thoroughly.

The assessment of the two chosen substrates includes defining typical substrate characteristics, providing an understanding of the value chain for retrieving the substrate, as well as an evaluation of possible pretreatment techniques. The more thorough insight about the specific substrates provides material for the conceptualisation of the activities and pretreatment design to be evaluated in the last section; the techno-economic evaluation. Sources of information mainly include published studies and contact with experts.

3.1 Techno-Economic Analysis

The purpose of the techno-economic analysis is to separately evaluate the chosen substrates by estimating the energy inputs and costs related to the retrieval and pretreatment of a substrate and to weigh it against the potential biomethane production from the substrate. It creates an energy balance that provides information about the excess energy that can be gained from the implementation of a new substrate as well as the potential costs generated by the same activities. The studied activities are illustrated in *figure 4*.

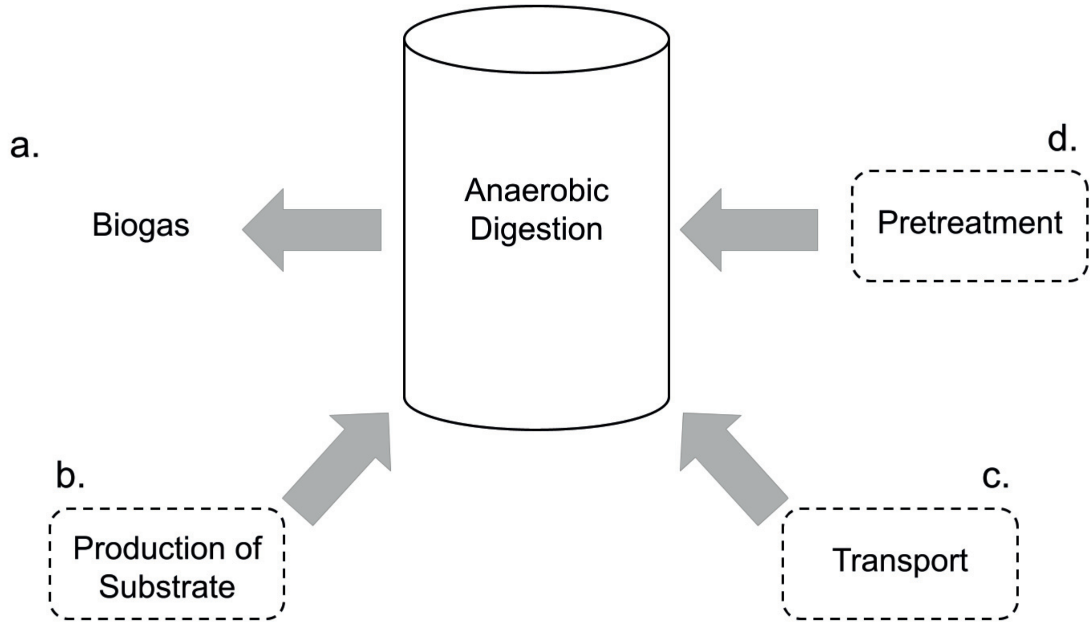

Figure 4. Overview of the activities included in the techno-economic analysis. a. is the energy (and economic) gain from the biogas produced by the substrate. b., c., and d. are the studied energy inputs and costs related to the generation of substrate, the transport from substrate source to the plant, and the pretreatment.

3.1.1 Energy Analysis

The energy evaluation includes both direct and indirect energy inputs. According to the work by Berglund and Börjesson (2003) the direct energy requirement of a certain activity can be multiplied by a factor to compensate for the indirect energy used, thus providing the total energy need in primary energy. Assuming that the heating of a biogas plant is provided by the burning of biogas, the primary energy factor is 1.3 MJ and for electricity generated from natural gas 2.2 MJ. (Berglund and Börjesson, 2003) This report will use the described primary energy factors as a method to compare how the energy consumption of the introduction of new substrates would mean in comparison to the results presented by Berglund and Börjesson (2003).

The foundation of the energy analysis is a net energy balance (*equation 3*) that includes the activities shown in *figure 4*.

$$E_{NET} = E_{PRODUCED} - E_{CONSUMED} \quad (3)$$

$E_{PRODUCED}$ is the potential energy yield from the AD of the studied substrate and $E_{CONSUMED}$ is the energy used by studied activities.

The required energy inputs can also be weighed against the potential energy yield by using the energy return of investment (EROI), or the energy output from a process divided by the total energy inputs used to produce the yielded energy. It provides the number of how many times greater the energy yield is compared to the energy input and is a formula that can be adapted to different processes, time frames and system boundaries, depending on the sought level of detail. (Murphy, D. J. et al., 2011)

$$EROI = \frac{E_{PRODUCED}}{E_{CONSUMED}} \quad (4)$$

Inversion of the EROI instead provides an energy efficiency quota (*equation 6*), which has been defined by Berglund och Börjesson (2003). It is an estimate of how large a share of the energy yields the energy inputs consume.

$$Energy\ Efficiency\ Quota\ (\%) = \frac{E_{CONSUMED}}{E_{PRODUCED}} \cdot 100 \quad (5)$$

The energy yield can be calculated from the OLR and biomethane potential (BMP) using *equation 6*.

$$V_{biomethane} = OLR \cdot BMP \cdot V_{reactor} \quad (6)$$

$V_{biomethane}$ is the acquired daily biomethane volume (Nm^3/day), OLR is the organic loading rate (kg VS/m^3day), BMP is the biomethane potential (Nm^3/kg VS) and $V_{reactor}$ is the active AD reactor volume (m^3).

The energy input required to change the temperature of a substrate can be calculated using the specific heat capacity according to *equation 7*.

$$Q = m \cdot c_p \cdot (t_{final} - t_{initial}) \quad (7)$$

Q is the energy input (J), m is the mass (kg) of the substrate. c_p is the average specific heat capacity (J/kgK) for the substrate. t_{final} is the temperature to be obtained and $t_{initial}$ is the initial temperature, both in Kelvin (K). The specific heat capacity (J/kgK) of a substrate of a certain TS content (in %) can be calculated using *equation 8*, adopted from Berglund and Börjesson (2003).

$$c_p = \frac{(100 - TS) \cdot 4180 + TS \cdot 1050}{100} \quad (8)$$

Calculating the energy required to raise the temperature of a substrate is required for instances such as pasteurisation and the temperature can changed using heat exchangers. The purpose of heat exchanging is to transfer heat from one fluid to another without mixing the streams. Instead, heat can be transferred between the fluids via walls and/or barriers and be coupled so that the media flows are counter-current or flows in the same direction. (Nilsson, 2016) The heat transfer that occurs in a heat exchanger can be described by *equation 9* (adopted from Alvarez, 2006). Heat transfer between two mediums through a wall is dependent on the attributes of the included components which is summarised in a heat transfer coefficient referred to as k, the contact area, and the temperature difference of the mediums.

$$Q = k \cdot A \cdot \Delta T_L \quad (9)$$

Q is the amount of heat being transferred (W), k is the heat transfer coefficient (W/m^2K), and ΔT_L is the logarithmic mean temperature difference (K).

The logarithmic mean temperature difference is used as the temperatures of the mediums change along the heat exchanger and is estimated using the media temperatures at the inlets and outlets of the exchanger (Alvarez, 2006). The logarithmic mean temperature difference of a counter-current heat exchanger is described by *equation 10* (adopted from Nilsson, 2016). Using counter-current flows means that the surface area of the heat exchanger can be kept smaller due to a higher ΔT_L (Nilsson, 2016).

$$\Delta T_L = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \quad (10)$$

$$\Delta T_1 = T_{hot,out} - T_{cold,in}$$

$$\Delta T_2 = T_{hot,in} - T_{cold,out}$$

ΔT_1 and ΔT_2 (K) are calculated from the inlet and outlet temperatures of the hot and cold streams. The heat transfer coefficient for an energy exchange between two water streams is typically 850-1 700 W/m^2K (Soleimani-Mohseni, Bäckström and Eklund, 2014). Grim (2014) utilised a k-value of 800 W/m^2K for the designing of tubular heat exchangers with a water circuit carrying the heat between a substrate and digester sludge. Jakobsson (2022) adopted 850 W/m^2K for a tubular heat exchanger with a water shell and digester sludge on the tubular side.

Liljestam Cerruto (2011) calculated the efficiency of a heat exchanger (η_{hex}) according to *equation 11*.

$$\eta_{hex}(\%) = \frac{Q_{cold}}{Q_{hot}} \cdot 100 \quad (11)$$

Q_{cold} (W) is the heat uptake by the cold media and Q_{hot} (W) is the heat loss from the hot media.

3.1.2 Economic Assessment

The economic analysis includes calculating the costs that are generated from the energy resources required by the energy inputs. Furthermore, it includes estimating the investment costs related to pretreatment equipment. Capital investment costs can be estimated using different indexes, for example the Marshall and Swift index for equipment costs (M&S Equipment Cost Index). The general formula when using an index can be seen in *equation 12*, adopted from Towler and Sinnott (2013).

$$Cost\ in\ year\ A = Cost\ in\ year\ B \cdot \frac{Cost\ index\ year\ A}{Cost\ index\ year\ B} \quad (12)$$

A construction cost index (CCI) gives indications on how costs related to the building of houses and other constructions has changed over time and is available through the Official Statistics of Sweden. (SCB, no date).

Björnsson et al. (2014) mentioned the rule of six-tenths as a formula to estimate investment costs of a differently sized plant when the cost of a plant of a certain size is known as constructing a plant that is twice the size is not twice as expensive. The remark was made that it should be used as a rough estimate and with caution. An effect of the "economy of scale" is that the price of products from high-capacity plants can be kept lower than competing products because of larger plants usually being less costly to build compared to smaller plants. The advantage in capacity means that the investment costs are lower per unit produced. (Towler and Sinnott, 2013). *Equation 13* describes the rule of six-tenths.

$$Cost\ 2 = Cost\ 1 \cdot \left(\frac{Scale\ 2}{Scale\ 1}\right)^{6/10} \quad (13)$$

Cost 1 and 2 are the costs for the differently sized plants or equipment and the scales are the size of the plants, capacity, or equipment dimensioning.

4 Results

4.1 Inventory of Substrates in Norrbotten

Norrbotten County includes the provinces of Lappland and Norrbotten, which together make up for a quarter of the total surface of Sweden and is ten times greater than Scania County. The main concentration of people and industries are located along the coast while natural resources can be found inland. (Länsstyrelsen Norrbotten, no date) A previous substrate inventory has pointed out the agricultural sector as the main potential source of biogas substrates in the north, specifically mentioning manure and energy crops (BioMil AB, 2012). The neighbouring county of Västerbotten has greater biogas potential than Norrbotten but the paper and pulping industry in Norrbotten county has also been deemed as having a high biogas potential (BioFuel Region, 2013).

4.1.1 Regional Biogas Production

Boden is a municipality bordering Luleå and produces biogas at the plant Svedjan. The plant treats WWTP sludge and food waste from households, restaurants and stores coming from both Boden, Luleå and other municipalities in Norrbotten. The 4 500 tonnes of household waste generated in Luleå every year is treated at Svedjan. Pretreatment of the different kinds of food waste takes place at a location that is separate from that of the plant and instead the generated slurry is transported to Svedjan by truck. (Larsson, personal communication)

Another biogas plant, located in Luleå municipality, is found at Alviksgården which is a farm run by Mikael Hugoson, one of the owners of the largest meat and charcuterie business in Norrland (Nyhléns Hugosons, no date). Alviksgården has 13 000 pigs that generate manure and slaughterhouse waste which is digested together with slaughterhouse waste originating from cattle from Norrbottensgården. These are the two largest farms in the county and the waste, together with a complementing wood chip boiler (supplied with wood from self-owned forests) is enough to keep Alviksgården self-sufficient in electricity. (Hugoson, personal communication) The farm uses a part of the digestate from the AD process on its own land as a biofertiliser and recently invested in an instalment that can pelletise the digestate, instead of it being in a liquid form. The pellets have been stated to be a potential contender to synthetic fertilisers, to which Russia is a supplier. (Rapp, 2022) The blood generated as a slaughterhouse byproduct from the two farms is not used for biogas production at Alviksgården due to the high nitrogen content. (Hugoson, personal communication) It is instead transported in tank trucks dispatched by Lumire, to the municipal biogas plant in Skellefteå (Samuelsson, personal communication).

The biogas plant located in Skellefteå, Västerbotten, around 130 km from Luleå city centre is called Tuvan. It is a wastewater treatment and biogas facility that digests WWTP sludge in a mesophilic process in one chamber and uses a second chamber to digestate other waste fractions thermophilically. In 2021 the plant treated 8 688 tonnes of sorted organic municipal waste, 669 tonnes of grease, 593 tonnes of blood, 83 tonnes of slaughterhouse waste, 5 tonnes of fishery waste, 120 tonnes of food grounds from kitchen waste mills and 105 tonnes of packaged food waste. This sums up to around 10 000 tonnes of organic waste each year, of which 18% became a rejected fraction in the pretreatment and produced 1.5 million normal m^3 of methane. (Pettersson, personal communication)

The pretreatment at Tuvan consists of an initial waste mill that coarsely grounds the waste that has a high TS content before it enters a pulper, which is an equipment type originating from the paper and pulp industry. In the pulper, the waste is ground and washed which generates a reject fraction that is sent for incineration. The formed slurry is pretreated by pasteurisation, which forms a bottleneck due to it only being two pasteurisation tanks to alternate between performing the three stages in the cycle: filling, pasteurisation and emptying into the reactor. (Pettersson, personal communication)

4.1.2 Overview of Regional Substrates

An earlier inventory from the region includes the unpublished literature study "Anaerobic digestion of substrates for methane production in the county of Norrbotten: A summary" from 2011 by Tommy Wikström and Anders Lagerkvist at Luleå University of Technology. Substrates were evaluated based on amount and distance from Svedjan biogas plant and substrates considered of certain interest included different kinds of manure, crops (field mustard and grasses), food industry waste (from berry, bakery, fish and potato industry) and industrial waste (from paper and pulp mills, glycerol and de-icing liquid).

A report from 2012 published by Norrbottens Energikontor (NENET) and written by BioMil AB, gathers the biogas potential from different substrates in the counties of Västerbotten and Norrbotten. Besides the previously mentioned substrates the report also includes slaughterhouse waste, harvest residues and the production of energy crops - assuming that 10% of the farmland can be used for this purpose. The result showed that the potential in Norrbotten was 140 GWh per year from the assumed production of energy crops, manure, sewage sludge, food waste from households and the food industry as well as harvest residues. Manure and energy crops were deemed to have the highest potential of 37 and 40 GWh each. This can be compared to the near 25 GWh worth of biogas produced in Norrbotten in 2011 (BioMil AB, 2012). By the year of 2021, 30 GWh was the reported biogas production from anaerobic digestion in Norrbotten county. The county of Scania produced 422 GWh and Sweden in total 2 135 GWh. (Energigas Sverige, 2022)

4.1.3 Agriculture

Norrbotten county consists of 58% forest (Statistikmyndigheten (SCB), 2023) and less than 5% of agricultural land (Jordbruksverket, 2022b). The total agricultural land was reported to be 40 909 hectares in 2020 (SCB, 2020). Based on statistics for the year of 2022, 75% of the agricultural land was used for cultivation and harvest, which means around 30 000 hectares, and the rest was used as grazing grounds (Jordbruksverket, 2022b). In comparison, Scania was reported to have almost 493 000 hectares of total agricultural land in 2020 (SCB, 2020).

The productive farmland in Norrbotten county has decreased over a long period of time (Länsstyrelsen Norrbotten, 2019). According to a report by the Swedish Board of Agriculture from 2008, Norrbotten and Västerbotten counties showed the greatest loss of farmland (in percentages of the total farmland area) over a period of 25 years (Jordbruksverket, 2008). Lundberg from the organisation Hushållningssällskapet Norrbotten-Västerbotten explained that much of the farmland in the region is currently unutilised or disused. The unutilised farmland can be unkept or be partially kept, while disused can be overgrown or reforested. Landowning structures are historically different in the north, compared to the south of Sweden. Svealand and Götaland (the southern half of Sweden) have historically had fewer but larger landowners with large farms that use land for the farm itself and lease parts of the land to tenants. The north has instead had a greater number of smaller landowners. Current landowners can be uninterested in using the farmland, or the competence has been lost through the generations. The price of land is lower compared to the south of Sweden and the incentive to sell unproductive land therefore also lower. (Lundberg, personal communication)

One investigation from 2016 used GIS analysis to estimate the amount of disused cultivation land and compared this to official statistics about the decrease in farmland area (Olofsson and Börjesson, 2016). The GIS analysis showed that 5 192 hectares of land had been disused in Norrbotten county while the total decrease of farmland according to official statistics (concerning the years 1999-2014) was 7 171 hectares in Norrbotten county.

The growth conditions in the north of Sweden are different from the southern parts. Temperatures are lower and the total growth season shorter but during summers growth is possible around the clock due to the amount of daylight (Ericson, 2013; SLU, 2022). Crop production in Norrbotten county is mainly located around the rivers and coastal areas (Karlsson, 2015). The main crop is ley, in 2022 cultivated on approximately three quarters of the 30 000 hectares of the arable land, while 12% was used for grain and 11% was reported as fallow land or used for other crops, including potato (Jordbruksverket, 2022b). Piteå and Luleå are the municipalities that have the most agricultural land (Jordbruksverket, 2023a).

4.1.3.1 Ley Crops

Green feed dominates the overall cultivation on arable land and is produced connected to animal husbandry (Lundberg, personal communication). A total harvest of 69 000 tonnes in Norrbotten county was reported to the Swedish Board of Agriculture in 2020 (Jordbruksverket, 2023a). Ley is currently used as a biogas substrate in Karlskoga (Karlskoga Energi & Miljö, no date).

4.1.3.2 Grain

The production area used for grain decreased by 47% from 1999 to 2019. Spring barley is the most important cereal in the county and accounted for 80% of the cultivation surface designated for grain in 2019, followed by oats at 14%. The harvest of barley was about 6 000 tonnes in 2018 and the total harvests have decreased by 30% since 1999. (Jordbruksverket, 2023a) Grain harvests can generate residual streams of kernels, hulls and straw (Carlsson and Uldal, 2009). Barley has not been included in the previous inventories of Wikström and Lagerkvist (2011) or the one by NENET (BioMil AB, 2012).

4.1.3.3 Potato

Potatoes are grown on less than 1% of the arable land in Norrbotten and 6 700 tonnes of potatoes were reported to have been harvested in the county in 2019 (Jordbruksverket, 2023a). Contact with Nyhléns Hugosons (through their affiliated company Haparanda Potatis AB), which is the main provider of local potato products, showed that the potatoes that are sorted out and potato peels are used as animal feed while water from the potato processing is sent to the local treatment plant in Haparanda (Juhlén, personal communication). The current amounts of sorted potatoes and peels used for fodder are 500 tonnes and 1 500 tonnes, respectively (Juhlén, personal communication).

A harvest residue from potato cultivation is the potato haulms. One trial performed in Laholm, Halland county, in 2010-2013 and financed by the Swedish Board of Agriculture investigated the development of a harvest strategy and anaerobic digestion of potato haulms (Jordbruksverket, 2013a). The study found that there are some advantages in harvesting the potato tops, such as eliminating the need of haulm-killing herbicide which is used so that the tops wilts in the field before harvest, and that the potatoes need not come in contact with anti-mold chemicals if the haulm is harvested before the potatoes. However, the concerns were that the haulm harvest risks uncovering or damaging the potato if the soil conditions are bad, that nutrient from the haulm is not refunded to the soil and mainly that the logistics is a challenge. For example, the cultivation rows need to be adapted for the harvest machines to retrieve the haulm and there must be flexibility concerning the time of harvest. The trial of mono-digesting potato tops anaerobically had many operational disturbances, giving unsatisfactory results. (Jordbruksverket, 2013a)

4.1.3.4 Food Crops

Crops other than potatoes are grown on such a low basis in Norrbotten that there is little harvest data reported to the Swedish Board of Agriculture and the crops mostly unspecified. Oilseed crops and "other crops" were reported to be grown at 65 hectares and 1 135 hectares in 2020, respectively. The oilseed crops consisted of spring oilseed rape at 4 hectares and turnip-rape at 61 hectares. (Jordbruksverket, 2023a)

The Swedish University of Agricultural Sciences (SLU) has undertaken a project (2020-2023) to reimburse the breeding of turnip-rape, a tough oil crop that is a relative to oilseed rape and that has been neglected in Sweden for some years. The purpose is to strengthen the cultivation of turnip-rape in the north of Sweden by developing new varieties, since the introduction of an oil crop in agricultural systems provides a break crop that has positive effects on the soil and can help make the north more self-sufficient. (SLU, 2023; Carlsson, personal communication) Turnip-rape is suitable for cultivation in the north as it has a shorter growth period and is more durable compared to spring and autumnal oilseed rape. Turnip-rape is also available in spring and autumn varieties, but the spring turnip-rape was the focus of the current SLU project as well as a previous from 2015 (Carlsson, personal communication; Bernes and Gustavsson, 2016). Spring turnip-rape is sown during early spring, grows during summer and is harvested in August or September (Carlsson, personal communication). Autumn varieties, sown during early fall, are meant to overwinter but cannot stand the harshness of winter in the north (Carlsson, personal communication). The residual from pressing seeds to recover oil is the press cake, which can be used as animal feed as it still contains a lot of nutrients, such as proteins. It has an amino acid profile that complements grain and legumes. The seeds can also be used directly as animal feed. (Bernes and Gustavsson, 2016)

4.1.3.5 Manure

Statistics from the Swedish Board of Agriculture show that the number of farm animals in Norrbotten county in June of 2022 were almost 22 000 cattle, 21 000 pigs and 6 000 sheep (Jordbruksverket, 2022c). Besides this, 5 700 horses have been reported for the year of 2016. A cow can produce roughly 30 kg of solid manure per day (LRF - Sveriges Bönder Skolkontakt, 2022), while a pig can generate around 8% of its body weight in urine and faeces daily (Hatfield, Brumm and Melvin, 1998). A horse that weighs half a tonne can form 20-30 kg of manure, including urine, each day (HästSverige, 2023). Animal husbandry in the north of Sweden entails other restrictions and exemptions from certain rules and regulations compared to the south of Sweden. Due to shorter grazing periods, cattle are allowed to be kept in stables longer and pigs need not be kept outside at all, if the meat is not meant to be organically certified. (Jordbruksverket, 2022d, 2022e, 2022f)

Börjesson (2007) estimated the annual manure production from cattle to be 2.8 tonnes of TS per individual and year. 22 000 individuals equal an amount of 61 600 tonnes of TS per year (including outdoors manure). Grazing was estimated to generate a loss of 20-25% of the manure, yielding 46-49 000 tonnes of TS per year. (Börjesson, 2007)

Manure can be spread on farmland as a fertiliser to mainly add nitrogen and phosphorus but also trace elements and organic material that can improve the soil quality (Jordbruksverket, 2013b). It also has the potential to release greenhouse gases, or nitrogen and phosphorus compounds that can contribute to eutrophication and acidification if washed out by rain into bodies of water (Jordbruksverket, 2022g). The Swedish Agricultural Board states that if manure is not regifted to the earth, the ecological cycle is broken (Jordbruksverket, 2013b).

4.1.4 Energy Crops

Energy crops can be different food crops such as maize, potato, hemp or sugar beet, oil crops, grain and legumes or grass and clover (Wellinger et al., 2013). The crops are either used after storage (for example by ensiling) or used directly after harvest (Wellinger et al., 2013) and can besides AD be employed for ethanol and biodiesel production, as well as being incinerated in boilers (Niemi Hjulfors and Hjerpe, 2013).

Certain crops, like grass and cereals can have a more positive effect on soil quality than for example maize and sugar beets that depletes the soil of nutrients in the long term (Jordbruksverket, 2023b) Perennial energy crops has a less resource demand and cultivation of such can entail that the soil is less touched (Niemi Hjulfors and Hjerpe, 2013). Ley is often pointed out as a soil-improving crop, but cultivation includes the fields being trafficked by heavy machinery several times per season, which affects the harvest and coming harvests as the machines damage the crop above ground and creates unwanted soil compaction. This affects the soil structure and future harvests. (Lundberg, personal communication)

Production of energy crops is in competition with farmland and can mean that farmland is not being used for food production (Wellinger et al., 2013). The case of land usage has been pointed out as an important factor regarding biofuel production from energy crops (Ahlgren et al., 2017). The report by Ahlgren et al. (2017) explains that direct land use change (dLUC) is linked to changing an area of land from one type to another, such as forest to farmland. Energy crops can also be supplied by using already existing farmland but then the need for production of the originally grown crops can increase and cause a land change elsewhere – an indirect land use change (iLUC). iLUC-free products are leftovers from existing farming activities. Pointed out in the report are several potential iLUC-free resources from farmland: unused hay and discarded ensiled crops, ley produced on currently unused and fallow farmland, break crops and other crops that are grown for the ecological benefit and are unused, and finally an intensification of the ley crop growth could generate iLUC-free resources.

In a report about energy grass published by the Swedish Board of Agriculture in 2011 reed canary grass is pointed out as a potential energy crop in the north because it is sturdy and can be cultivated on most soils, including those that do not have the quality for producing edible crops (Landfors and Hollsten, 2011). Nutrient composition and hence fuel properties are affected by soil type, land preparation and harvest where a peat-rich soil gives a lower ash content. Reed canary grass is specifically deemed suitable for direct combustion in heating plants or by firstly pelletising before burning to retrieve the energy (Landfors and Hollsten, 2011). It is also interesting to grow as animal feed and bedding since there is a limited supply of straw from grain (Gunnarsson et al., 2015). Reed canary grass should be harvested green to be used for biogas production (Eliasson, 2010).

Ley crops are also mentioned as an energy grass of interest and specifically for biogas production (Landfors and Hollsten, 2011). A report from 2008 by the Swedish Board of Agriculture states that there is a general overproduction of ley crops by 20% in the country and that it is possible to free some of the cultivation land (Jordbruksverket, 2008). There are reports calculating that 10-20% of the agricultural land currently used for ley crop production in the county of Norrbotten can be used for energy crops (BioFuel Region, 2013). Critical to this estimation is the report written by Cederberg and Henriksson in 2020. The report instead shows that the production of greenfeed generally is in balance with the consumption, nationwide, and concludes that there is a need for updated statistics and information about the subject (Henriksson and Cederberg). Ley is currently used as a biogas substrate in Karlskoga (Karlskoga Energi & Miljö, no date).

4.1.5 Food Industry

The consumption of food in the north of Sweden exceeds the production and Norrbotten county would only be able to supply 20-25% of the demand if a crisis occurred (*P4 Norrbotten*, 2022).

4.1.5.1 Bakery

Polarbröd is the largest producer of bread in the north with the main bakery located in Älvsbyn (BioMil AB, 2012). Circularity work is performed by the company, for example by initiating a collaboration with a food-tech company in 2021 to make plant protein from waste. At present, bread waste and spill become ethanol and animal feed. (Polarbrödskoncernen, 2022)

4.1.5.2 Eggs

Eggs have a high protein content and can be used for biogas production, but eggshells can be a burden to the reactor because of their recalcitrant nature (Carlsson and Uldal, 2009). This recently became apparent and caused confusion among the public in Norrbotten. The shells were found to cause wear on the piping and equipment as well as build up in the reactor at the plant in Boden, decreasing the active digester volume. (*P4 Norrbotten*, 2023) At the same time, the instructions on the waste sorting bags said that eggshells were meant to be sorted in the organic waste (*SVT Nyheter Norrbotten*, 2023a).

4.1.5.3 Dairy

Norrmejerier has been referred to as one of the main providers of dairy products in Sweden (Linné et al., 2008). The waste fractions, for example generated by cleaning of equipment, are already being used at Uddebo WWTP (Larsson, personal communication). Dairy has decreased in importance and this, together with high investment costs, can lead to the closing of the Norrmejerier dairy plant located in Luleå, in the near future (*SVT Nyheter Norrbotten*, 2023b).

4.1.5.4 Fishery

One of the main providers of fish products in Norrbotten is BD Fisk (BD Fisk, 2023). Much of the generated waste is sold to be used for dog food production, at high demand. Some of the waste is also used as mink feed in Finland and other parts, such as fermented herring, ends up at the biogas plant in Boden. (Lundenor, personal communication)

4.1.5.5 Meat

One of the most important agricultural products in Norrbotten, together with dairy, is meat (Karlsson, 2015). Slaughterhouse waste from the two largest farms in Luleå municipality, Alviksgården and Norrbottensgården, is used for biogas production at Alviksgården. Alviksgården always keeps 13 000 pigs and the slaughterhouse generated is combined with slaughterhouse waste from around 10 000 cattle yearly. Around 10 tonnes of slaughterhouse waste together with 100 tonnes of manure is used for biogas production daily. (Hugoson, personal communication). This means that the majority of the slaughterhouse waste generated in the region is accounted for. Blood from the slaughter is not used at the plant due to the high nitrogen content (Hugoson, personal communication). It is instead transported 130 km to Skellefteå to be converted into biogas.

4.1.6 Other Industries

Forestry, mining, and hydroelectric power are large industries in the north (Länsstyrelsen Norrbotten, no date). Great industrial investments and establishments are planned in the coming years to take steps towards a fossil-free future, partly due to the access to clean and cheap electricity. Coming establishments include the building of an anode factory and fertiliser production plant, and investments into fossil-free steel, as well as into hydrogen generation and storage. (Mörtsell, 2022)

4.1.6.1 Paper and Pulp Mills

The importance of forestry means that several paper and pulp mills are established in the north (Norrlin et al., 2016). Paper and pulp mills can generate several residual streams that are interesting for biogas production and can contain bio sludge (generated in aerated treatment of industrial wastewater), fibre sludge, or methanol-rich condensates (Larsson, 2015). Two kraft-pulping mills found in the north are the Billerud Karlsborg mill in Kalix and the Smurfit Kappa mill in Piteå. According to the sustainability report of Billerud the fibre and bio sludges that are formed in the process and wastewater treatment are used for internal energy recycling through combustion, used in the construction sector or as a means to enhance soil qualities (Billerud, 2023). Smurfit Kappa also reports using wastewater treatment and water recycling, and that generated sludge can be used for agricultural, construction and industrial applications (Smurfit Kappa, 2023).

In March of 2023, it was reported that old waste from paper and pulping mills can emit great amounts of methane from the bottom of the Baltic Sea as well as rivers and lakes (*Vetenskapsradion På djupet*, 2023a). Until the 70s, paper and pulping mills could release untreated waste directly to the water recipients, forming fibre rich sediments and fibre banks that also contain pollutants like heavy metals, DDTs, and other organic toxins (*SVT Nyheter Västernorrland*, 2023). An investigation in 2016 found that waters close to the mentioned mills, as well as the mill SCA Munksund in Piteå, contained fibre rich sediments and fibre banks (Norrlin, 2016).

Toxins remain bound if the fibres are left alone but the methane that is formed under anaerobic conditions remains a problem (*Vetenskapsradion På djupet*, 2023b). Scientists from the Mid Sweden University are currently developing methods for bioremediation of the coastal regions of the county of Västernorrland (south of Västerbotten county) and the technique is also meant to include refining of the biomass into valuable products, such as biofuels (Mittuniversitetet, 2023; *SVT Nyheter Västernorrland*, 2023).

4.1.6.2 Aircraft Deicing Liquid

Monopropylene glycol (hereafter simply called glycol) is sprayed on the wings of aircrafts at Luleå Airport during wintertime, on a designated deicing spot (Sundqvist and Viklund, 2023). The liquid that reaches the ground is transported through a drainage system to a treatment plant run by Vilokan ADF Solutions where the glycol is purified up to 99.8% through distillation before being transported south and resold. The treatment plant also treats deicing liquid from other airports; mainly Östersund and Kiruna airports. Around 120 m^3 purified glycol is resold yearly. (Sundqvist and Viklund, 2023; Skogqvist, personal communication). A residual fraction with a total yearly volume of 10 m^3 per year is also formed and has a glycol concentration of around 20-30% but also contains heavy metals. It is sent away for further treatment (Skogqvist, personal communication).

4.2 Substrate Evaluation and Selection

The following section provides a more in-depth evaluation of the potential substrate sources to point out strengths and weaknesses. It also includes a selection of the two substrates to be assessed further and used in the techno-economic analysis.

4.2.1 Agriculture

BioFuel Region (2013) concluded that the agricultural sector holds the key to an increased biogas production. The agricultural sector is scarce in comparison to other parts of the country and what residuals are left is generally used for husbandry. Agricultural production is centred around the coastal region, with for example potatoes being commonly cultivated in the Tornedalen area (located north of Luleå). Biogas from potato haulm has been briefly studied and puts certain demands on the logistics and require adaptation of the cultivation. The other wastes generated from potato production could be process water, which will have a low TS content and therefore be expensive and inefficient to transport from Haparanda (approximately 130 km away). Furthermore, it is already treated by a local WWTP. Potatoes that are sorted out and peels can be bought but competes with animal feed supplies. Oil crops can become more important in the future but hold no important share in agriculture today. The press cake is also a potential source of fodder, along with the oil that can be used to increase the self-sufficiency in the region. The plant stems that are generated from the cultivation of turnip-rape has been described as tough and woody and probably less suitable for biogas production (Carlsson, personal communication).

Manure can be deemed to exist in considerable amounts, partially due to the longer stable periods and with dairy and meat production being an important industry. Furthermore, biogas production at Alviksgården only uses manure from pigs at the farm (Hugoson, personal communication). Ruminant-generated manure gives lower biogas yields as anaerobic digestion partially takes place in the digestive systems (Carlsson and Uldal, 2009). According to the report published by NENET in 2012, manure can only be transported around 20 kilometres to not consume more than 5% of the energy content and according to the report from BioFuel Region (2013) manure can only be transported 20-50 km to not consume it fully (BioMil AB, 2012). One source state that liquid manure should only be transported 15-20 km (Deublein and Steinhauser, 2011). The BioFuel Region (2013) report also found that the main potential is found on smaller farms and that the potential was greater in Västerbotten than in Norrbotten county (BioFuel Region, 2013). An important point of investigation would be to map out the distance between manure source and biogas plant.

Several assumptions need to be made if selecting manure, for example concerning the content and amounts. Urine can be collected apart or together with the solid fraction and the manure can contain a lower or higher amount of straw from bedding (Länsstyrelsen Västerbotten, 2018). Liquid manure, or slurry, can be defined as having a TS content below 12%, solid manure a TS content above 20% and deep litter manure a TS content above 25% (Linné et al., 2008; Jordbruksverket, 1995). A summary published by the Swedish Board of Agriculture (2014) shows key figures; a TS content of 6% and 8% regarding liquid manure from swine and cattle, respectively and up to around 30% for deep litter and 40% TS for straw litter manure from horses. The corresponding VS contents are 81-82% of TS and 90% of TS for the horse deep litter. The same report states that the biomethane potential from AD in a continuously stirred tank reactor with a hydraulic retention time of 30 days at mesophilic conditions shows that all manure types yield around 200 Nm^3 methane per tonne of VS. (Jordbruksverket, 2014)

Manure often contains many micro and macro nutrients needed in a biogas process but can become problematic if the lignocellulosic content or nitrogen content is high (Carlsson and Uldal, 2009). It can also contain impurities that can accumulate in the reactor (Deublein and Steinhauser, 2011). The C/N ratio is lower for slurries than solid manure and has been reported to be 3.5-7 for pig slurry (Deublein and Steinhauser, 2011; Wellinger et al., 2013; Carlsson and Uldal, 2009). Cattle slurry can have slightly higher C/N ratio of up to 20. Solid manure contains a larger carbon fraction (Wellinger et al., 2013) and can be balanced around the optimal ratio of 25 (Carlsson and Uldal, 2009).

Another aspect to consider is the effects of potentially removing manure from the farmland carbon cycle. One report about logistics optimisation related to biogas production stated that it is important to consider both biogas and digestate as commercial products and that digestate normally is transported to fields within 50 km of the biogas plant (Ljungberg, Gunnarsson and de Toro, 2013).

4.2.2 Energy Crops

Amongst the energy crops, the most obvious alternatives become different types of grass as this is the crop that is most grown, grows well in the north and does not compete with a human food supply. The fact that there is an estimation of around 5 000 hectares of unused farmland (in 2016) means that the energy crops can be iLUC-free.

Reed canary grass can yield a similar or higher biomethane production than ley and has been shown to produce almost 300 (Seppälä et al., 2009) or 340-390 Nm^3/tonne VS (Lehtomäki, Viinikainen and Rantala, 2008). Ley has been shown to produce 300 (Carlsson and Uldal, 2009) or 330 Nm^3/tonne VS (Prade et al., 2015). One trial testing reed canary grass for biogas production in the north of Sweden showed similar traits concerning harvest yields and biomethane potential compared to ley crops (Gunnarsson et al., 2015).

Estimated energy consumption for production of reed canary grass and ley crops have been estimated at around 8-11% of the energy content for ley and 8-9% for reed canary grass (Börjesson, 2007). A ley harvest can amount to 8-10 tonnes TS per hectare (Lundberg, personal communication). Reed canary grass can yield 3-6 tonnes TS, depending on the amount of fertiliser used (Lundmark et al., 2010), or up to 7 tonnes TS per hectare (Gunnarsson et al., 2015). The C/N ratio of ley varies depending on the content of legumes (which contributes with nitrogen), ranging from 15 up to 27 (Nordberg et al., 1997). The lignin content has been found to correlate to around 20% of the TS content (Gunnarsson and Lund, 2020). An average lignin content of reed canary grass is 13.8% of the TS content (Prade, 2012).

Lignocellulosic materials can become a challenge in a biogas plant, both in terms of degradability and due to the potential to cause floating layers (and thus affecting the digestion by decreasing the substrate-microbe contact area) (Sun, 2015; Victorin, 2016). A thick floating layer also reduces the active digester volume. A suitable pretreatment can fragment the lignocellulosic material and reduce the risk of a floating layer being formed (Sun, 2015). Different pretreatment choices would require different equipment investments and operating inputs (i.e., energy and resources).

4.2.3 Food Industry

Waste generated by the food industry is generally already in use for biogas production, as animal feed or for other purposes. This is true for bakery, dairy and fishery waste. Much like the potential substrates from agriculture, the consequences of changing the utilisation from its current form should be considered and studied. Furthermore, the current usage implies creating value from a residual and the implementation of the potential substrate at Uddebo WWTP would not only mean competing for resources but is likely also a financial competition where the part that can pay the most gets the resource. This would affect the price of the produced biogas.

Collecting waste from egg production means that the process design needs to be adapted for this purpose or else be problematic. Egg production will be omitted as a potential substrate on the basis of having caused problems in the region before. It is a residual stream considered to be of less interest at the moment.

Regarding the meat production, though the local slaughterhouse waste is used, the blood is being sent out from the county and into another. The transport covers around 140 kilometres one way, and the trailers are empty on the way back. The trucks are currently driven on diesel (Samuelsson, personal communication). Blood has a high water content but also contains proteins that provide a relatively high nitrogen content (Nazifa et al., 2021). Local implementation of blood as a biogas substrate would decrease the costs for the farms as well as facilitate the logistics for Lumire (Samuelsson, personal communication). Furthermore, it would reduce the fossil fuel consumption. At the same time, usage of an animal byproduct would require additional processing in terms of a sanitising technique, which would require changing the mode of operation at Uddebo WWTP and/or supplementary equipment investments.

4.2.4 Other Industries

Paper and pulping sludges can be considered not available as these are used for internal energy recycling. A previous inventory has reported that fibre sludge is unsuitable as a biogas substrate (Linné et al., 2008). It remains to see what the future usage of fibre banks and sediments will be.

Glycol is a readily biodegradable diol (Sigma-Aldrich, 2022). Two fractions containing glycol are formed at the glycol recycling plant at Luleå Airport, one consisting of pure glycol and one residual. The smaller fraction of 10 m^3 contains heavy metals, which are unwanted in large concentrations in an AD process. Glycol can be derived from renewable resources but is generally derived from petroleum (Forkner et al., 2022). Production of biogas from glycol would not directly fulfil the definition of biofuel in the Swedish law (Lag 2010:598) concerning biofuels since it is not necessarily generated from biomass (Klimat- och näringslivsdepartementet RSE). Biomass refers to organic compounds originating from organisms or the organisms themselves and the matter should be renewable to be considered biomass (Tokay, 2000). Recycling of glycol means that it can be used again instead of virgin glycol being produced from possibly fossil sources.

4.2.5 Selection

Slaughterhouse blood and ley crops will be assessed as model substrates in the techno-economic assessment. The reason behind the choice is that one potential substrate represents a resource that is currently available, and the other a substrate that can be made available. The unused farmland becomes the asset that could unlock a future biomethane production, while blood is a substrate that is “exported” out of the region today.

4.3 Ley Crops

In the following section, ley crops will be discussed in more detail. The purpose is to give an overview on how ley crops are produced, what decisions must be taken in terms of production and shed light on available pretreatment methods.

4.3.1 Value Chain

A report by Ljungberg, Gunnarsson and de Toro (2013) investigates the value chain for obtaining biogas crops, including ley. Costs studied included those for sowing, caring for the land, harvest, transport, and storage but excluded costs for handling and pretreatment before feeding into the reactor. A part of the work consisted of gathering information from Swedish biogas plants and included interviews from five plants that used crops for biogas production. A defining decision that must be made when regarding ley as a potential biogas substrate is who will be responsible for production of the crops and the different plants used different solutions. One alternative is that the plant takes full responsibility of the production by leasing land and growing crops, or the crops can be bought while standing in the field. Another way is to buy the crops produced and ready and get it delivered to the plant. The most common way to obtain the substrate was by using contracts lasting the period that the crop is produced in the same fields, around 2-3 years. The payment was commonly made based on the delivered amount of TS (in weight) and plants expressed a desire to, in the future, pay according to the quality of the crops. Some plants combined growing themselves and buying readymade crops. (Ljungberg, Gunnarsson and de Toro, 2013)

Prade et al. (2015) investigated how the harvest time and cutting lengths before ensiling of ley and cereals (rye and wheat) affect biogas production. In the report, the activities needed to establish the crops and the studied model system shows that production of ley crops includes less activities compared to cereals, needing only sowing, one land processing and spreading of fertiliser before the first harvest. The harvest activities of grasses have been described by Gunnarsson et al. (2015); Ljungberg, Gunnarsson and de Toro (2013) and Prade et al. (2015). After harvest the grass is ordered and left in windrows in the field, allowing it to dry ("strängläggning" in Swedish), up to a TS of 35% according to the study by Prade et al. (2015).

After raking and drying, a sort of a raker or swather with an automatic chopping device picks up the grass from the field and cuts it to the preset length, one of the parameters that was studied by Prade et al. (2015). They found that coarsely and mid-length cut ley (12 and 8 mm, respectively) gave a higher methane yield compared to finely cut (4 mm), while reducing the harvest costs, partly due to lower diesel consumption. The longer cuttings had a yield of around 330 Nm^3 CH_4/tonne VS, while the shorter had 300 Nm^3 CH_4/tonne VS (Prade et al., 2015). In the report on ethanol production from ley by Gunnarsson and Lund (2020), it is stated that every treatment step added is a cost and that it therefore can be economically efficient to chop the grass during the in-field activities, instead of before feeding into a reactor.

While chopping, the treated grass is transferred into a loader wagon driven along the chopping machinery (Prade et al., 2015; Ljungberg, Gunnarsson and de Toro, 2013). The chopping device could also be complemented by a "biogas drum" that chopped the grass even more, (to lengths <1 cm) (Ljungberg, Gunnarsson and de Toro, 2013). The tractor can be driven directly to the storage facility, or, at longer distances, the grass is reloaded into trucks (Ljungberg, Gunnarsson and de Toro, 2013).

The distance between the substrate source and the plant in the study by Ljungberg, Gunnarsson and de Toro (2013) ranged from 10 to 20 kilometres with one plant having an average of 20 km with a maximum of 50 km. Transport from field to storage by tractor was deemed suitable up to 10-15 kilometres, otherwise the crops needed to be reloaded into trucks. Storage was almost exclusively done in bag silos, most commonly by the farm but by the plant or at satellite storage also occurred. One plant bought the grass as bales.

Ensilage losses measured in lab trials by Prade et al. (2015) showed average losses of 2.3% and a maximum of 4.9% of the energy potential but it is also mentioned that losses are somewhat greater in bunker silos, due to contact with air leading to aerobic activity. During the ensiling process, lactic acid bacteria consume sugars from the biomass, fermenting it into lactic acid which lowers the pH and outcompetes pathogens (Wellinger, 2013). The process can be quick, only taking days, and especially quick when adding aids (Murphy et al., 2011). This results in a pH of 4-4.5 (Murphy et al., 2011; Wellinger, 2013).

Ensiling in bag silos uses plastic to cover the biomass and pack it tight. Ley crops can be estimated to be packed with a density of 200 kg of TS per m^3. An example is 3.5 m wide and 100 m long (Murphy et al., 2011). The packing requires equipment especially designed for the purpose and puts special requirements on the land quality as it must withstand heavy vehicles all year round. If several bags are to be used, these require a distance inbetween, according to Sundberg (2007) 0.5 m, which claims even more land. The biomass can be collected from the bag using a tractor or wheel loader. As soon as a removal has been made, air enters the bag causing aerobic activity and consuming nutrients. (Sundberg, 2007) Gunnarsson and Lund (2020) have stated that several reports have shown ensiling to aid the further conversion of cellulose, compared to processing of biomass that has been conserved by being kept dry.

In the same report by Gunnarsson and Lund (2020) it is stated that ley for ethanol production can be stored in the same way as when it will be used as fodder, namely: bunker, bag or storage clamps. Bales were considered ineffective as it requires removal of plastics and since the straws are longer would need effective disintegration. An example of the value chain for production of ley crops can be seen in *figure 5*.

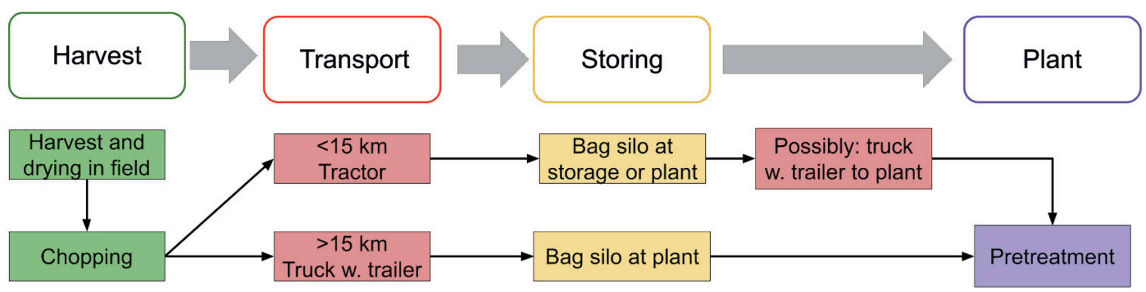

Figure 5. Value chain of ley crop production. Examples of activities and equipment used for production of ley crops as a biogas substrate. Inspired by Gunnarsson et al. (2015).

When the biomass in the studied cases of Ljungberg, Gunnarsson and de Toro (2013) reached the plant, it was tipped into a "reception pocket" or on a cement plate. The first stage, thereafter, was described to commonly be a dry process where a mixer wagon, or other device, tears the substrate. It could then be transported by screws or conveyor into a reception tank where it is mixed with other substrates, before being pumped into the digester. The crops could also be mixed with another liquid, such as recirculated digestate, before mixing with other substrates in the reception tank or being directly injected into the reactor. It was common that the "wet stage" included another disintegrative device at some point before the reactor, such as a chopping pump, macerator or deflaker. (Ljungberg, Gunnarsson and de Toro, 2013)

In the report "Co-digestion of ley crops and source sorted municipal solid waste" a design for using ley crops in a full-scale plant is described (Nordberg et al., 1997). The example design shows that ley crops are transported to a storage device that can automatically feed substrate into a slicer. The biomass then passes a metal detector and mill before being mixed with liquid from the reactor and injected into the AD chamber. The example milling device was a meat mill. The report discussed power usage for a pilot plant and pointed out stirring of the reactor as the main power consumer but that it is strongly tied to the scale of the plant. The energy used for transporters was deemed to decrease somewhat (per treated amount) with the size of the plant, while the power needed for milling, pumping and substrate mixing was deemed to stay the same per treated amount. (Nordberg et al., 1997) A conceptualisation of the substrate flow on-site of a biogas plant when implementing ensiled ley as a biogas substrate is shown in *figure 6*.

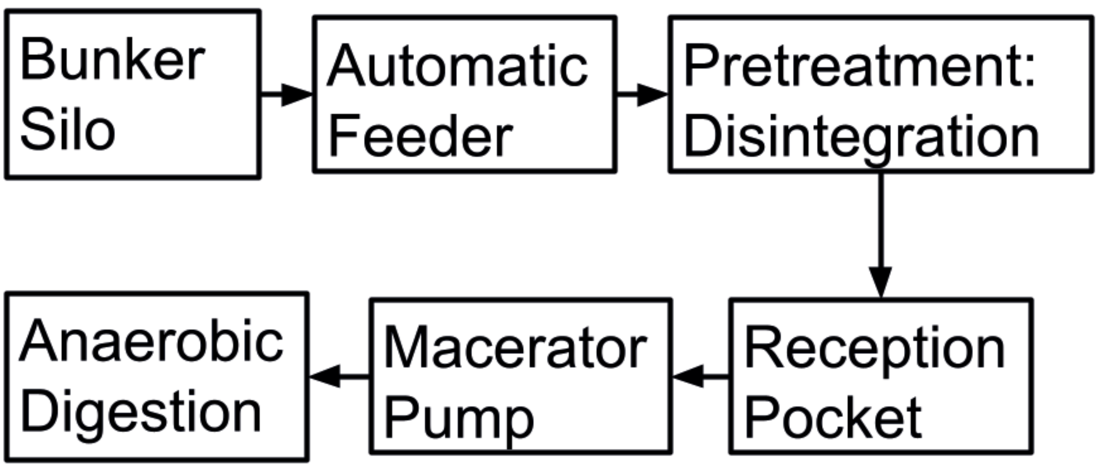

Figure 6. Example of the substrate flow, activities and methods included on-site of a biogas plant when implementing ensiled ley as a substrate. The substrate flow is shown from on-site storage to injection into the AD reactor.

The energy usage for production and harvest of ley has been estimated by Berglund and Börjesson (2003) to vary between 1.8-1.9 GJ/tonne TS from both *direct* and *indirect energy inputs*, assuming a TS content of 23% and including harvest losses. An example of *direct* energy consumption can be the consumption of fuel from a vehicle while *indirect* refers to the energy and resources required to produce that fuel. Two sources that are mentioned in the study by Berglund and Börjesson (2003) report energy usages of up to 1.9 GJ/tonne TS (assuming 23% TS or 20% harvest loss, with yields of 7.7 tonne TS/ha) while one study including transport of 1 km to a farm and 15 km to a plant shows 2.8 GJ/tonne TS. Prade et al. (2015) presented 1.4 GJ/tonne TS for roughly chopped ley (assuming a yield of 12.2 tonne TS/ha) including transport to a biogas plant and losses. (Prade et al., 2015). Berglund and Börjesson (2003) have also stated that the cultivation and harvest of ley can consume up to 45% of the total energy required in the complete life cycle, from sowing to dewatering of digestate, when using ley as a biogas substrate. Prade et al. (2015) showed that the net energy balance of ley as a biogas substrate could yield an energy gain of almost 2.3 MWh/tonne TS and year. The energy efficiency quota in the same report was around 28% for roughly chopped ley in a two-harvest system and consequently, the EROI became slightly less than 4.

4.3.2 Evaluation of Pretreatment Techniques

Pretreatment of lignocellulosic biomass can be performed with the purpose to increase the surface area to make the nutrients more available, to decrease the risk of a floating layer of biomass forming inside of the AD reactor, and to facilitate the injection into the digester (Björnsson et al., 2014). In the publication from 2014 by Björnsson et al., different pretreatment methods for lignocellulosic material are investigated and describes several examples, including simpler trials and full-scale implementations. The examples mostly include mechanical pretreatment as well as chemical techniques. Mentioned mechanical disintegration methods include extrusion, maceration, hammer milling, and chopping pumps. The chemical methods used acids or bases such as acetic acid, sodium hydroxide and ammonia.

Andersen et al. (2022) performed a theoretical technical-economic assessment on hammer milling, steam explosion and alkaline impregnation of straw which showed that the mechanical option was the most viable even though it has less effect on the biodegradability. While milling a substrate improves the surface available for microbial attack but keep complex structures intact, a chemical method can have a decomposing effect on lignin (F. R. Montgomery and Bochmann, 2014). Hammer milling showed the potential to have the lowest capital costs, while steam and alkali pretreatment were assumed to require greater investments and more equipment, such as tanks and possibly spare tanks, and furthermore require additional manpower. However, alkali pretreatment was deemed to increase the bioavailability of the substrate while having a low need for electrical power and heating. (Andersen et al., 2022)

An investigation by Rodriguez et al. (2017) showed that mechanical pretreatment held the potential to increase the biogas yield from grass crops the most, compared to untreated biomass. Despite the significant energy demand of mechanical processes, these were pointed out as the techniques of highest interest. Other examples of mechanical techniques tested on ley includes deflakers and dispersers, equipment that has been developed for paper and pulping industry. These could require addition of water to run efficiently (Lindmark et al., 2012).

The suitable pretreatment method should be chosen after consideration of the substrate type as well as economical aspects (Björnsson et al., 2014). In a review, Kratky and Jirout (2011) points out that selecting a suitable pretreatment method is dependent on the moisture content of the substrate, the desired particle size outcome and power usage. The same review state that 1-2 mm large pieces of biomass is optimal for an efficient hydrolysis.

Colloid mills and extrusion are useful in cases of having substrates with higher water contents, while other milling equipment, such as hammer and knife mills, can be used in instances of lower moisture or dense substrates. Knife mills were pointed out to be useful for substances of 15% moisture or lower. (Kratky and Jirout, 2011) Substrate of a high moisture content risks hinder the disintegration procedure in a hammer mill because it can stick to walls and a drier substrate is therefore preferred (Arce and Kratky, 2022). Examples of substrates treated with a hammer mill include wheat straw, cotton stalks and whole rice straw (Acre and Kratky, 2022). There are examples of hammer mills that are designed to treat a broad range of substrates, such as the BHS Biogrinder from Lobe (Lobe ApS, 2019).

Gunnarsson et al. (2014) compiled a table that includes several publications about mechanical pretreatment of lignocellulosic biomass. Substrates that are close in TS content (+/- 5 percentage points, 27-37%) to ley crop silage have been pretreated with hammer mills, knife mills and extruders (Gunnarsson et al., 2014). In a report from 2021, the impact crusher, having the similar machinery to that of a hammer mill was mentioned as a machine that possibly could treat several kinds of substrates from the agricultural sector (Gunnarsson et al., 2021). Examples of energy usages from the report by Gunnarsson et al. (2014) includes a knife mill treating ensiled crops from a round bale (37% TS), shown to use 25 kWh/tonne wet weight (WW) and an extruder treating chopped ensiled ley (35% TS) using 15 kWh/tonne WW. A trial performed by Nordberg and Edström (1997) showed that a fodder mixing wagon could disintegrate silage from a round bale with a TS content of 46% at an energy usage of 35 kWh/tonne WW.

According to Odhner et al. (2015), extrusion has the potential to increase the biogas yield from ley by 30-50%. Biogasbolaget i Mellansverige AB, a biogas plant located in Karlskoga, currently uses ensiled ley as a substrate. The ley process line includes an extruder that crushes the material for a faster and facilitated digestion. It has a maximum energy consumption of 72 kW but at normal operation consumes 30 kWh. The process line for ley has been costly from the beginning, after being taken in use in 2013. Electricity costs and spare parts for the extruder have accounted for a significant share of the costs. The maintenance of the extruder is dependent on the constant feeding of substrate. Disturbances that lead to no substrate being fed into the extruder causes faster wear on the mechanical parts as the substrate is a part of the function of the equipment. The process line has the capacity to treat around 60 tonnes of substrate per day but is operated according to the availability of substrate, as well as how much biogas is to be produced. It is operated around 6-8 h/day split in periods over 24 hours and treats around 15-20 tonnes of ley per day. The TS content of the ley is around 25-30% but varies depending on the harvest. (Perttunen, personal communication)

4.4 Slaughterhouse Blood

The following section provides an overview on the current handling chain of slaughterhouse blood and to assess different pretreatment options before finally showing an example of a process design for including blood as a substrate at Uddebo WWTP.

A review about anaerobic digestion of different kinds of livestock blood by Nazifa et al. (2021) has characterised animal blood as mostly consisting of water (~80%) and 20% proteins. The density of animal blood was described to commonly be around 1 tonne/m^3 but blood coming from cattle could have densities that are up to 50% higher according to the review. TS contents for bovine and swine blood were found to be around 20% and the VS (in % of TS) near or around 95%. The C/N ratio was low, near 3. (Nazifa et al., 2021)

Hejnfelt and Angelidaki (2009) evaluated biogas production from slaughterhouse byproducts from pigs. Thermophilic and mesophilic conditions (55 °C and 37 °C, respectively) were used to test several different byproducts with the latter conditions resulting in greater methane yields. This was associated with less free ammonia due to the lower temperature. Exclusively using swine blood diluted with water for digestion at 55 °C resulted in dramatically lower methane yields at high blood concentrations (50% and 100% seen to weight), compared to only 5 weight% of blood. The low concentration of blood instead gave an accumulated methane production near the theoretical, which was calculated to approximately 500 L of methane per kg

VS. The same trend was seen for the other slaughterhouse substrate types, giving higher methane yields at high dilutions. The negative trend seen at high substrate concentrations was explained to be the consequence of inhibition caused by the high concentrations of breakdown products from the fat and protein-rich substrates. (Hejnfelt and Angelidaki, 2009) Edström, Nordberg and Thyselius (2003) has stated that slaughterhouse waste is suitable for co-digestion. Nazifa et al. (2021) further showed that the biogas yield from blood depends on substrate concentrations and substrate blend where, for example, mixtures of bovine blood and other slaughterhouse waste together with manure could result in yields above 500 L of methane per kg VS.

4.4.1 Current Value Chain

Every week, bovine blood from Norrbottensgården and swine blood from Alviksgården is collected in a tank truck and driven to the biogas plant Tuvan in Skellefteå, around 140 kilometres away. The blood has tendencies to foam, even though being sucked into the truck tanks under low pressure which means that trucks cannot be loaded full. Normally, the trucks can carry 13-14 000 L but instead carries around 11 000 L. (Samuelsson, personal communication) This has been estimated to weigh around 11 tonnes (Adolfsson, personal communication). A tank truck with a trailer is needed every other week to transport approximately 16 000 L of blood (and 20 000 L in connection to holidays). (Samuelsson, personal communication) The foaming phenomenon has been described to have occurred by other mechanisms at an instance at Kungsängen biogas plant in Uppsala. It happened in a buffer tank when an increase in retention time coincided with an unusually high concentration of slaughterhouse waste (24%, in the normal case 13-15%). The buffer tanks were 30 °C and the substrate fermented, leading to foaming and flooding. (Grim, 2014)

The tanks are unloaded at Tuvan by using pressure and are driven empty on the return because of the need for washing the tanks with water before being allowed to transport anything else. The two-way transport takes around 4 hours, and 70 litres of diesel is consumed on the delivery, while the empty truck consumes around 49 litres of diesel. The work to deliver the blood and clean the truck claims almost a full workday of 8 hours. Lumire takes a fixed charge from the farms depending on the size of the tank vehicle, which is shared on both farms, and has an hourly charging rate for the truck and driver meant to cover all the expenses and make a profit. The charge is adjusted yearly and can also be changed if something unexpected happens, for example if fuel prices escalate. (Samuelsson, personal communication) Tuvan biogas plant also charges the farms (Pettersson, personal communication) A decrease in costs to the customer and in fuel consumption are two effects if the substrate was to be used at Uddebo WWTP (Samuelsson, personal communication).

The blood is treated in the thermophilic digester chamber (3 800 m^3) at Tuvan WWTP in Skellefteå along with other organic waste fractions. A second, mesophilic, chamber is also available at the plant and solely treats sewage sludge, of an amount corresponding to around 40 000 pe. (Pettersson, personal communication) Upon arrival, the blood is unloaded into a reception pocket with other slaughterhouse waste and grease before being transported by screws to a disperser which dilutes the substrate and finely disintegrates larger particles. The substrate is then transported to buffer tanks where it is mixed with the slurry made from pretreatment of the other waste fractions. The TS content in the buffer tanks is around 5-7%. (Pettersson, personal communication)

The other waste fractions are pretreated initially using a crusher with rotating knives that roughly breaks the waste and allows large wrongly sorted objects to be removed. The substrate then enters a high consistency pulper that divides particles more finely while diluting with water from around 30% TS to 22% TS. It is then diluted to a TS of 11% in connection to treatment in a reject separator where the crushed waste is pressed and washed to a slurry, while the solid fraction consisting of large particles (>6 mm) is retained. (Pettersson, personal communication; Skellefteå Kommun, 2023) The liquid slurry is then led to buffer tanks for storage before pasteurisation, together with the disperser-treated substrate. (Skellefteå Kommun, 2023)

4.4.2 Evaluation of Pretreatment Techniques

Blood is an animal byproduct that can be classified as category 3, or least infectious risk (Avfall Sverige, 2022a). Material from the category generally require pasteurisation or treatment with an interchangeable method such as internal sanitation through thermophilic digestion where the reactor temperature reaches a temperature above 52 °C that is kept for at least 10 hours in a row and has an HRT of at least 7 days (Jordbruksverket, 2016). The bench-scale trial investigating slaughterhouse byproducts from pigs by Hejnfelt and Angelidaki (2009) showed that pretreatments such as pasteurisation on the substrate called "mixed pork waste" did not affect the methane yield in a positive or negative way. Edström, Nordberg and Thyselius (2003) instead found that pasteurising slaughterhouse waste could significantly improve the biogas yield.

4.4.2.1 Sanitising Techniques

Tuvan uses pasteurisation for sanitising substrates and the technique employed in 2016 has been described by Lundberg (2016) to consist of two tanks using direct steam injection. Steam generated using a pellet boiler was injected into the substrate mixture heating it to 70 °C, which was kept for one hour before the substrate was cooled to 55 °C using river water. The substrate was then described to be pumped into the reactor with a speed of 3.5-4.5 m^3/h 24 hours a day. The effective volume of the tanks was 24 m^3. Filling took 65 min, heating 3 hours and pasteurisation for at least 60 minutes, leading to a total pasteurisation time of 4 hours and 40 minutes. Emptying 24 m^3 was deemed to take 3 hours (8 m^3/h being the maximum inflow into the AD). The steam demand was reported to be dependent on the temperature changes resulting from the passing of seasons, which affected the temperatures in the buffer tanks which could keep 2.5°C during winter and 12°C during summer. (Lundberg, 2016)

The possibility to only alter between two pasteurisation tanks has been described to be a potential bottleneck (Pettersson, personal communication). Having at least three would mean that the tanks could alter between the three activities of filling, pasteurisation and emptying.

Lundberg (2016) also investigated if a change from direct steam injection to pasteurisation using tanks with hot water jackets heated with the otherwise torched gas would be more beneficial for the plant. The jacket medium was designed to have a temperature of 95 °C and a return temperature of 75 °C to not act cooling on the substrate. Forced convection of water (heat transfer through a continuous water flow) was compared to natural convection (still standing water) and the forced method was more efficient and required less gas to heat the water. However, the results indicated that changing pasteurisation technique to a system with hot water jackets and burning of excess raw gas would be negative from an economic point of view. The torched excess gas was discussed as possibly being useful for applications that would not require constant additions of heat. It was also suggested that investigation on water jackets using high energetic district heating be performed.

An unpublished documentation from 2015 produced by SWECO in connection to the commissioning and building of the second AD chamber at Uddebo briefly assessed the inclusion of a pasteurisation unit. It was evaluated due to discussions at the time by the EU and Sweden which could mean that WWTP sludge possibly could be subjected to stricter rules and pathogen control. The pasteurisation design in the commissioning suggested jacketed tanks heated using district heating complemented by additional heat injection to compensate for when the delivery temperature of the water was below 83 °C, which could occur during summer and spring. (Johannesson and Larsson, 2015) The energy compensation was estimated to be equal to 8 000 hours of extra energy generation or 800 MWh of extra energy (Ramboll, 2015). The pasteurisation unit was designed to have three tanks dimensioned for 20 m^3/h of raw sludge, to be made of acid-resistant steel with a diameter of 2.5 metres and a total height of 5.5 metres, with the hot water jackets having a height of 4.5 metres. It was assumed to require the constructing of a new building in between the digestate storage and WWTP sludge dewatering. (Johannesson and Larsson, 2015)

The unpasteurised sludge was designed to pass two counter-current tubular heat exchangers with water circuits as the mantle side medium, before reaching the pasteurisation tanks. The water circuits were designed to be heated by the pasteurised sludge on its way to the digestion chamber, recovering the heat. Temperatures of the unpasteurised sludge was estimated to be elevated from 10 °C to 37-43 °C after passing the two heat exchangers. Pasteurised sludge would transfer heat to the water circuits, decreasing in temperature from 70 °C to 37 °C.

The heat exchanger meant to heat the pasteurisation tank (jacket) was also suggested to be tubular with the water circuit being district heating, compensated by a boiler when needed. It would heat the sludge from 37-43 °C to 72 °C. (Johannesson and Larsson, 2015) Introducing district heating for pasteurisation would mean increasing the return temperature of the district heating to around 63 °C, an increase of approximately 10 °C (Klang, Niva and Lundgren, 2015).

A master thesis by Grim from 2014 assessed the biogas plant Kungsängen in Uppsala. The biogas plant treated sorted household waste, industrial food waste and slaughterhouse byproducts. It had two digestion chambers with a temperature of 52 °C. The complete heating demand of the plant was described to be supplied by a boiler run on biogas or oil. The thesis evaluated the, at the time, used pasteurisation technique of direct steam injection in comparison to changing to internal thermophilic sanitation. Pasteurisation was described to be initiated by pumping of substrate from a buffer tank to one of the three pasteurisation tanks, passing two heat exchangers (HEXs) on its way. The heat transferring media in both exchangers was water and both were of the countercurrent type. In the first HEX, the substrate was heat exchanged with digestate that exits the digestion chamber on its way to digestate storage. In the second HEX, the substrate was exchanged against the pasteurised substrate being transported towards the digester. This preheated the untreated substrate and decreased the risk of overheating the chamber with the pasteurised substrate. (Grim, 2014)

Different systems for integrated thermophilic sanitation were designed, with differences for example regarding preheating. The model that was chosen included heat exchanging untreated substrate against a water circulation current from the digestate storage. (Grim, 2014)

Pasteurisation was found to account for 85% of the total energy needed for the biogas plant. A change in sanitising technique to an internal thermophilic showed an energy-saving capacity of 46% of the current input need. Sensitivity analysis showed that assumptions regarding energy losses in heat exchangers was important for the result and that an energy loss of 10% greatly affected the winnings of an internal thermophilic sanitation, instead giving a yearly saving of 25% of the energy required when utilising pasteurisation. Grim (2014) also emphasised that internal thermophilic sanitation risk being especially sensitive against process changes such as increased loads (from 3.5 kg VS/m^3 and day) and that a decrease in only 4.2% of the total biogas production would mean a complete loss of the benefits of the thermophilic technique compared to the pasteurisation. This could be exemplified by an operation stop of 15 days. (Grim, 2014)

A remark was made that the steam demand varies over the year as temperatures in the substrate buffer tank varies, but with an average temperature of 24.5 °C during the studied period. Outside temperatures were also commented to affect the heating needs of the digestion chambers. Grim (2014) refers to an unpublished document that has evaluated similar cases and shown that Swedish biogas plants with integrated thermophilic sanitation have half the energy needs of those with pasteurisation. The thesis by Grim (2014) showed that investing in internal thermophilic sanitation had a fast payback period of 2.2 years. Grim (2014) also states that the advantages of the thermophilic method compared to pasteurisation lies in how well the heat of the pasteurised substrate is recovered and utilised. It is elaborated that efficient heat recovery would minimise the advantages of thermophilic sanitation and heat exchanging is therefore an important optimisation point if using pasteurisation. (Grim, 2014)

4.4.2.2 Suggested Pretreatment Design

The suggested process design to be assessed in the techno-economic analysis was based on the pasteurisation process proposed by SWECO in 2015 and illustrated in *figure 7*. The pasteurisation unit was designed to include three hot water-jacketed tanks supplied with jacket medium from the district heating, supplied with additional heat by a boiler when required. Preheating and heat recovery was designed to be performed by tubular heat exchangers with water circuits.

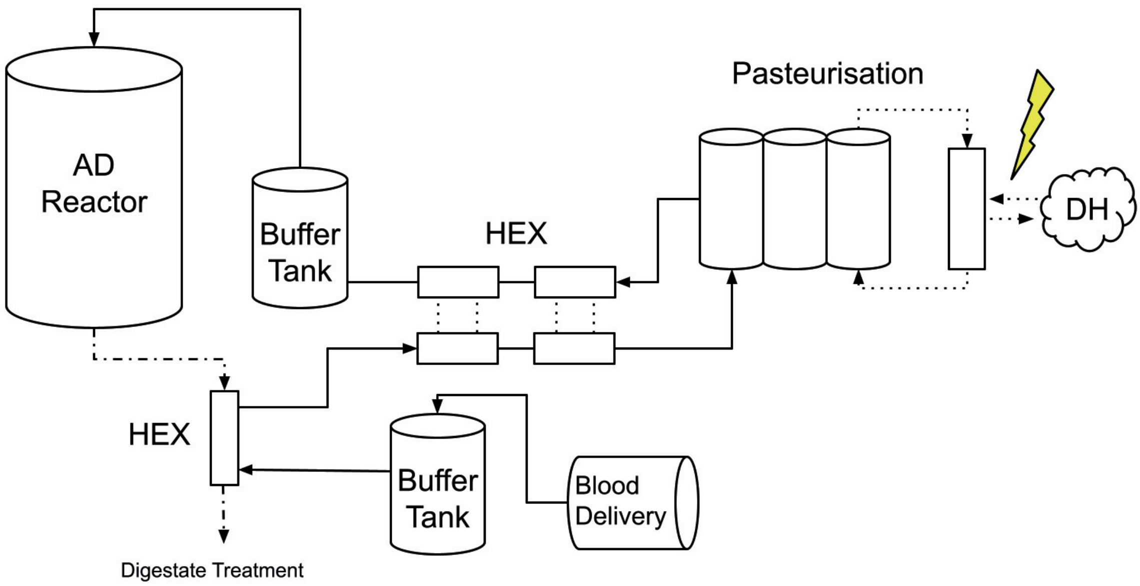

Figure 7. Example of a pasteurisation process when including blood as a biogas substrate. All heat exchangers (HEXs) were assumed to be of the tubular kind and dotted lines (..) signifies water circuits or water flows. Dots and lines (-.) signifies the flow of digester sludge. The blood was designed to be stored in a buffer tank upon delivery and to be pumped from the buffer tank and preheated by heat exchange with digester sludge. Heat recovery from pasteurisation was included through heat exchange between pasteurised and unpasteurised substrate. The blood could be pasteurised in one out of three jacketed pasteurisation tanks. The water jackets were assumed to be filled with hot water supplied by district heating (DH) and additional heat from a boiler.

4.5 Techno-Economic Assessment

The techno-economic analysis was based on *figure 4* presented in methodology section (3.1) and consists of energy and cost estimations, calculated for both ley and slaughterhouse blood. The analyses were also performed assuming a biomethane potential loss of 9.5%, a number adopted from the average torching of biomethane in Sweden in 2021 and an additional methane slip from Uddebo WWTP.

4.5.1 Techno-Economic Assessment of Ley Crops

The following section describes how the techno-economic model used for calculations regarding ley crops was built, before presenting the results of the model.

4.5.1.1 Model

4.5.1.1.1 Energy Analysis

The energy yielding process (i.e., the biogas production) was evaluated using three different cases of an increased organic loading rate (OLR), the highest being 90% of the maximum OLR.

The energy consumption from the production of the biomass required to fulfil the OLR was estimated using the work by Prade et al. (2012) and adapted to the conditions defined for ley crop production in the north of Sweden. The estimation included both direct and indirect energy inputs, the details of which are presented in *Appendix B*. Prade et al. (2015) performed a sensitivity analysis and found that changes in the harvest yield had little effect on the energy consumption related to the production of ley. It increased by 8% when the harvest yield decreased by 40% from around 12 tonne TS/ha. (Prade et al., 2015) Due to this, the production energy for ley was increased by 8% to adjust to a harvest yield of 8 000 kg TS/ha.

The second energy input included in the energy balance was the transportation of substrate from source to plant. The transport energy from fuel usage was converted into primary energy according to the work by Berglund and Börjesson (2003) that used 45.7 MJ as the total – *direct* plus *indirect* – energy consumption related to the usage of one litre of diesel, for a truck. Berglund and Börjesson (2003) found that the transport distance between farm and biogas plant to give a break-even net energy balance was 400 km for ley crops when including activities in the complete life cycle of ley, from production of the crop to spreading of dewatered digestate. Other findings in the report by Berglund and Börjesson (2003) presented results related to distances up to 20 km and 250 km. The three distances 20, 250 and 400 km were adopted as model distances for the energy analysis. The shortest distance is also the approximate distance between Uddebo WWTP and Sunderby landfill, both operated by Lumire and it was assumed that a truck could carry 35 tonnes of biomass (in wet weight). The fuel consumption adopted from Berglund and Börjesson (2003) was 0.023 L diesel per tonne of load and kilometre. It assumed a full delivery load and empty return, with the kilometres in the one-way distance (Berglund and Börjesson, 2003).

It is forbidden by law to bury organic and combustible material since the year of 2002 and more landfills are continuously being closed and covered due to this (Naturvårdsverket, no date). Sunderby landfill has an approximate size of 74 hectares (Adolfsson, personal communication). A report from Avfall Sverige (Matsson et al., 2022) investigated potential uses for covered landfills. Assessed usage areas included the establishing of recreational areas or parks, grazing grounds, energy crop cultivations, or energy production from building of wind turbines or solar cell parks. All alternatives had advantages and disadvantages that could include economic, social, and ecological aspects (Mattsson et al., 2022).

The direct energy usage from pretreatment of ley crops was conceptualised by using three scenarios of different energy consumptions which was converted into primary energy. Indirect energy usage was excluded from the assessment. A specific equipment type was not chosen, but instead the scenarios were meant to represent the variation in electricity usage amongst different equipment types that yields the same result, the disintegration of lignocellulosic material.

The potential energy yield and three energy inputs were calculated into annual quantities, finally weighing the potential energy production against the energy consumption. An overview of the base scenarios evaluated are illustrated in *figure 8*.

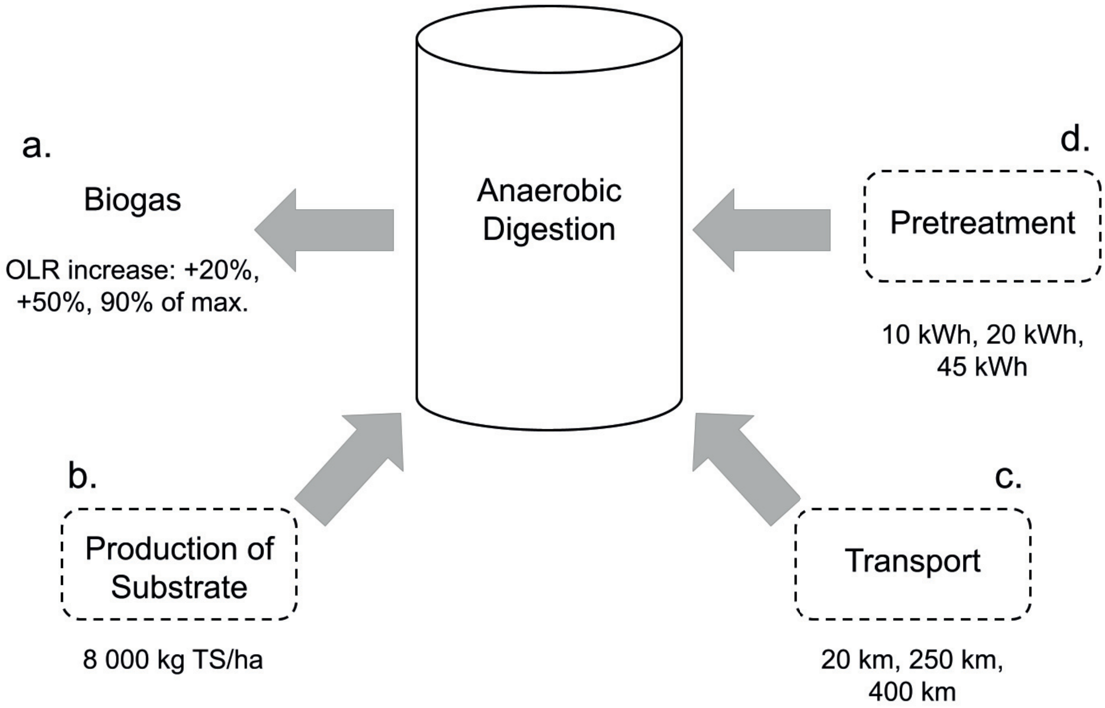

Figure 8. Evaluated activities related to the usage of ley as a biogas substrate. Energy inputs are circled in broken lines. a. Evaluation of the biogas production and related calculations, such as energy yield. b. Energy inputs related to the production of ley crops. c. Assessment of the energy input from transportation of ley. d. Evaluation of the energy consumption used in pretreatment.

4.5.1.1.2 Economic Assessment

A brief economic analysis assessed the production cost of ley, transport cost and the electricity cost from pretreatment. The economic analysis focused on the scenario of an OLR increase of 50%. An estimation of the cost of investing in an extruder was also included.

An article from 2022 in *Jordbruksaktuellt* summarises a project that investigated the production costs of ley crops at ten organic farms during 2021. It was found that the production cost varied between 0.75-1.44 SEK/kg TS. (Wahlberg, 2022) A calculation example from 2020 shows 1.48 SEK/kg TS as the selling price of ley. The cost of nitrogen fertiliser made up for around 18% of the costs of the production means and the cost of fuel used in the example was 10.52 SEK/L

(Länsstyrelsen Västra Götaland, 2020). A report from 2013 by Björnsson and Lantz shows a production cost for ley crops of just above 1.5 SEK/kg TS (Björnsson and Lantz, 2013).

Dalemo et al. (1993) showed that the production cost of ley was lower in the north of Sweden compared to the southern parts, partly due to the lower cost of land usage. The estimation of the land usage cost was dependent on the actual cost of land and the initially intended production purpose of the land. The alternative use of the land in the north of Sweden was assumed to be for production of ley as animal fodder, while energy crop production was assumed to replace grain in the south. (Dalemo et al, 1993) Prade et al. (2015) estimated the production costs of ley, including transport, to around 0.7 SEK/kg TS or 1 SEK/kg TS using an alternative land cost.

2022 was a costly year for the production of green feed according to an article written by Theo den Braver and published on the website of the advisory company *Gård & Djurhälsan* (2023). The writer states that the production of a tonne TS of ley can require around 20 kg of nitrogen fertiliser, which previously cost 200 SEK but cost 600 SEK for the year of 2022. Due to the increased cost of other production means, the cost of ley for the year of 2022 increased by 1 SEK/kg TS, compared to the year before, according to the writer. (den Braver, 2023) In a debate article from *Lantbruksnytt* published in March 2023, Anders Niléhn states that the price of nitrogen fertiliser had been 39 SEK/kg during spring 2022 but that the market had restabilised and cost 14 SEK/kg at the time of the publication (Niléhn, 2023).

The cost of fuel consists of the production cost (with a profit margin), taxes and a consumption value-added tax (VAT, called "moms" in Swedish) (Torstensson, 2023). The taxes include an energy tax, carbon dioxide tax and an additional VAT on the two mentioned taxes. The agricultural sector was completely relieved from the taxes on diesel from the first of July this year (Finansdepartementet, 2023). The fuel price notably escalated around the time of the Russian full-scale invasion of Ukraine and has generally kept a price of above 20 SEK/L but below 30 SEK/L. (Torstensson, 2023) The tax relief is applicable for agricultural machines but not for fuel used in trucks (Skatteverket, no date).

The price of electricity in Sweden differs depending on the situated electricity area (Energimarknadsinspektionen, no date). Prices reached new peaks during last winter (*SVT Nyheter Stockholm*, 2022). According to the energy company Luleå Energi, the average "spot" price of electricity for the year of 2022 was around 0.66 SEK/kWh and around 0.46 SEK/kWh the year before (Luleå Energi, 2023a). Spot price is the buying price of electricity for the energy company (Tekniska Verken i Linköping, no date).

The investment estimation was based on the cost of an extruder 2015 capable of treating 35 tonnes of substrate per day when run 12-20 hours a day (Odhner et al., 2015).

The complete economic analysis regarding ley crops was based on the OLR increase of 50% and a production cost of 1.5 SEK/kg TS, a fuel cost of 20 SEK/L of diesel coupled to the previous model distances (20, 250 and 400 km). Finally, the different pretreatment electricity inputs (10, 20 and 45 kWh) were assessed according to the electricity price equal to the spot price in Luleå in 2022.

4.5.1.2 General Parameters

The plant was assumed to be operated 365 days of the year and to be fed once an hour. The substrate was characterised according to the information collected about ley, as presented in *table 1*.

Table 1. Adopted characteristics regarding ley as a biogas substrate. WW referring to the wet weight, and ha meaning hectares.

Parameter		**Unit**	**Source**
TS	34	% of WW	Prade et al., 2015
VS	88	% of WW	Carlsson and Uldal, 2009
Harvest yield	8 000	kg TS/ha	Lundberg, personal communication
BMP	300	Nm^3/tonne VS	Carlsson and Uldal, 2009

4.5.1.3 Energy Potential

The biogas production and energy potential of ley was calculated using three different cases of OLR. The base cases included the assumption that the BMP was the actual biomethane yield, i.e., that no substrate was lost in the production and retrieving process, ensiling and storage caused no losses in biomethane potential and no biomethane was lost in the upgrading or post-digestion stages. Any effect, positive or negative, that co-digestion at Uddebo WWTP could cause on the biomethane yield was left out. The biomethane production was calculated using *equation 6* and the result presented in *table 2*.

Table 2. Calculated biomethane production, assuming no energy losses, and the potential energy production linked to the different increases in OLR at Uddebo WWTP.

	20% OLR increase	***50% OLR increase***	***OLR 90% of maximum***	**Unit**
Biomethane production	130 305	325 762	452 235	Nm^3/year
Energy content of biomethane	1.3	3.2	4.4	GWh/year

The amounts of biomass and land usage related to the increased OLR conditions were calculated by converting the OLR to loads of wet weight and the results are shown in *table 3*.

Table 3. Amount of biomass (in WW) and hectares of land needed to fulfil the increased OLRs.

	20% OLR increase	***50% OLR increase***	***OLR 90% of maximum***	**Unit**
Biomass amount	1 452	3 629	5 038	Tonnes/year
Land usage	62	154	214	ha/year

These base scenarios were compared against an assumed BMP loss of 9.5%.

4.5.1.4 Production

The total, direct plus indirect, energy input required to produce ley adjusted to the evaluated circumstances (a harvest yield of 8 000 kg TS/ha) resulted in a total energy need of 4 544 kWh/ha, out of which the direct energy made up for 633 kWh/ha. The included indirect and direct energy inputs can be found in *Appendix B*.

4.5.1.5 Pretreatment

Evaluation of the energy required for pretreatment was centred around the main activity of disintegrating the biomass through one mechanical process and the result is presented in *table 4*.

Table 4. The yearly primary energy consumption from mechanical pretreatment of ley.

	10	***20***	***45***	***kWh/tonne biomass***
20% OLR increase	32	64	144	MWh/year
50% OLR increase	80	160	359	MWh/year
OLR 90% of maximum	111	222	499	MWh/year

4.5.1.6 Transport

The energy consumption related to the transport and delivery of ley crops (*table 5*) was estimated assuming that the delivery was performed by a truck with a trailer capable to carry 35 tonnes (WW) of ensiled ley.

Table 5. Total primary energy needed for the transport of ley.

	20	***250***	***400***	***km***
20% OLR increase	8	106	169	MWh/year
50% OLR increase	21	265	424	MWh/year
OLR 90% of maximum	29	368	588	MWh/year

4.5.1.7 Energy Analysis

The net energy balance was positive for all scenarios, no matter the pretreatment or transport alternative or by including a BMP loss of 9.5%; the highest net energy gain being around 1.9 MWh/tonne TS with the lowest pretreatment energy, shortest transport, and no BMP loss. Adding the BMP loss and the highest required energy inputs yielded an energy gain of around 1.1 MWh/tonne TS.

The EROI showed that the lowest pretreatment input and shortest transport gave near 4 times the invested energy, assuming no BMP loss, and close to 2 if using the high pretreatment energy input and longest transport. Consequently, the energy efficiency quota showed a consumption of 25% and roughly 46% of the potential energy content, respectively. *Figure 9* shows the energy balance.

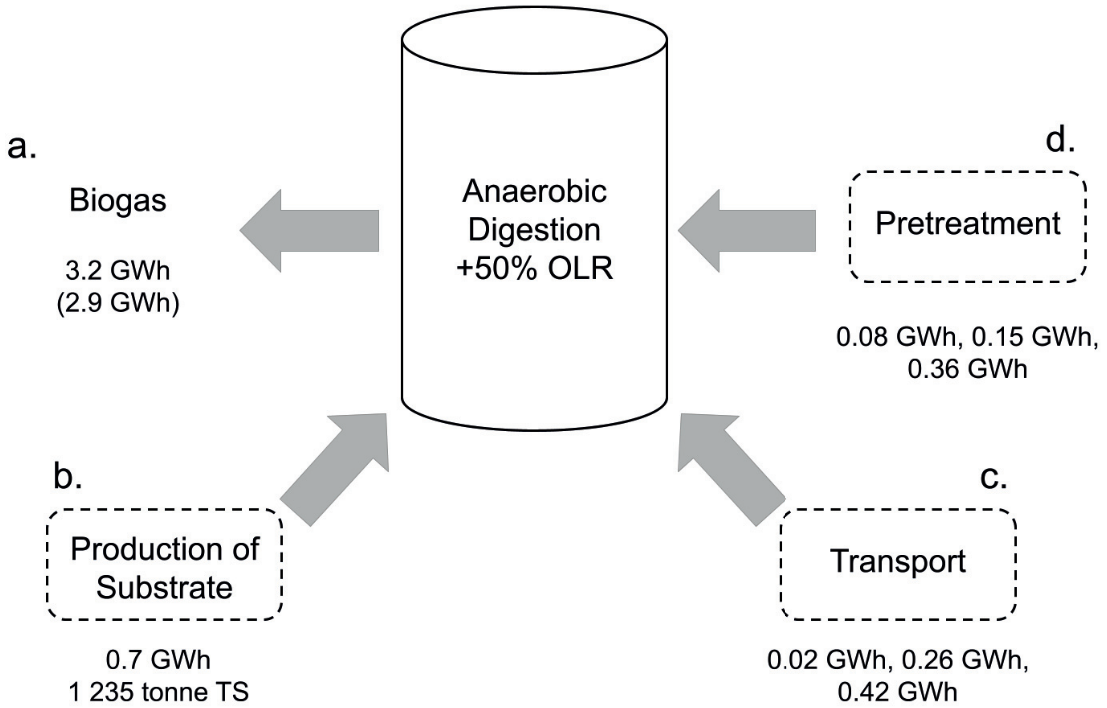

Figure 9. Illustration of the elements in the annual energy balance for the implementation of ley equivalent to an OLR increase of 50%. a. Biogas production with a BMP loss of 9.5% in parentheses. b. the energy input for a yearly production of 1 235 tonnes of TS required to fulfil the OLR. c. the energy input from transport (20, 250 and 400 km respectively). d. energy input from pretreatment (10, 20, 45 kWh respectively).

The impact of transportation distance on the total energy input can be seen in *figures 10-12*. It concerns the highest pretreatment energy input and is valid for all three scenarios of an OLR increase.

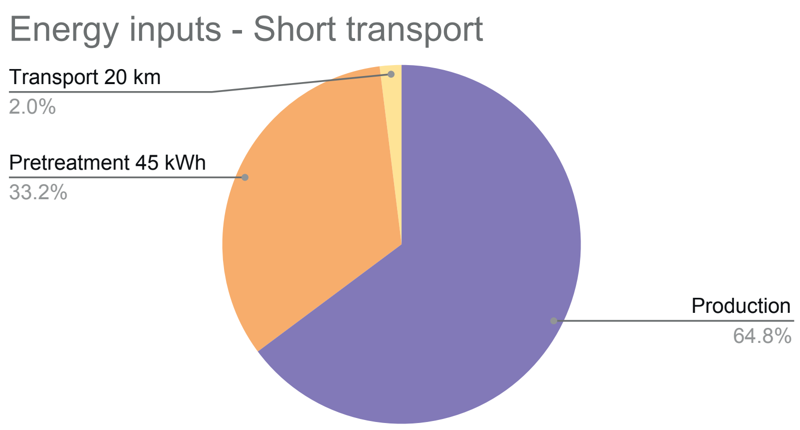

Figure 10. Energy inputs for ley concerning the highest pretreatment input energy and ***shortest*** *transportation distance.*

The impact of the middle-length transportation distance is seen in figure 11.

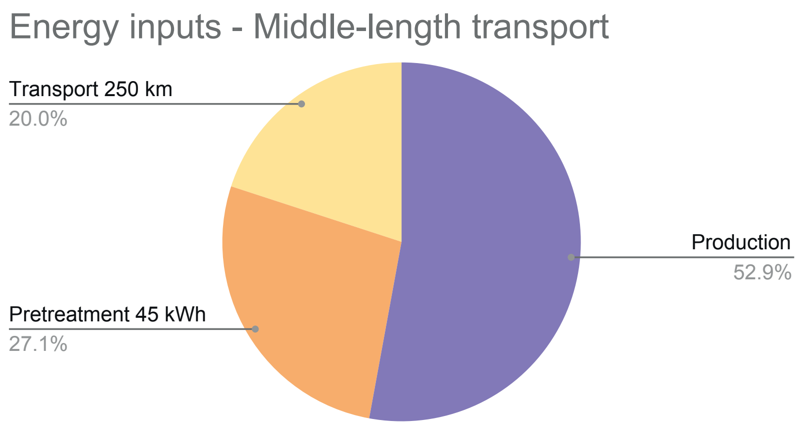

Figure 11. Energy inputs for ley concerning the highest pretreatment input energy and ***middle-length*** *transportation distance.*

The energetic impact of the longest transportation distance is seen in figure 12.

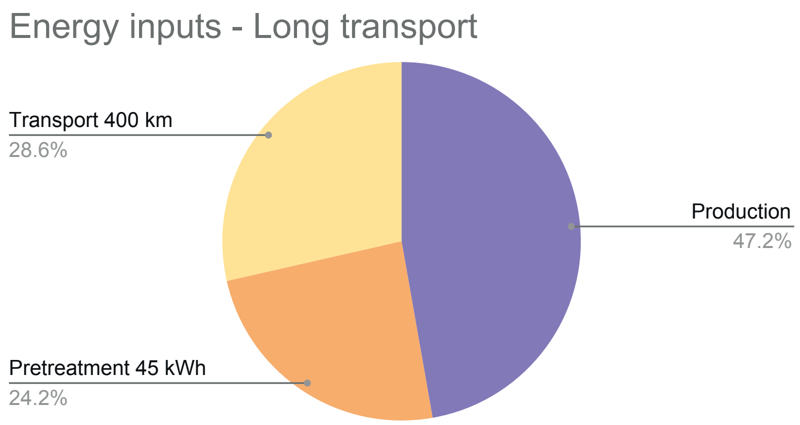

Figure 12. Energy inputs for ley concerning the highest pretreatment input energy and ***longest*** *transport distance.*

The direct electricity consumption from pretreatment would increase the electricity demand of Uddebo WWTP by 2.4% for the lowest OLR increase and pretreatment energy and up to around 37% for the implementation of the highest OLR increase and highest pretreatment energy input.

4.5.1.8 Economic Assessment

The assumption that the production cost of ley is 1.5 SEK/kg TS yielded an annual cost of around 1.85 million SEK for the biomass required to increase the OLR by 50%. The longest transportation distance (400 km) resulted in a direct fuel cost of almost 670 000 SEK and pre-treatment costs varied between 24 000 SEK for the least electricity demanding alternative up to 107 000 SEK for the most demanding scenario. *Figure 13* shows the costs that needs to be covered per kg fuel gas produced from ley crops when increasing the OLR with 50%.

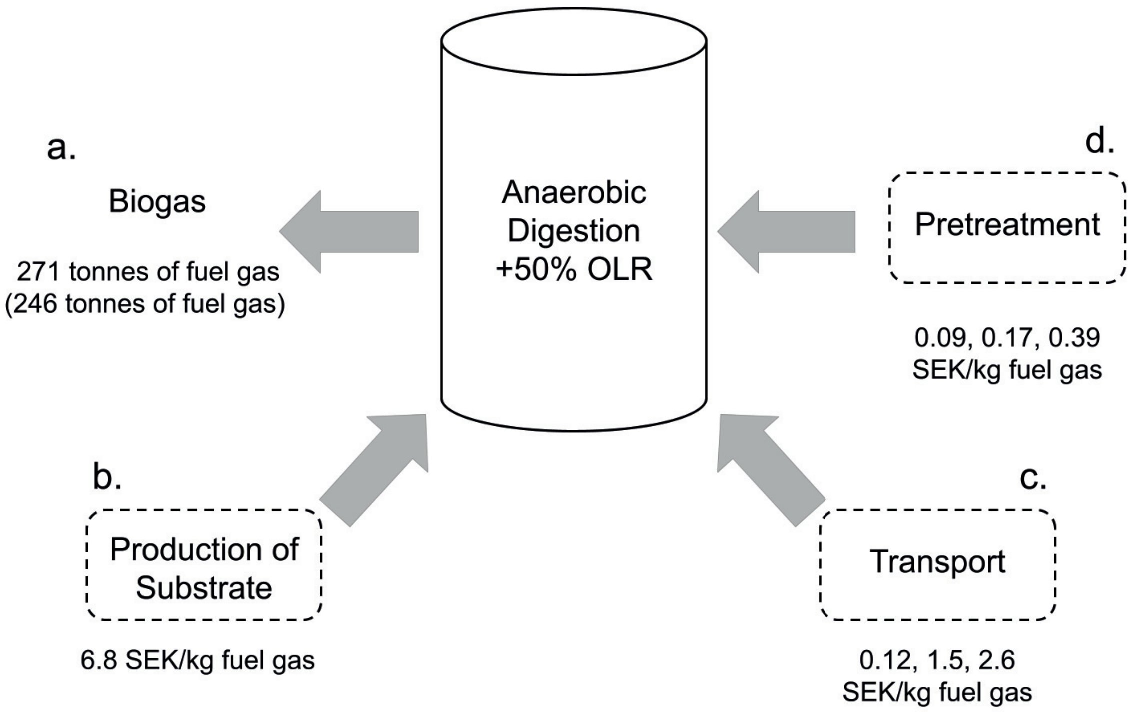

Figure 13. Costs to be covered in SEK per kg fuel gas produced from ley crops for the scenario concerning an OLR increase of 50%. The potential fuel gas yield in parentheses includes a BMP loss of 9.5%.

The impact of transportation on the cost distribution can be seen in *figures 14-16* and is true for all scenarios of increased OLRs.

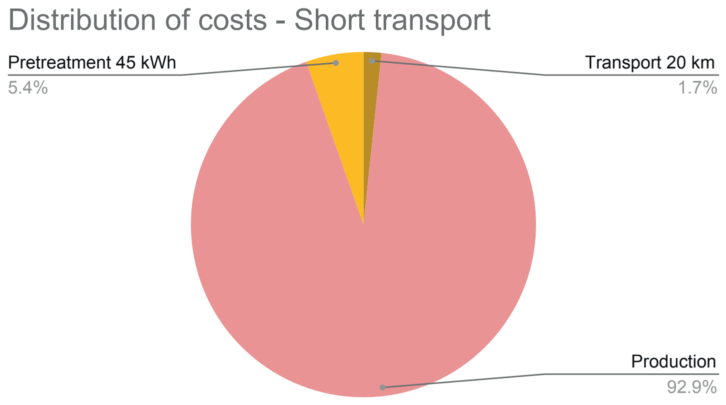

Figure 14. Distribution of costs for the scenario of the shortest transportation distance and highest pretreatment energy.

The impact of the middle-length transportation distance on the total costs is shown in *figure 15*.

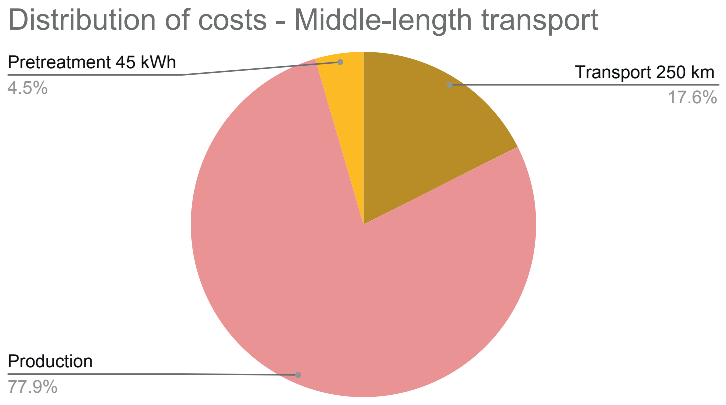

Figure 15. Distribution of costs for the scenario of the middle-length transport distance and highest pretreatment energy.

The impact of the longest transportation distance on the total costs is shown in *figure 16*.

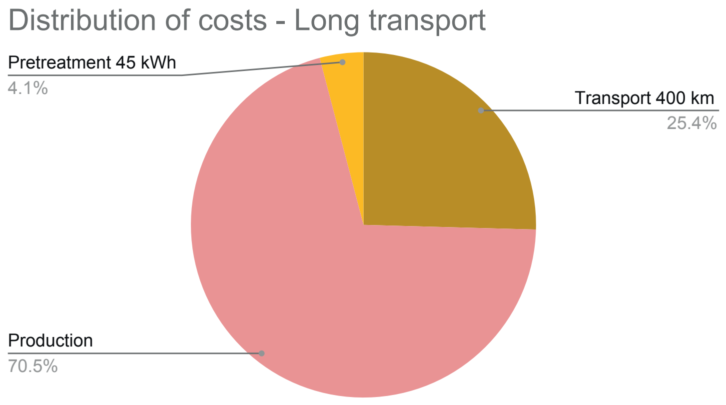

Figure 16. Distribution of costs for the scenario of the longest transport distance and highest pretreatment energy.

Table 6 shows the costs to be covered in SEK per kg of produced fuel gas in the least and most costly scenarios calculated for the OLR increase of 50%.

Table 6. The costs to be covered when retailing fuel gas produced from ley in the scenario of an OLR increase of 50%. Includes the least and most costly scenarios with and without a BMP loss of 9.5%.

	Production, 20 km, 10 kWh	***Production, 400 km, 45 kWh***	**Unit**
No BMP loss	7.0	9.7	SEK/kg fuel gas
9.5% BMP loss	7.8	10.7	SEK/kg fuel gas

4.5.2 Techno-Economic Assessment of Slaughterhouse Blood

Figure 17 shows the suggested pasteurisation design including flow temperatures which was the basis for the techno-economic analysis of slaughterhouse blood.

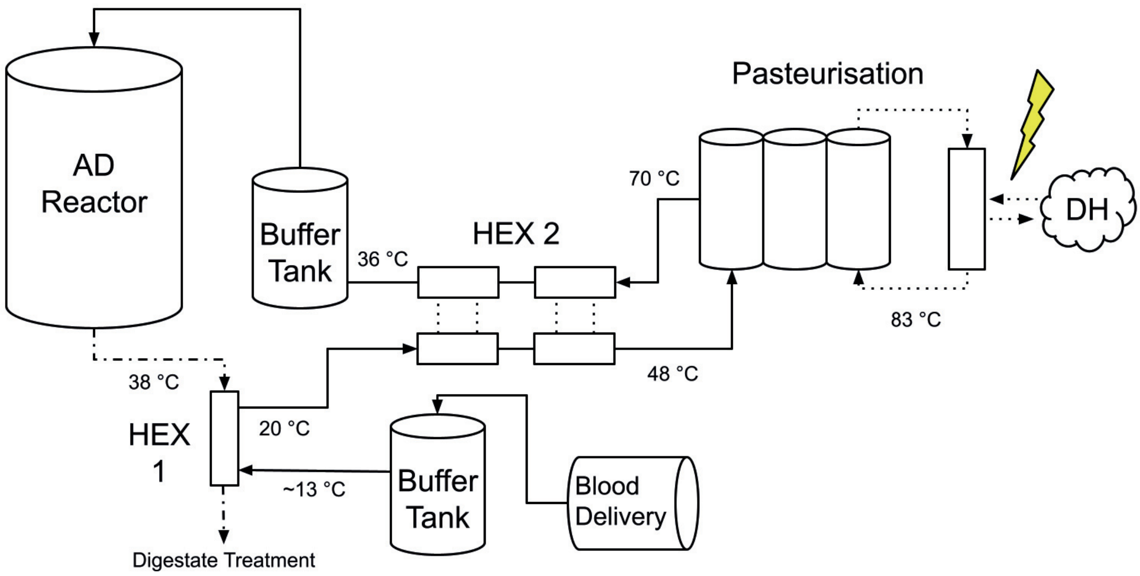

Figure 17. Example of a pasteurisation process when including blood as a biogas substrate. All heat exchangers (HEXs) were assumed to be of the tubular kind and dotted lines (..) signifies water circuits or water flows. Dots and lines (-.) signifies the flow of digester sludge. Preheating of substrate was assumed to be performed in HEX 1 and HEX 2 to be used for heat recovery from the pasteurisation. Temperatures adapted after the report by Tamm and Olsson (2021).

Approximate temperatures in the design were partly adapted from the real-life example seen at a farm in Vårgårda presented in the report by Tamm and Olsson (2021) about farm-based biogas plants.

4.5.2.1 Model

4.5.2.1.1 Energy Analysis

Similar to the techno-economic assessment of ley, the energy analysis of blood included estimations of the potential biomethane production and energy inputs, forming a net energy balance, and calculating the corresponding EROI and energy efficiency quotas. Assessed energy inputs contained the transportation, comparing the current transport distance from Luleå to Skellefteå to the approximate distance if the substrate was to be used within Luleå, together with an evaluation of pasteurisation using jacketed tanks as the chosen pretreatment technique. The technical assessment also included providing a design suggestion for the pasteurisation unit and dimensioning of the required heat exchangers.

The energy inputs required for the generation of blood was not assessed as the blood is an already existing residual stream (compared to an energy crop), with the production energy and costs covered by the slaughterhouses. The highest weekly delivery volume of 16 m^3 was used for dimensioning of flows and equipment. *Figure 18* shows an overview of the techno-economic assessment of slaughterhouse blood.

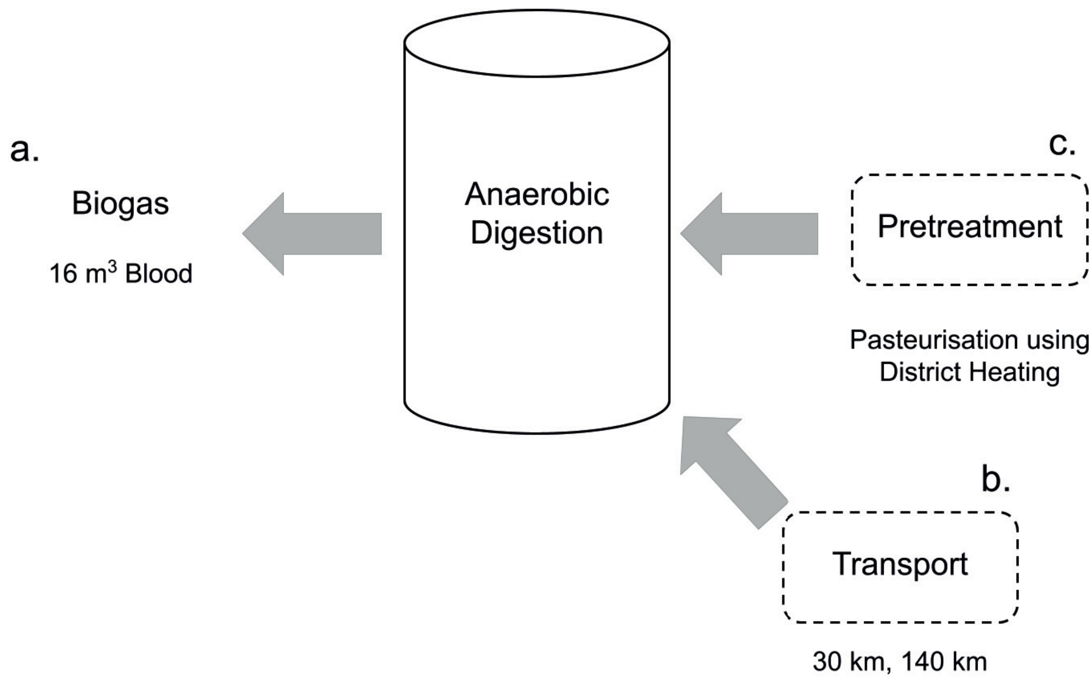

Figure 18. Evaluated activities related to the implementation of blood as a biogas substrate. Energy inputs are circled in broken lines. a. Evaluation of the biogas production and energy yield from 16 m^3 of undiluted blood. b. Assessment of the energy input from transportation of blood. c. Evaluation of the energy required for the pretreatment of blood.

As the true characteristics of the blood was unknown, it was assumed to have properties similar to water. Rosentrater and Flores (1997) showed that pure swine blood had densities higher than water at all studied temperatures, for example just over 1 050 kg/m^3 at 5°C and around 1 035 kg/m^3 at 25°C. The blood collected from Luleå was assumed to have the density of 1 000 kg/m^3

and to be diluted (using water of the same density) from 16 m^3 and a TS content of 18% to 10% TS upon arrival, to allow sufficient pumping and potentially reduce foaming effects.

4.5.2.1.2 Economic Assessment

The economic analysis included an estimation of the cost of transport, comparing the current transport distance of 140 km with a shorter of 30 km and using the same fuel cost as when assessing ley silage. As district heating was assumed to be used for the pasteurisation it was also included in the economic calculation. The price of district heating is determined by three components according to Luleå Energi (2023b): an energy cost (SEK/MWh), one cost based on the volumetric usage of district heating (SEK/m^3), along with a cost based on the daily measured heating usage (kW). The price of district heating varies over a year, depending on the season. Cost examples for industries are 131 106 SEK for the usage of 193 MWh/year and 333 091 SEK for the usage of 500 MWh/year. (Luleå Energi, 2023b) District heating has become more expensive in Norrbotten during the year but is the cheapest in Luleå (*SVT Nyheter Norrbotten*, 2023c). The two examples of industrial district heating costs were included in the economic assessment.

The equipment investment analysis included an estimation of the costs for constructing the pasteurisation facilities based on the budget presented by SWECO in 2015.

4.5.2.2 General Parameters

The maximum daily flow of blood was provided from the general maximum weekly deliveries, around 16 m^3. It was assumed that the substrate was diluted with water upon arrival, to 10% TS. The assumed density was 1 000 kg/m^3, resulting in a total weekly volume of 23 m^3 per week after dilution. Adopted parameters are presented in *table 7*.

Table 7. Adopted parameters concerning slaughterhouse blood as a biogas substrate. BMP decided according to the number presented in section 4.4.

Parameter		**Unit**
Maximum delivery volume (undiluted)	16	m^3/week
Maximum delivery weight (undiluted)	16 000	kg/week
Density	1 000	kg TS/m^3
$TS_{initial}$	18	% of WW
TS_{final}	10	% of WW
BMP	490	Nm^3/tonne VS

As the true characteristics of the blood was unknown, data corresponding to water of the relevant temperatures was used when required.

4.5.2.3 Energy Analysis

Both HEX 1 and the HEX 2 battery (from *figure 17*) were assumed to have heat transfer coefficients of 800 W/ m^2K. HEX 1 was assumed to have an efficiency of 80% which resulted in a required heat transfer area of around 0.5 m^2. The calculations regarding the battery of four heat exchangers that make up HEX 2 were simplified into calculations for two heat exchangers, the HEXs of the battery left in *figure 17* requiring an area of 0.8 m^2 and the right 1.1 m^2. The total efficiency of HEX 2 was 82%. Simplifying the pasteurisation unit into a heat exchanger with a heat transfer coefficient of 1 300 W/ m^2K yielded a surface area of 1.3 m^2. Calculations are presented in *Appendix D*.

Calculations of the biomethane potential of blood showed a possible yearly energy output of 691 MWh assuming no BMP loss and 626 MWh assuming 9.5% BMP loss. Net energy balances were positive under the assumption that it only included energy inputs from transport and the energy required from the district heating during pasteurisation; excluding the heat transfer from HEX 1 and 2 as it was assumed to not require extra energy input but instead recover energy. The net energy balances showed the potential to a maximum energy gain of 383 MWh/year assuming no BMP loss and the shortest transport distance, and 256 MWh/year in the case including the BMP loss and long transport. *Figure 19* shows the net energy balance.

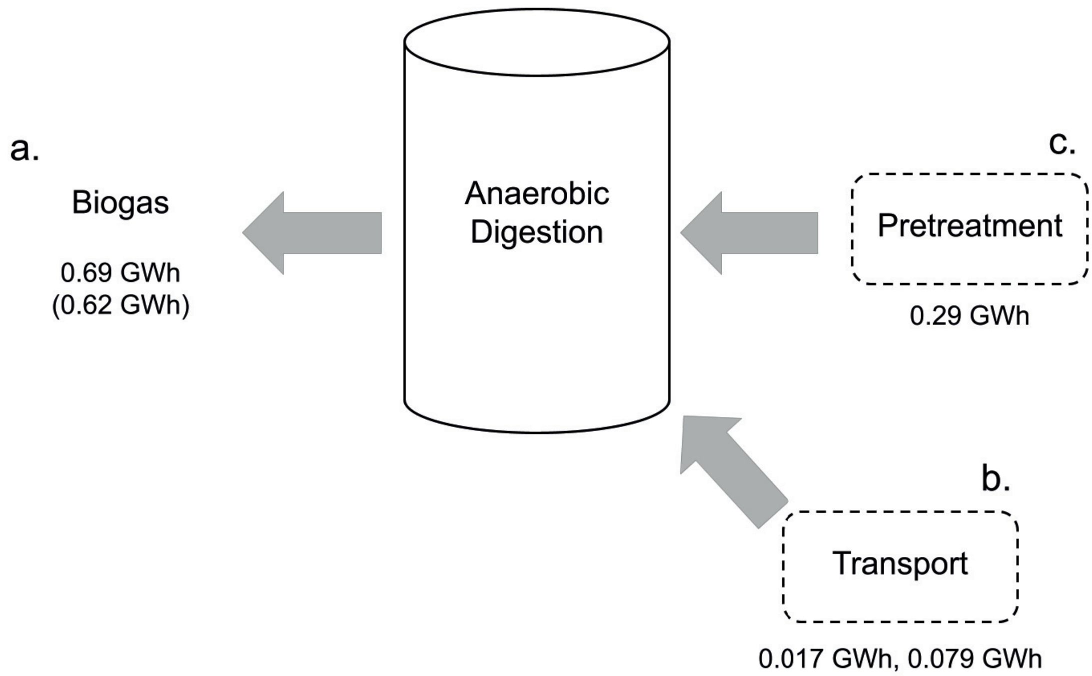

Figure 19. Net energy balance of blood as a biogas substrate. The biogas yield in parentheses assumes a BMP loss of 9.5%.

The energy return of investment was close to 2 for all scenarios and the energy efficiency quota showed input energy requirements of 45% up to almost 60%.

The impact from the two energy inputs on the total energy usage is illustrated in *figure 20* and *21*.

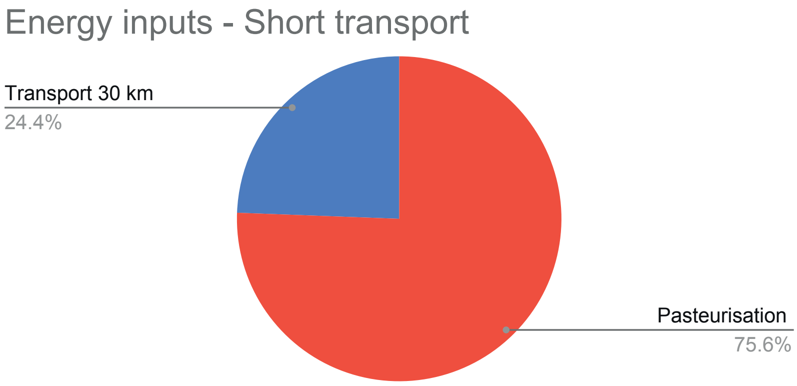

Figure 20. Energy distribution impact assuming a short transport distance along with pasteurisation.

The primary energy input from transport became higher than the primary energy required from pasteurisation when the current one-way transport distance was used (*figure 21*).

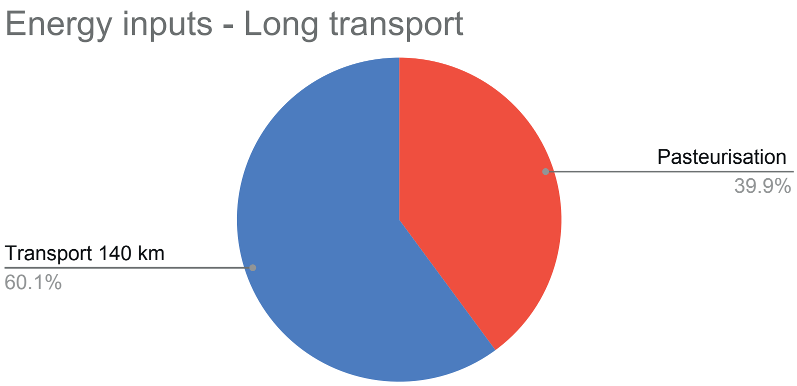

Figure 21. Energy distribution impact assuming a long transport distance along with pasteurisation.

4.5.2.4 Economic Assessment

Utilising the two example costs for district heating and the different transport scenarios showed that the cost to be covered per kilogram of fuel gas varied between 2.2 SEK/kg of fuel gas, assuming no BMP loss coupled with a short transport distance and low district heating cost, and up to 8.6 SEK/kg of fuel gas in the opposite case. A scenario that included high district heating costs, but short transport showed that the cost to be covered was 6.1 SEK/kg of fuel gas assuming no BMP loss and almost 6.8 SEK/kg of fuel gas when including a BMP loss of 9.5%. The potential fuel gas production and costs are shown in *figure 22*.

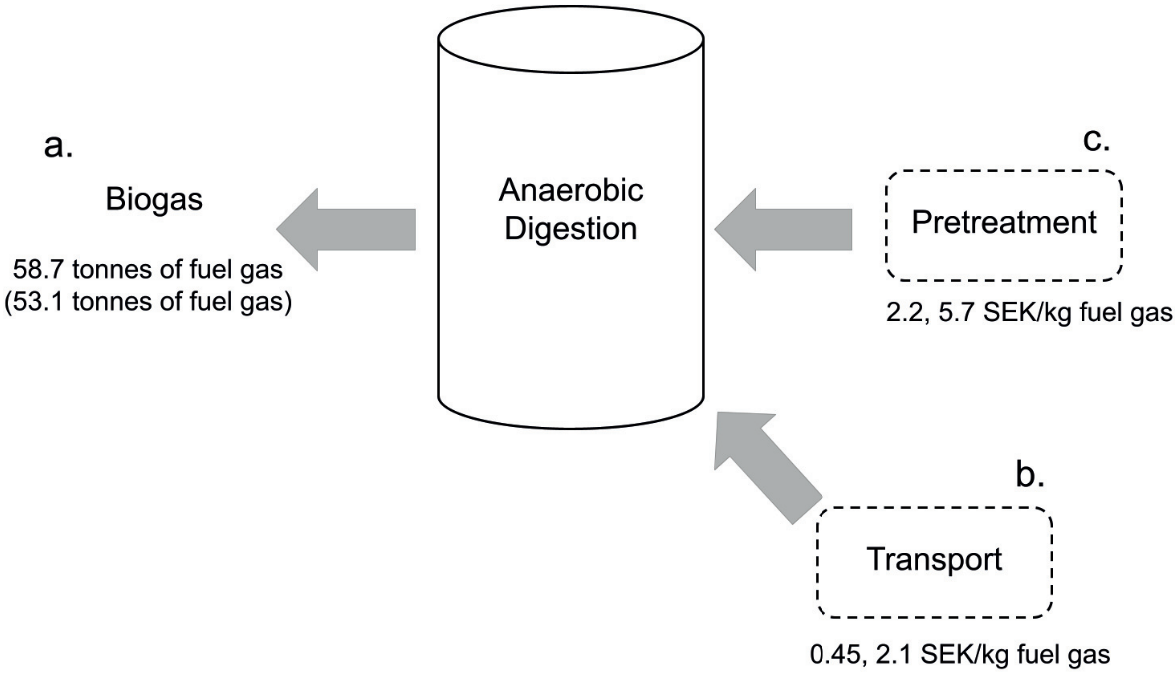

Figure 22. a. Yearly potential fuel gas production with the fuel yield in parentheses assuming a BMP loss of 9.5%. b. and c. show the costs to be covered per kilogram of fuel gas produced from slaughterhouse blood.

The impact that the two energy inputs have on the implementation costs is shown in *figures 23* and *24*.

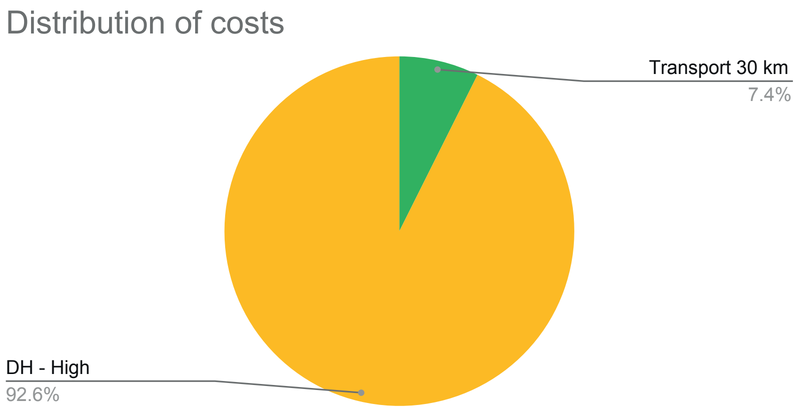

Figure 23. Economic impact from the different activities for the scenario of the shortest transport distance and highest district heating (DH) cost.

The impact of the current transport distance along with a high district heating cost is seen in *figure 24*.

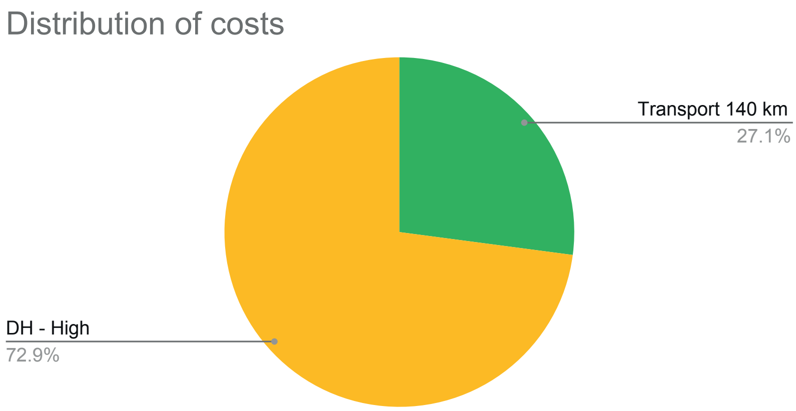

Figure 24. Economic impact from the different activities for the scenario of the current transport distance and highest district heating (DH) cost.

Estimation of the investment cost for the pasteurisation facilities and equipment based on the six-tenths rule and the construction cost index showed a cost of 4.8 million SEK.

5 Discussion and Conclusions

5.1 Discussion

This thesis does not present a comprehensive picture of the consequences of implementing a new substrate into an existing biogas production process. It instead evaluates a selection of activities relating to the embedding of a new substrate. Implementation of more organic material from a new source would not only affect the processes upstream of the AD chamber, as was the focus of this thesis, but also the digester itself and the downstream processes such as digestate generation, increasing energy consumption for dewatering, upgrading and more. The whole life cycle of a substrate can be evaluated from a plant capacity perspective and through conversions into primary energy that truly represents the sources of electricity and heating at the studied plant. The thesis does not present the optimal strategies or process designs for implementation of new substrates but was meant to be an investigatory paper that sheds light on potential energy sources, pretreatment strategies and factors that can be assessed when evaluating a change in a biogas process.

5.1.1 Inventory of Substrates in Norrbotten

The vast forest-rich landscape of Norrbotten county, with low agricultural productivity, puts special restraints on the biogas production compared to other sites in Sweden, since sources of organic residual streams can be found in dilute amounts or spread over potentially great distances. The inventory shows that there are several potential substrates currently generated in the region but that few are left unused. Several substrates might be available if *bought* from the source, but it could mean that other resources are required to fill those purposes, which for example could be animal feed or ethanol production. In instances where a substrate could be available, the location, actual amounts and composition need inquiring. An example of such a substrate could be manure. But using manure as a biogas substrate in the current process at Uddebo would also mean that the manure is removed from the intended purpose and ecological cycle of being returned to the earth as it would be digested together with wastewater sludge and form a digestate that is currently uncertified.

The substrate availability could change in the future, potentially decreasing due to the closure of Norrmejerier in Luleå, or increasing, if farmland is used for energy or food crops to a greater extent. Ley could become a break crop in connection to turnip-rape cultivation and aspiring to become a more self-sufficient region could implicate that greater agricultural residual streams are generated. As previous studies indicated, the agricultural sector stood out as a potential source of substrates for biogas production. Several more substrates showed potential and could have been interesting for the techno-economic analysis and the selection of the two specific substrates can be thought of as an exemplification.

5.1.2 Techno-Economic Assessment of Ley Crops

The net energy balances were positive but lower compared to the numbers presented by Prade et al. (2015). The scenario of a BMP loss, short transport and low pretreatment energy came closest to the EROI and energy efficiency quota presented by Prade et al. (2015): 3.6 and 28%, respectively. Losses compared to the potential biomethane yield is highly likely to occur due to loss of substrate in the value chain, during onsite storage and/or from methane losses during other process operations.

Berglund and Börjesson (2003) stated that the cultivation and harvest could account for 45% of the total energy input in the life cycle of ley as a biogas substrate. The results in this study show that it accounted for around 50% or higher when compared to the few other activities included in the analysis. Under the used assumptions, the production of ley was shown to be a great energy user and expenditure. But production, which included both direct and indirect energy inputs was compared to the energy inputs of transport and pretreatment, the latter which was only assessed based on direct electricity usage converted into primary energy. The indirect energy used for production accounted for 86% of the total production energy, a substantial share, while the indirect energy from transport was represented by increasing the heating value of diesel by 18%. Including the indirect energy requirement from the making and maintenance of certain pretreatment equipment could yield a different energy distribution where pretreatment could have an even greater impact in the total energy balance.

The production chain of ensiled ley can look different, and it can be produced and bought using different business systems where the biogas plant only becomes a buyer or has greater responsibility for the production. Transport of silage was evaluated separately from the production but could be included and modelled, as in the case of Prade et al. (2015). The true cost to produce ley in the north remains to be uncovered and for example depends on the price of land, production means and the degree of tax-relief. Indications are that the cost of land is lower in the north but that it can be difficult to acquire, due to this.

Synthetic fertilisers potentially make up for a significant share of the cost for production of ley and is also a high indirect energy-consumer, according to the numbers adopted from Prade et al. (2015). Digestate can be returned to the soil as a fertiliser if it is certified and the production of biofertiliser or certified digestate could be a means to decrease production costs (and the price of ley) as well as the indirect energy usage but could signify that the operation of Uddebo WWTP would need to change. For example, so that both reactors are active, and ley digested separately from the wastewater treatment sludge or by working towards becoming a Revaq certified plant. Another way to potentially affect the production costs of ley is to use Sunderby landfill, either as farmland (if possible, in the future) or as a substrate storage facility. The landfill would be able to fulfil the farmland requirements when increasing the OLR by 20%, according to the calculations. The area required for storage of ley depends on the chosen storage method and the amount of substrate produced but risk to result in a high areal footprint.

The transport of 400 km did not result in a break-even net energy balance, as expected, since the assessment of ley did not include the whole life cycle compared to the results presented by Berglund and Börjesson (2003). Prade et al. (2015) showed that the net energy balance could give an energy gain of almost 2.3 MWh/tonne TS and year for the usage of ley as a biogas substrate, while the result nearest to Prade et al. (2015) in this instance showed 1.9 MWh/tonne TS. The numbers presented by Prade et al. (2015) did include a higher harvest yield along with other assumptions such as a different principle for the modelling of the transportation.

Conceptualisation of the pretreatment shows an energetic impact that is relatively low compared to the production of ley and the transport, even at the highest input energy assessed. What pretreatment technique is suitable for the plant remains to be determined along with the complete value chain. Extrusion serves as the example for the investment estimation but has shown to possibly contribute to a high operation cost, which is not assessed in more detail in this study.

5.1.3 Techno-Economic Assessment of Slaughterhouse Blood

It is important to state that the true characteristics of the slaughterhouse blood was not determined and that the results are dependent on the assumed properties. Dilution of 16 m^3 to 10% TS shows that the areas of the suggested heat exchangers were small compared to other studies examining similar pasteurisation techniques, as the substrate flow is smaller. The simplification of the pasteurisation unit into a heat exchanger shows a surface area close to 0.25 m^3 and the factor of substrate amount and the economy of scale raises questions if it is suitable to design and invest in a pasteurisation unit that includes three pasteurisation tanks and several heat exchangers. HEX 1 in the suggested process design exchanges digestate against unpasteurised substrate. The flow of digester sludge is much greater (175 m^3/d plus the input from the substrate) than the substrate flow (23 m^3/d) which can mean that a great amount of energy could be recovered and possibly theoretically raise the temperature of the substrate even more. This is however not investigated in this thesis, as the design suggestion is a concept based on other examples of pasteurisation units from literature and actual applications. The design suggestion is equipment intensive seen to the amount of substrate being treated and alternative designs could be explored. Other sanitising techniques, such as internal thermophilic sanitation with all the pros and cons it would mean to implement, could be an alternative but would change the operation of the AD reactor at Uddebo, which is currently out of scope. Another way to motivate the investment could be to implement several substrates that require pasteurisation, such as organic sorted household waste, currently treated in Boden but this was also currently out of scope.

5.2 Conclusions

The inventory shows that few potential substrates are immediately available for biogas production in Luleå and that retrieving certain substrates could mean that the compounds are removed from the current usage, leading to the need for other resources to fill the gap. Unused farmland can be pointed out as a high interest source regarding biogas potential. The implementation of ley would require the development of a suitable production and business model. Implementation of slaughterhouse blood risk being equipment intensive and/or mean that the operation of the plant needs to be changed, to fulfil legal requirements. But the local usage of slaughterhouse blood for biogas production would mean that the consumption of diesel would decrease considerably as well as improve logistics for Lumire.

5.3 Suggested Future Research

This thesis has not investigated where unused farmland could be located or how to develop a business model that suits both biogas producer and landowner. The true production costs for ley and how it should be produced in an economically and energetically feasible way remains to be investigated. Furthermore, by excluding assessment of the indirect energy from pretreatment it did not provide a full energy analysis of the included activities and the analysis could therefore be expanded or revised following the protocols of a life cycle assessment.

The blood that is currently sent to Skellefteå could be examined and properly characterised and an eventual implementation at Uddebo properly assessed by looking at alternative operating conditions such as internal thermophilic sanitation and what might be the benefits or drawbacks of employing other modes of operation. Uddebo has two AD chambers and there might be potential to change to digestion in series or separate substrates to retrieve biofertiliser for internal or external usage.

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Carlsson, A., Head of Department and Professor at the Department of Plant Breeding, SLU, the Swedish University of Agricultural Sciences. E-mail contact and Zoom meeting (16/3-2023), March 2023.

Hugoson, M., Entrepreneur, Farmer (Alviksgården), owner of Nyhléns Hugoson. Contact through telephone, study visit 23/3-2023.

Juhlén, J., Site Manager, Haparanda Potatis AB, telephone and E-mail contact, March 2023.

Larsson, B., Business Area Manager Biogas, Lumire (Luleå Miljöresurs AB). Continuous contact.

Lundberg, M., Business Area Manager Agriculture and Countryside, telephone and E-mail contact, June and September 2023.

Lundenor, N., Head of Quality, Acquisition, BD Fisk AB. Contact through telephone, July 2023.

Perttunen, J., Owner and Manager, Biogasbolaget i Mellansverige AB (a part of Karlskoga Energi & Miljö AB). Contact through telephone E-mail, May and September 2023.

Pettersson, R., Process Engineer Tuvan Biogas Plant Skellefteå Kommun. Study visit (11/5-2023) and E-mail contact from May.

Samuelsson, J., Head of Municipal Collection, Lumire Luleå Miljöresurs AB), E-mail contact Spring 2023.

Skoqvist, A., Operations Manager of the Luleå Airport Plant, Vilokan ADF Solutions AB, E-mail contact from March 2023, study visit 31/3-2023.

Appendix A: Energy Conversion Parameters and Primary data from Uddebo WWTP

Table A.1. Energy conversion parameters used for calculations.

		Unit	Comment	Source
Energy units				
MJ and kWh	3.6	MJ/kWh	Conversion between MJ and kWh	
Primary energy				
Heating	1.3	MJ of primary energy/MJ	Assuming biogas burning	Berglund and Börjesson (2003)
Electricity	2.2	MJ of primary energy/MJ	Assuming generation using natural gas	-
Conversion factor - diesel	1.18	MJ of primary energy/MJ	Assuming production and distribution of fuel accounts for 10% of the heating value and 8% for the production of the vehicle	-
Diesel consumption	45.7	MJ primary energy/L diesel consumed for a truck	Assuming the original heating value of diesel is 38.7 MJ/L - giving 38.7*1.18 MJ of primary energy/L	-
Energy content of biomethane				
1 Nm^3 biomethane (97% methane)	9.67	kWh/Nm^3		SGC (2012)*
1 Nm^3 biomethane (100% methane)	35.3	MJ/Nm^3		Berglund and Börjesson (2003)
Volume to kg of fuel gas				
Conversion of Nm^3 to mass of fuel gas	1.2	Nm^3/kg		Kraftringen (2023)**

**Svenskt Gastekniskt Center (SGC) (2012).* BASDATA OM BIOGAS.
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Table A.2. Primary data from Uddebo WWTP assuming that one digester is active.

	Current	Maximum	Unit
Anaerobic Digester			
Active volume	3500		m^3
Digester temperature	38	40	°C
HRT	20	11.1	days
OLR	1.7	3.2	kg VS/(m^3*d)
Substrate (WWT sludge + liquid waste)			
Daily feed rate	175	314	m^3/d
TS	0.045	0.05	*100 %
VS	0.755	0.713	*100 % of TS

Table A.3. Current energy production and energy usage from the biogas production at Uddebo WWTP.

		Unit
Approx. production and energy of biomethane 2022		
Biomethane	450000	Nm^3
Energy content of biomethane (assuming 97% methane)	4351500	kWh
	4351.5	MWh
Energy need for digestion		
Electricity	200000	kWh/year
Heating (in biogas) for digestion	1100000	kWh/year
Heating (in district heating) for digestion	1000000	kWh/year
Energy need for upgrading of biogas		
Electricity	404705	kWh/year
Heating	49000	kWh/year
TOTAL energy need	2753705	kWh/year
	2754	MWh/year
	9913	GJ/year
	7.54	MWh/day
Energy converted into primary energy		
Total heating	2793700	kWh/year
Total electricity	1330351	kWh/year
Total primary energy	4124051	kWh/year

Appendix B: Ley Crops – Energy Calculations

Table B.1. Adopted substrate parameters for ley crops.

		Unit
Harvest		
Yield	8000	kg TS/hectare and year
Substrate parameters		
TS	0.34	*100 % of WW
VS	0.88	*100 % of TS
BMP	0.3	Nm^3 methane/kg VS
Methane content in biogas	0.56	*100 volume%

Table B.2. Calculations of the increased OLR input from ley and the related VS, TS and biomass amounts as well as the hectare requirement and potential biomethane production assuming no loss of substrate or BMP.

	20% OLR increase	**50% OLR increase**	**OLR in tot. 90% of max**	**Unit**
OLR addition from ley				
OLR addition from ley	0.34	0.85	1.18	kg VS/(m3*d)
VS amount				
Daily	1190	2975	4130	kg VS/d
Yearly	434350	1085875	1507450	kg VS/year
TS amount				
Daily	1352.27	3380.68	4693.18	kg TS/d
Yearly	493579.54	1233948.86	1713011.36	kg TS/year
	494	1234	1713	tonne TS/year
Biomass amount				
Daily	3977.27	9943.18	13803.47	kg biomass/d
Yearly	1451704.54	3629261.36	5038268.71	kg biomass/year
	1452	3629	5038	tonne biomass/year
Hectare need				
Yearly	61.7	154.2	214.1	ha/year
Biomethane production				
Daily	357	892.5	1239	Nm^3 biomethane/day
Yearly	130305	325762.5	452235	Nm^3 biomethane/year
Energy content of biomethane				
Daily	12602.1	31505.25	43736.7	MJ/d
Yearly	4599766.5	11499416.25	15963895.5	MJ/year
	1277712.8	3194282.2	4434415.3	kWh/year
	1.28	3.19	4.43	GWh/year

Tablel B.3. Energy inputs from the production of ley assuming that it is roughly chopped and yields two harvests per year. Adapted from Prade et al. (2015). Including the adaption to the harvest yield used in the thesis (+8% energy) and the energy for the increases in OLR.

	Direct usage	**Indirect usage**		**Unit**
Pesticides, fertiliser and other production means				
N fert.		10578		MJ/ha
P fert.		294		MJ/ha
K fert.		764		MJ/ha
Seeds		115		MJ/ha
Pesticides		322		MJ/ha
Liming		22		MJ/ha
Field work				
Sowing	87	58		MJ/ha
Compaction	87	90		MJ/ha
Fertiliser spreading	175	119		MJ/ha
Rolling/aligning 1	408	124		MJ/ha
Rolling/aligning 2	198	82		MJ/ha
Chopping 1	661	251		MJ/ha
Chopping 2	494	217		MJ/ha
SUM:	2110	13036		MJ/ha
SUM TOT:		15146		MJ/ha
Addition of 8% energy				
SUM:	2278.8	14078.9		MJ/ha
	632.99	3910.79		kWh/ha
SUM TOT:		16357.68		MJ/ha
		4543.79		kWh/ha
Energy need for OLR increase	**20% increase**	**50% increase**	**90% of max**	
Total energy input for ley production	280341	700852	972948	kWh/year

Tabell B.4. Energy input from the transportation of ley with the direct diesel consumption adopted from Berglund and Börjesson (2003).

				Unit
Direct diesel consumption				
A truck and trailer capable of carrying 35 tonnes of ley			0.023	L diesel/ (tonne load*km)
Model distances	**20**	**250**	**400**	**km**
Direct fuel consumption	16.1	201.25	322	L diesel/35 tonnes biomass
Energy needs for model transport distances				
Energy needed in primary energy	735.77	9197.125	14715.4	MJ/35 tonnes biomass
	204.38	2554.76	4087.61	kWh/ 35 tonnes biomass
Energy need for yearly transport				
OLR +20%	8477.15	105964.35	169542.96	kWh/year
OLR +50%	21192.87	264910.87	423857.39	kWh/year
OLR 90% of max	29420.69	367758.62	588413.79	kWh/year

Table B.5. Energy inputs for the pretreatment of ley.

Direct energy usage				
Model energies	**10**	**20**	**45**	**kWh/tonne biomass**
Converted according to primary energy factor	79.2	158.4	356.4	MJ/tonne biomass
	22	44	99	kWh/tonne biomass
Yearly energy usage in primary energy				
20% OLR increase	31937.50	63875.00	143718.75	kWh/year
50% OLR increase	79843.75	159687.50	359296.87	kWh/year
90% of maximum OLR	110841.91	221683.82	498788.59	kWh/year

Table B.6. Net energy balance based on primary energy assessing the least and most energy demanding scenarios. Including the cases of a BMP loss of 9.5%.

Net energy balance	**20% OLR increase**	**50% OLR increase**	**OLR in tot. 90% of max**	**Unit**
No BMP loss, short transp., low pretr.	956957	2392393	3321205	kWh/year
	1939	1939	1939	kWh/tonne TS
No BMP loss, long transp, high pretr.	684110	1710276	2374265	kWh/year
	1386	1386	1386	kWh/tonne TS
BMP loss, short transp, low pretr.	835575	2088937	2899936	kWh/year
	1693	1693	1693	kWh/tonne TS
BMP loss, long transp, high pretr.	562728	1406819	1952996	kWh/year
	1140	1140	1140	kWh/tonne TS

Table B.7. EROI and energy efficiency quotas assessing the least and most energy demanding scenarios. Including the cases of a BMP loss of 9.5%.

	EROI	***Energy efficiency quota***	
No BMP loss, short transp., low pretr.	3.98	0.25	*100 %
No BMP loss, long transp, high pretr.	2.15	0.46	*100 %
BMP loss, short transp, low pretr.	3.60	0.28	*100 %
BMP loss, long transp, high pretr.	1.95	0.51	*100 %

Table B.8. Increase in electricity demand from pretreatment of ley at Uddebo WWTP.

Impact of pretreatment on Uddebo electricity usage	**20% OLR increase**	**50% OLR increase**	**OLR in tot. 90% of max**	
10 kWh	0.024	0.060	0.083	*100 %
20 kWh	0.048	0.120	0.166	*100 %
45 kWh	0.108	0.270	0.375	*100 %

Appendix C: Ley Crops – Economic Calculations

Table C.1 Implementation costs when increasing the OLR by 50%.

Production cost				
	1.5	SEK/kg TS		
	1850923	SEK/year		
	6.82	SEK/kg biomethane fuel gas		
Fuel costs	**20 km**	**250 km**	**400 km**	
20 SEK/L diesel	33389	417365	667784	SEK/year
	0.123	1.537	2.460	SEK/kg biomethane fuel gas
Electricity cost	**10**	**20**	**45**	**kWh**
0.6574 SEK/kWh	23859	47717	107364	SEK/year
	0.088	0.175	0.395	SEK/kg biomethane fuel gas

Table C.2 Cost for the production of 1 kg of fuel gas from ley assessing the least and most energy demanding scenarios when increasing the OLR by 50%. Including the cases of a BMP loss of 9.5%.

Cost per kg of fuel gas		
No BMP loss, short transp., low pretr.	7.03	SEK/kg fuel
No BMP loss, long transp, high pretr.	9.67	SEK/kg fuel
BMP loss, short transp, low pretr.	7.77	SEK/kg fuel
BMP loss, long transp, high pretr.	10.69	SEK/kg fuel

Table C.3 Estimated investment cost of an extruder.

Exchange rate 2015	8.4366	SEK/USD
Cost of an extruder 2015		
Price in SEK	790000	SEK
Price in USD	93639.6	USD
Cost estimation using M&S index		
M&S Index 2020	2171.6	
M&S Index 2014*	1906.8	
Cost estimation:	106643.5	USD
	1186643.4	SEK (2020)
Cost estimation using Construction Cost Index		
CCI Jan 2015	962.8	
CCI July 2023	1268.7	
Cost estimation:	1040998.1	SEK

**Index of 2015 was not accessible.*

Appendix D: Blood – Energy Calculations

Table D.1 Adopted parameters for slaughterhouse blood.

Parameters		
TS	0.179	*100 %
VS	0.9637	*100 % of TS
BMP	0.49	Nm^3/kg VS

Table D.2 Initial volumetric loads, VS load and BMP yield including the scenario of a BMP loss of 9.5%.

Loads and BMP yield		
Volume	16	m^3/week
	2.28	m^3/d
Weight	16000	kg/week
	2285.7	kg/d
VS load	2760	kg VS/week
	394.3	kg VS/d
BMP yield	193.2	Nm3/d
	70518.9	Nm3/year
Fuel gas yield	58765.8	kg fuel gas/year
Incl. BMP loss	53183	kg fuel gas/year

Table D.3 Substrate parameters after dilution to 10% TS.

Dilution to 10% TS		
Specific heat capacity (10% TS)	3867	J/kg*K
Density of substrate and water	1000	kg/m^3
Added water	1805.7	kg water/d
New total weight	1493371	kg/year
	4091.4	kg/d
	170.47	kg/h
	0.047	kg/s
New volume	22.86	m^3/d
	8343	m^3/year
Approximated dimensioning flow volume	23	m^3/d
Volume to be pasteurised	8	m^3/d and tank

Table D.4 Dimensioning and energy calculations regarding HEX 1.

Dimensioning and heat transfer of HEX 1 (digestate/unpast. blood)		
	IN	*OUT*
Hot media	38	28
Cold media	13	20
	dT1	*dT2*
Logarithmic temp. diff. (T_L)	15	18
T_L	16.45	K
Heat transfer coefficient	800	W/m^2*K
Q_blood	1281.84	J/s
	40424071200	J/year
	40424	MJ/year
Q_blood - primary heating energy	14598	kWh/year
Digestate flow	197.86	m^3/d (Assuming 175+23 m^3/d)
Assumed TS content	2	%
Digestate density	1000	kg/m^3
m_digestate	2.29	kg/s
Cp_digestate	4117.4	J/kg*K
Q_digestate	94289	J/s
Assumed HEX efficiency of 80%		
Q_digestate	1602.29	J/s
m_digestate	0.039	kg/s
HEX 1 - area	0.097	m2

Table D.5 Dimensioning and energy calculations regarding the HEX 2 battery.

Dimensioning and heat transfer of the HEX 2 battery		
	IN	*OUT*
Temp change 1		
Hot media	70	53
Cold media	35	48
	dT1	*dT2*
Logarithmic temp. diff. (T_L)	18	22
T_L	19.93	K
Heat transfer coefficient (k value)	800	W/m^2*K
Q_cold media	2380.56	W
	2.38	kW
HEX 2.1 - area	0.149	m2
	IN	*OUT*
Temp change 2		
Hot media	53	36
Cold media	20	35
	dT1	*dT2*
Logarithmic temp. diff. 1	16	18
T_L	16.98	K
Heat transfer coefficient (k value)	800	W/m^2*K
Q_cold media	2746.80	W
	2.747	kW
HEX 2.2 - area	0.202	m^2
HEX 2 Total		
Total efficiency	0.82	*100 %
Q_cold media tot.	190570621371	J/year
	190571	MJ/year
Q_cold media tot. primary heating energy	68817	kWh/year

Table D.6 Energy required for pasteurisation and dimensioning of pasteurisation unit assuming it is a HEX and that the district heating has a temperature of 80 °C. Including the energy input in primary energy.

Energy need for pasteurisation		
Q_blood_year		
	144371682857	J/year
	144372	MJ/year
	4577.99	W
	40103	kWh/year
Q_blood_year - Heating in primary energy		
	187683	MJ/year
	52134	kWh/year
Area of pasteurisation unit, assuming it is a HEX - dimensioning after summer DH temp		
	IN	*OUT*
T_dh	80	75
T_blood	48	73
	dT1	*dT2*
	7	27
T_L	14.82	Logarithmic aver. temp.
Heat transfer coefficient	1300	W/m^2*K
Heat transfer area	0.238	m^2
District heating (80 °C)		
Density	996.7	kg/m^3
Cp	4200	J/kg*K
Yearly amounts		
Mass	6874842	kg/year
Volume	6898	m^3/year
	574.8	m^3/month

Table D.7 Energy input for transport, including amount in primary energy.

Fuel consumption from transport			
Current distance	140	km	
Diesel cons. 140 km	70	L full tank	
	49	L empty tank	
	119	L/week	
Specific diesel consumption	0.85	L diesel/km	km in one way. Calc according to Berglund and Börjesson (2003)
Model distance	30	km	
Diesel cons. 30 km	25.5	L/week	
	30 km	**140 km**	
Primary energy	1165.35	5438.3	MJ/week
	60598	282792	MJ/year
	16833	78553	kWh/year

Table D.8 Net energy balances, EROI and energy efficiency quotas based on primary energy and including a scenario of 9.5% BMP loss.

Energy output			
	16 m^3/week		
No BMP loss	2489318	MJ/year	
	691477	kWh/year	
	691.5	MWh/year	
9.5% BMP loss	2252833	MJ/year	
	625787	kWh/year	
	625.8	MWh/year	
Energy input			
Transport	*30 km*	*140 km*	
	16833	78553	kWh/year
	0.017	0.078	GWh/year
Pasteurisation	52134	kWh/year	
	0.052	GWh/year	
Net energy balance	*30 km*	*140 km*	
No BMP loss	622510	560790	kWh/year
	622.5	560.8	MWh/year
9.5% BMP loss	556820	495100	kWh/year
	556.8	495.1	MWh/year
EROI			
No BMP loss	10.0	5.3	kWh/year
9.5% BMP loss	9.1	4.8	kWh/year
Energy efficiency quota			
No BMP loss	0.099	0.189	*100 % energy input
9.5% BMP loss	0.110	0.209	*100% energy input

Appendix E: Blood – Economic Calculations

Table E.1 Costs from transport and district heating (dh) for pasteurisation including the scenario of a BMP loss of 9.5%. Including scenarios of long and short transport as well as scenarios of a "high" and "low" dh cost.

Transport cost	*30 km*	*140 km*	
Diesel cost	26520	123760	SEK/year
Cost/kg fuel			
No BMP loss	0.45	2.11	SEK/kg fuel gas
District heating cost	*193 MWh/year*	*500 MWh/year*	
	131106	333091	SEK/year
Cost/kg of fuel			
No BMP loss	2.23	5.67	SEK/kg fuel
Cost to be covered:	*No BMP loss*	*BMP loss*	
Cost/Nm^3			
Short transport, low dh	2.23	2.47	SEK/Nm^3
Long transport, high dh	6.48	7.16	SEK/Nm^3
Short transport, high dh	5.10	5.63	SEK/Nm^3
Cost/kg fuel gas			
Short transport, low dh	2.68	2.96	SEK/kg fuel gas
Long transport, high dh	7.77	8.59	SEK/kg fuel gas
Short transport, high dh	6.12	6.76	SEK/kg fuel gas

Table E.2 Estimated investment costs based on the commissioning of a facility dimensioned to treat 480 m^3/d proposed by SWECO (2015) scaled down to 25 m^3/d.

Cost estimation of pasteurisation unit in 2015			
Investment cost estimation 2015	21500000	SEK/480 m^3/d	
Dimensions	480	25	m^3/d
Six-tenths rule		3651385.8	SEK/25 m^3/d 2015
Cost estimation using Construction Cost Index			
CCI Jan 2015	962.8		
CCI July 2023	1268.7		
Cost estimation 2023:	4811501		SEK

Appendix F: Summary of Substrate Inventory

Substrate	Availability/Usage	Amount
Agriculture		
Ley crops	Animal feed	In balance with consumption
Grain	Food	Low production
Potato residues	Animal feed and/or to WWTP	In total 2 000 tonnes of peels and sorted out potatoes
Other Food Crops	Food	Low production
Manure	Farm based usage	Possibly significant
Energy Crops		
Ley crops	Farmland can be available	8–10 tonnes/ha
Reed canary grass	Farmland can be available	3–7 tonnes/ha
Food Industry Waste		
Bakery	Internal usage	-
Eggs	Unwanted	-
Dairy	Biogas production in Luleå	-
Fishery	Animal feed	-
Meat	Biogas production at Alviksgården	-
Blood	Biogas production in Skellefteå	11–16 tonnes/week
Industrial Waste		
Fibre sludge from paper and pulping industry	Internal usage	Deemed unsuitable due to high fibre content
Bio sludge from paper and pulping industry	Internal usage	-
Fibre and sediment banks	-	-
De-icing fluid	Recycling and reselling	120 m^3 pure glycol/year, 10 m^3 residual fraction

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