NTNU – Trondheim
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Resource efficiency and life cycle environmental impacts of biogas production from sewage sludge and organic substrates in Bergen

Ressurseffektivitet og livsløps
miljøpåvirkning av biogassproduksjon fra
avløpsslam og organiske substrater i Bergen

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Preface

The report is written as a master assignment at the Department of Energy and Process Engineering for the Industrial Ecology programme at the Norwegian University of Science and Technology (NTNU) and as part of the BIOTENMARE research project.

I want to thank my supervisor Helge Brattebø at NTNU for good guidance throughout the master. Thanks goes also to my co-supervisor in Bergen municipal, at the water and sewage department, Kristine Akervold, a busy and cheerful woman that always find time to help with any questions. Further I want to give thanks to Linda Kanders at Purac AB for taking time to instruct me in calculating process energy and supplying the newest process data for the system they deliver.

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Sammendrag

Bakgrunn, målsetting og omfang. Denne studien baserer seg på ferdigstillingen av ett biogassanlegg i Rådalen, Bergen, som er under utbygging. Grunnen for denne utbyggingen har med krav om sekundærrensing ved byens kloakkrenseanlegg (WWTPs), dette kravet vil øke mengden kloakkslam fra dagens 4 000 tonn til 40 000 tonn ved ferdigstilling. Det avvannede kloakkslammet ville vanligvis bli transportert til videre sluttbehandling, den forutsatte økningen i slam gjør at byen må se etter nye løsninger for sluttbehandling. Valget falt på ett biogassanlegg, ved siden av dagens kommunale forbrenningsanlegg som i dag leverer varme til byen og industri, samt elektrisitet, og er en fornuftig løsning ved samlokalisering av avfallsbehandling. Anlegget skal hovedsakelig benytte kloakkslam fra byens kloakkrenseanlegg, samt annet organisk avfall fra industri og bedrifter rundt om i Bergen. Målet med denne studien er å belyse miljøforbedringene som eventuelt finner sted ved overgang fra dagens avfallsløsning, til ett biogass system, og bruker den funksjonelle enheten ett tonn tørrstoff inn i systemet.

Metode. Gjennom studien er tre metoder benyttet; litteratur studie og kvantitativ metode gjennom materialflytanalyse (MFA) og livsløpsanalyse (LCA). Litteraturstudien fokuserte hovedsakelig på å bygge opp kunnskapen rundt systemet, hvor hovedsakelig litteratur fra Norge, Sverige o g lærebøker om emnet er benyttet. Gjennom MFA spores flyten av masse og energi som entrer og forlater de forskjellige prosessene, som så vil gi en definert energieffektivitet of gjenvinningsgrad av material/næringsstoffer (RR, NR eller PR). Alle utregninger og defineringer var utført i henhold til den definerte funksjonelle enheten (FE), ett tonn tørrstoff behandlet organisk avfall substrat. Kalkulasjonene var gjort med forhåndsbestemte parametere og antagelser basert på litteratur og nødvendige kalkulasjoner, og alle miljøeffektene ble regnet ut gjennom dataprogrammet SimaPro.

Resultater og diskusjon. Resultatene fra MFA på den valgte casen viser en RR på 53.96%, NR på 35.37%, PR på 90% og energi effektivitet på 32.23%. Videre fra gjennomført LCA, for alle miljøpåvirkningskategoriene, viser en total miljøpåvirkning på 147.62 kg CO_2-ekvivalenter/FE og en total miljøpåvirkningsreduksjon på -556.4 kg CO_2-ekvivalenter/FE og med en total miljøpåvirkning fra systemet på -408.78 kg CO_2-ekvivalenter/FE. Buss substituering representerer utbytting av diesel i bruk og den største miljøpåvirkningsreduksjonen på -408.78 kg CO_2-ekvivalenter/FE, imidlertid siden det allerede i Bergen driftes en del busser som drives av naturgass, er det mer trolig at naturgass vil bli erstattet, noe som vil redusere substitusjonseffekten noe, selv ved en 80% reduksjon av prosessen buss substituering vil systemet ha en total negativ miljøpåvirkning.

Konklusjon. Bruken av biometan som erstatning av fossile drivstoff, og biorest som erstatning av kunstgjødsel er en fornuftig løsning for fremtiden, og er over det hele den beste løsningen for Rådalen biogassanlegg i Bergen.

Nøkkelord: Life cycle assessment; Material flow analysis; anaerobic digestion; sewage sludge; biomethane; bioresidual

Abstract

Background, Aims and Scope. This study bases itself on the completion of a biogas plant in Rådalen, Bergen, currently under construction. The reason for the construction of the plant is the mandatory secondary cleaning at the wastewater treatment plants (WWTPs), this demand will increase the amount of sewage sludge from present 4,000 tons to 40,000 tons when completed. The dewatered sewage sludge would normally be transported for further treatment; this predicted increase of sludge is forcing the city to look into new solution for its waste management. Location for the biogas plant is chosen to be next door to the municipal incineration plant that delivers heat to the city and industry, and is a reasonable solution of co-location of waste management. The plant is mainly to utilise sewage sludge from the city's WWTPs, including other organic waste from industries and companies around in Bergen. The aim of this study is to highlight the environmental improvements that might happen with a transfer from today's waste management, to a biogas system, and using the functional unit one-ton dry matter into the system.

Methods. Through the study, three methods are used; literature study and quantitative methods through material flow analysis (MFA) and life cycle assessment (LCA). The literature study focus mainly on building up the knowledge around the system; where most literature is from Norway, Sweden, and books on the system are used. Through MFA, the flow of mass and energy that enter and leaves the processes, that further will give a defined energy efficiency and material rate of recovery of materials and nutrients (RR, NR, and PR). All calculations and definitions where done according to the defined functional unit (FU), one ton dry matter treated organic waste substrate. Calculations were done with predetermined parameters and assumptions based on literature and necessary calculations, and all environmental impacts were calculated through the program SimaPro.

Results and Discussion. Results from the MFA shows for the case chosen a RR at 53.96%, NR at 35.37%, PR at 90%, and with an energy efficiency at 32.23%. Further from the LCA performed reductions are shown in all impact categories looked at, with a total impact at 147.62 kg CO_2-equivalents/FU and a total impact reduction at -556.4 kg CO_2-equivalents/FU with a total impact from the system at -408.78 kg CO_2-equivalents/FU. The Bus substitution represent the replacement of diesel and the largest impact reduction, however as Bergen has several buses running on natural gas, it is more likely that natural gas will be replaced, this would reduce the substitution effect somewhat, even with a 80% reduction of this process the system would still have a total negative impact.

Conclusion. The use of biomethane for replacement of fossil fuels, and bioresidual as replacement of chemical fertiliser is a sound solution for the future, and overall is the best choice for the case of Rådalen Biogas Plant in Bergen.

Keywords: Life cycle assessment; Material flow analysis; anaerobic digestion; sewage sludge; biomethane; bioresidual

Terminology

CH_4 – methane

CO_2 – carbon dioxide

SO_2 – sulphur dioxide

NH_3 – ammonia

N_2O – dinitrogen monoxide

N_2 – nitrogen gas

N - nitrogen

P - phosphorus

DM – dry matter, measurement of solid mass content

VS – volatile solids, measurement for organic content of DM

LCA – life cycle assessment

MFA – material flow analysis

RR – rate of recovery, for materials (mass and nutrients)

EE – energy efficiency

HHV – higher heating value

Nm^3 – normal cubic meter

tkm – ton kilometre, measurement of 1 ton transported 1 km

VFA – volatile fatty acids

GWP – global warming potential

TAP – terrestrial acidification potential

HTP – human toxicity potential

FDP – fossil depletion potential

RBP – Rådalen biogas plant

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1. Introduction

1.1. Background

The background for this master thesis is the construction of a biogas plant in Bergen, as the city has a demand of increasing the quality of the cleansing in the wastewater treatment plants (Akervold 2013), thusly the city will experience an increase in the amount of sewage sludge collected and needed treated every year. The solution, as hoped to be, is a centralised biogas plant running on sewage sludge in co-digestion with commercial food waste, organic industrial waste and glycol from the airport.

According to "Underlagsmaterialet til tverrsektoriell biogas – strategi" by Sletten & Maass (2013) the realistic potential for biogas production in Norway will be around 2.3 TWh from todays 0.5 TWh. The technical potential assumes around six TWh. From sewage sludge the theoretical potential is 0.266 TWh per year while for food waste it is 1.066 TWh/year (includes both domestic and commercial food wastes). Klimakur 2020 by (Klima- og Forurensingsdirektoratet 2010) explains that biogas is looked at as a way of reducing the climate emissions of Norway by 2020 and onward, and the plant in Bergen will optimally realise up to nine percent of the sewage sludge potential and around one percent of the total realistic potential (year 2020, Akervold 2013).

1.2. Objective

The objective of this master thesis is to carry out a system analysis of the planned system for biogas production in Bergen, in order to estimate the environmental performance, in terms of energy- and resource efficiency (organic matter and nutrients) and the life cycle environmental impacts (climate change, acidification, eutrophication potential, etc.). Also to understand how given critical variables and assumptions may affect the results of the system performance, this last part will be especially important for Bergen municipal as they will be looking for places to improve in order to lift the environmental performance.

Research question. What is the environmental performance of the planned biogas production system in Bergen, and which variables are most relevant for such a context?

- What is the energy- and resource efficiency (organic matter and nutrients)?
- What is the environmental performance of the planned biogas production system and other relevant systems compared to today's situation?
- What are the parameters and parts of the system where Bergen municipal need showing extra vigilance?

1.3. Scope of work

MFA and LCA will be the focus of the master, thus being able to compare the situation of today with future situations. Creation of different cases will enable comparison to the present and thus determining the best system via the environmental performances. More so, the energy- and resource efficiency will also be in focus, here looking at the energy performance of the system as a whole, same for resources, with a focus on recovering as much of the bioresidual as possible for the use of biofertiliser. All while reaching the best environmental performance in term of example climate change. In both methodologies, the Functional Unit (FU) is used, thus making them comparable and easy to measure, and the FU defines the treatment of one ton dry matter (DM) of waste entering the Anaerobic Digestion (AD) chamber.

The basic numbers for the thesis are premade from former reports on the feedstock potential and from the system deliverer, Purac AB, where such information as energy requirements for machinery are given. Despite this, performing calculations and consulting more literature is necessary.

1.4. Report outline

Chapter 2 represent the literature study done in this project assignment. This includes the description of different biogas technologies, including the sorting, pretreatment, types of anaerobic digestion and lastly methods of upgrading the biogas to fuel quality. Chapter 3 represents the methods used in the project, including description of the literature study, the case study done and, LCA and MFA methodology. Chapter 4 presents the results. Chapter 5 presents the discussion around the results, critics of the methods used and recommendations for future works, and lastly Chapter 6 brings the conclusion.

2. Literature study

2.1. LCA

Life cycle assessments are normally applied on products or production, to find the impacts related and then take action if necessary, also called “cradle to grave”, while waste management is often is often simplified when looked at, LCA normally looks at the product while waste is considered the output. For LCA of waste, the end-of-life is the focus of the assessment; there are uncertainties around such assessment as many studies varies in what they look at as well as the data used.

2.1.1. Former LCA of biogas production and technologies

When utilising anaerobic digestion from waste, many ways open for use of the by-products from such waste management, or from the use of energy crops, here can be biogas for heat and or CHP, fuel and bioresidual as fertiliser. Poeschl et al. (2012) argues that reduction of environmental impacts varies on the type of feedstock and the mix, either as singe feedstock digestion of co-digestion with other feedstock. For the single feedstock digestion, the variation is significant; this would mean that what one chose to digest has a lot to say on the actual benefit of biogas production. For climate change the largest reduction is from the digestion of straw residues from agriculture, residues that normally would rot on the fields. While emission reduction decreases the “newer” the feedstock gets, as the use of energy crops is a primary product and not considered a waste product.

In the study “Biogas from municipal organic waste – Trondheim’s environmental holy grail?” by Hung & Solli (2012) about the potential of biomethane as substitute for fuel in buses in Trondheim they found that there was not a significant reduction in the climate change emission, where the largest reduction amounted to around 5% for a biogas plant situated in Trondheim. However, significant reduction shows in other impact categories such as photochemical oxidation formation, where for the case of Trondheim was a reduction of over 80% compared to normal, also found was large reductions for particular matter formation and fossil depletion.

Adelt et al. (2011) argues that the best way of reducing greenhouse gases (GHG) emissions in production of substrates is to utilise the bioresidual and its nutrients as fertiliser, and give the opportunity to replace chemical fertiliser. Adelt et al. (2011) further argues that the use of biomethane is currently the best option of renewable energies to replace natural gas, and based on the experiences in the paper an 80% reduction in GHG emisisons seems reasonable.

In the article “Life cycle assessment of biogas infrastructure options on a regional scale” written by Patterson et al. (2011) it focuses on doing a life cycle assessment on a biogas system at a regional scale. As argued this is done for the reason that many articles only focuses on parts of the system, and different technologies, making the scope of work very varying and not easily compared, and the purpose of doing the whole system is to determine any clear environmental benefit of such a system. The conclusion of the paper is that in the regional system case of Wales the CHP situation, with 80% of the surplus heat utilised, gives the least environmental impacts, however if utilisation is not possible, the upgrading of the fuel would be the best solution. Patterson et al. (2011) further argues that there are significant human toxicity potential from the use of the bioresidual due to high levels of heavy metals as well as the loss of methane from upgrading represented a large impact.

The use of biogas to reduce GHG emissions are widely concluded to be a viable solution of substitute for natural gas, it is also found that the use of CHP with use of the heat produced, if not possible the best would be to upgrade the produced biogas to fuel standard and thusly being able to substitute fuel in use. The use of the bioresidual to substitute chemical fertiliser can also increase the emission reduction from the use of biogas production; however, discussed also is that the human toxicity potential can increase if sewage sludge is in the mix due to heavy metal contents.

2.2. Biogas technologies

2.2.1. Pretreatment

Physical pretreatment

Pretreatment of the substrates before the biogas production yields many benefits, the use of different treatment methods will lead to a reduction in solids, removal of odours and pathogens, reduction of energy needs at a later time, and an increase in methane production (Forster-carneiro et al. 2012). Physical pretreatment divides into the following three categories, which includes different technologies.

Mechanical pretreatment. The mechanical pretreatment is about reducing the size of the solids of the substrates, thus increasing the surface area of the substrates making it more available to be biodegraded; this will also improve the speed and efficiency of the hydrolysis. The basic operations for mechanical pretreatment are as following:

- *Reduction by size:* the reduction of size utilises mainly for direct use of, or for recovery of material. Typical size reduction machines are hammer mills, and crushers (Forster-carneiro et al. 2012).
- *Separation:* during this step different sizes separates, examples of methods can be by the use of a trammel screen where larger sizes separates from the rest. Separation of substrates are also done based on the density of the different materials, such as wood, and metal (Forster-carneiro et al. 2012).
- *Compaction:* the purpose is to make the substrates as easy to transport as possible, or to storage. Here examples are different means of packaging, but also dewatering off for

example sewage sludge before transport to end-of-life treatment (Forster-carneiro et al. 2012; Sande et al. 2008).

Even though studies have shown an increase in yield after mechanical treatment, there is always the problem of high energy needs that could present a challenge (Forster-carneiro et al. 2012).

Thermal pretreatment. The thermal pretreatment is the stage where the efficiency of anaerobic digestion improves due to the thermal hydrolysis. The thermal treatment dissolves both the organic and the inorganic matter, which leads to a reduction of the digester volume and enhances the production of biogas (Forster-carneiro et al. 2012). Hygienisation is a good choice for the thermal pretreatment, as it makes the matter more dissolvable, and also removes allot of the pathogens; done for example by heating the substances to 70 degrees Celsius for an hour (Akervold 2013). The hygienisation will also cover the demands of pathogen removal if the bioresidual are to be used as fertiliser (Coultry et al. 2013; Sande et al. 2008). Another example is the thermal hydrolysis, which works at temperatures of example 165-170 °C, at half an hour, this method also utilises pressure changes in order to further break down the solid structure of the feedstock, thus resulting in a higher degradation (Normak et al. 2011).

Ultrasonic pretreatment. The application of ultrasonic pretreatment implies using intense ultrasonic waves to a liquid system, which can modify the structure of the material. This will create local conditions of extreme temperature and pressure, making the material more available for degradation (Forster-carneiro et al. 2012).

Chemical pretreatment

For the chemical pretreatment where the purpose of the anaerobic digestion is biogas production, the use of alkali pretreatment are the most common, thus further methods will not be taken into consideration.

Alkaline pretreatment consist of adding a dose of alkaline agents, such as NaOH (sodium hydroxide), at room temperature for 24 hours, before the sample are filtered. The alkaline pretreatment cause the substances to swell, thus making them more susceptible for enzymes, and improving the biodegradation in the solid phase. The adding of alkali can help to neutralize the organic acids, thus reducing the inhibition effect (Forster-carneiro et al. 2012).

Biological pretreatment

The biological pretreatment aims to ready the substrates for the enzymatic degradation, where fungi or bacteria are used. The main advantages are very low energy requirements, no chemicals, and mild environment conditions, while the disadvantage is that the treatment efficiency in most cases are very low (Forster-carneiro et al. 2012).

2.2.2. Anaerobic digestion

The term anaerobic digestion means “breaking down of organic matter”. Under the process of anaerobic digestion, the organic substances are not oxidised but rather fermented, which means reduced, which leads to an energy-rich product. It is under this oxygen free digestion of organic matter that biogas is produced, when producing biogas, one utilise oxygen poor conditions with the help of several types of microorganisms, where the conditions for the microorganisms has a lot to say for the efficiency of the process. The waste products from the anaerobic digestion are biogas and bioresidual residue. The biogas contain mainly CO_2 and CH_4, the mix between the main components differ depending on the matter used in the production, energy rich waste produce more biogas where fats are a good source (Svenskt Gastekniskt Center AB 2012; Seadi et al. 2008).

The biological processes

Hydrolysis. The hydrolysis process is in theory considered the very first step of the anaerobic digestion, which during the organic matter decomposes into smaller bits. It is during this process that organic matter such as carbohydrates, lipids, acids, and proteins are converted to glucose, glycerine, purines, and pyridines (Seadi et al. 2008).

Acidogenesis. This is the stage where the hydrolysis converts by the fermented bacteria into methanogenic substrates. Here substances that can be converted, converted into carbon and hydrogen (ca. 70%) and also into volatile fatty acids and alcohols (30%) (Seadi et al. 2008).

Acetogenesis. In this process, the substances that could not be converted in the acidogenesis are then oxidised into different methanogenic substances (Seadi et al. 2008).

Methanogenesis. The methanogenesis process is the most critical of the biochemical processes, and is highly affected by operation conditions, such as temperatures, feedstock, pH, etc. (Seadi et al. 2008).

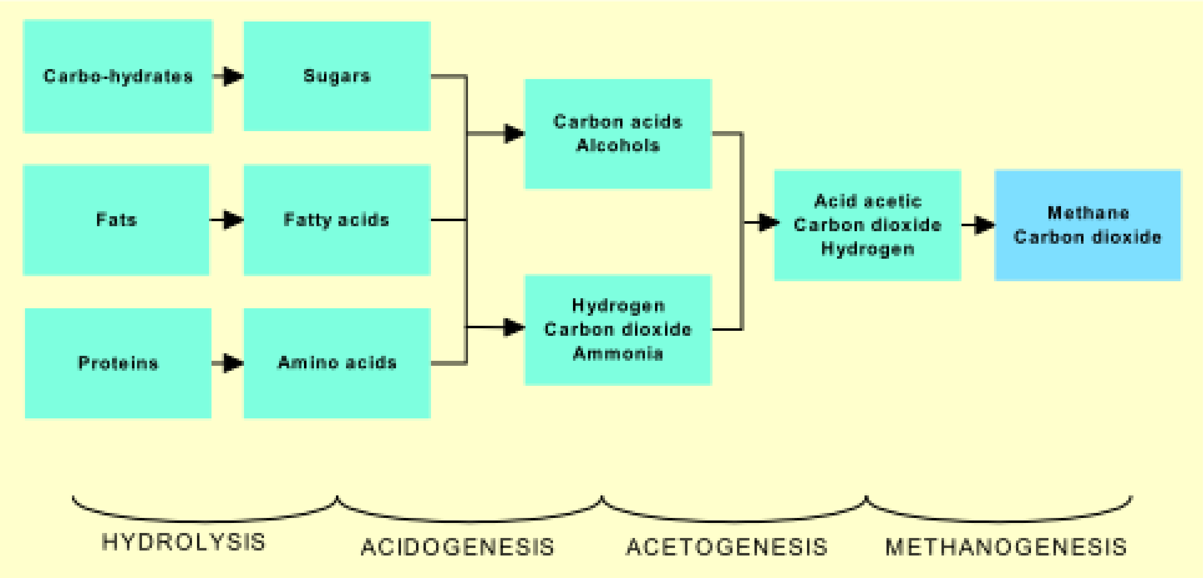


Figure 1: The biochemical processes (Seadi 2002).

Anaerobic Digestion parameters

The anaerobic digestion efficiency is influenced by some critical parameters. The first critical parameter is the temperature range, the temperature range divides into three temperature ranges: psychrophilic (below 25 degrees Celsius), mesophilic (25-40 degrees Celsius), and thermophilic (45-70 degrees Celsius). Only the last two temperature ranges are used in practice, and depends on the incoming feedstock. The choice of temperature range is an important decision as it can give advantages choosing the one over the other. Thusly, there are some advantages utilising the thermophilic temperature range over the mesophilic range. Some advantages are effective destruction of pathogens, and higher growth of methanogenic bacteria at higher temperature. Some disadvantages are larger degree of imbalance, and larger energy demand due to the higher temperature demand in the thermophilic temperature range (Seadi et al. 2008).

The second critical parameter is pH values and optimum intervals the pH value affects the growth rate of the methanogenic microorganisms and the separation of some compounds of importance, such as ammonia. Research has shown that methane production takes place between the pH values of 5.5 to 8.5, with an optimum between 6.5 and 8.0 pH for the mesophilic digestion and is higher for the thermophilic digestion because the solubility of carbon dioxide in water decreases with higher temperatures (Seadi et al. 2008).

The third critical criterion is the volatile fatty acids (VFA), which reflects the stability of the anaerobic process. In most cases instability in the anaerobic digester will lead to an accumulation of the VFA inside the digester, this however is not always the case, large amounts of animal manure with high VFA levels can also lead to an concentration that will greatly inhibit the anaerobic process (Seadi et al. 2008).

The fourth critical criterion is ammonia, which is an important nutrient, used in foods and fertilisers, and is also an important compound with a significant function for the anaerobic digestion process. Problems arise when the ammonia content gets too high; This occurs specially with free ammonia (unionised form), thus inhibiting the process. The free ammonia levels are directly proportional to the temperature, thus the levels are expected to be higher in the thermophilic temperature range, thusly increasing the risk of inhibition caused by ammonia, compared to the mesophilic process (Seadi et al. 2008), this also leads to a limit of reject water reuse because of the extra input of nitrogen (Akervold 2015a).

The fifth critical criterion is trace elements and toxic compounds, where trace elements considers very important for the AD process, where both too high, and to low levels can cause inhibition of the process. Toxic compounds can also influence the activity of the anaerobic microorganisms, but what levels cause inhibition in the process is hard to know considering the adaptively capacity of the microorganisms (Seadi et al. 2008).

Anaerobic Digestion technologies

For the anaerobic digestion, there exist many different technologies for the process, but it falls down to four main characteristics of the technologies, which are as follows:

Dry/wet digestion. The dry and wet digestion are divided into the moisture levels of the substrates treated, the dry process utilises moisture levels less than 75% and the wet process utilises moisture levels above 90% (Jansen 2011).

Separation of the temperatures of digestion. There are two mainstream microbial operation regimes that uses anaerobic digestion; they are mesophilic and thermophilic temperatures. The mesophilic temperature works at a range 32-42 degrees Celsius while the thermophilic works at a range of 50-58 degrees Celsius. The organisms with the optimal operation within the regimes give the names for the operation regimes. The higher temperature range gives a faster degradation of the biological matter, the higher temperature also makes it harder to operate and requires some higher costs for operation. Because of the need for hygienisation if the bioresidual is to be used as fertiliser the thermophilic process is preferred over the mesophilic, however the mesophilic digestion process is the most commonly used (Jansen 2011).

One or two stage digestion. This refers to the part where the biogas is produced, the biogas production is a staged process where several bacteria’s cooperate to degrade the organic material and produce the methane, and it is therefore according to Christiansen (2011) to choose a staged process. The multi-stage process seeks to separate biochemical processes of the digestion process in order to get the best results, due to the differences in optimal conditions. The most common is two stages, where the first stage is the acidification and the second stage the methanogenesis, even though both the one- and two-stage process is implemented, the one-stage is the most common (Jansen 2011).

One or two phase digestion. The phase processes utilises in combination with the one- or two-stage process. Where the biomass, after the acidification is separated into a solid fraction and further treated in the acidification. While the liquid fraction which is the acid high fraction is sent to the methanogenic stage, this leads to a higher methane yield (Jansen 2011).

2.2.3. Post-treatments

Dewatering (mechanical separation)

After the anaerobic digestion process, the wet bioresidual can be set under mechanical separation, which in basic is a separation of the solid and liquid fraction of the wet bioresidual. This makes for further use of the dry fraction as fertiliser and or the liquid fraction as fertiliser of reuse as process water in the pretreatment process (Purac AB 2012; Normak et al. 2011).

Technology for mechanical separation can be by the use of centrifuges, where the use of high velocity increases the efficiency of separation of components and with the adding of polymers the efficiency can further be increased (Purac AB 2012; Normak et al. 2011).

Post-digestion tank

The post-digestion tank is part of the internal biogas plant and makes it possible to continuously feed bioresidual into the closed tank for storage, this is important for stabilisation of the bioresidual and minimisation of emissions (Normak et al. 2011). Also according to Normak et al. (2011), the biogas potential in the bioresidual is large and may be as much as 10-30% of the total biogas production if utilised, meaning there is quite a potential of methane capture during such a post-treatment of the bioresidual. The post-digestion tank is not heated as the digestion tank is, however, as it would often be situated underground the temperature would be stable throughout the year as according to Normak et al. (2011), from Loustarinen et al. (2008).

Cleaning of contaminants

Depending on what purpose the use of biogas is for, there are cleaning steps needed to take place to best utilise the biogas (Normak et al. 2011). Hydrogen sulphide can cause corrosion when mixed with water; if the concentration is too high it may require removal. Ammonia, together with condensation can also cause corrosion; also if the conditions are correct it can cause deposition in the fuel gas system. High impurities of the above-mentioned substances can respectively cause higher emissions of sulphuric acid and increase in the nitrogen oxide emissions. Depending on the use of biogas, other than heat boiler, it may be required that there are steps taken to remove hydrogen sulphide and to dry the biogas in order to reduce condensation in the utilisation.

Upgrade of biogas to biomethane

For the upgrading of the biogas there are several technologies that could be utilised, the following technologies are the most common in use, a summary is made in the below table.

Table 1: Examples of techniques for removal of carbon dioxide from biogas (Svenskt Gastekniskt Center AB 2012).

Upgrading technologies, summary:
Amino scrubbing *Absorbtion of carbon dioxide using amines (molecules with carbon and nitrogen)*
Water scrubber (HPWS) *Absorption of carbon dioxide in water by pressurising the biogas*
Pressure Swing Adsorption (PSA) *Adsorption of carbon dioxide on e.g. activated water*
Membrane *Seperation through a membrane that is permable for carbon dioxide*
Organic physical scrubbing *Absorption of carbon dioxide in an organic solvent*

Amino scrubbing. The main feature of the technology is use of a reagent that chemically binds the CO_2 molecule, thus removing it from the gas. The most common is the use of amines; amines are molecules with carbon and nitrogen, and exist either in form of molecules or ions. The process requires certain inputs, the water requirements are set to 3.00E-05 m^3/Nm^3 biogas, and electricity varies from 0.12-0.14 kWh/Nm^3. Lastly, the stripper that removes the CO_2 from the amino mix requires circa 0.55 kWh/Nm^3 biogas, the technology has a loss of 0.06% giving the process and efficiency of 99.4% (Bauer et al. 2013; Starr et al. 2014).

Water scrubber. This technology uses a scrubber that utilises the fact that CO2 has a higher solubility in water than CH_4, the CO_2 separated from the biogas and dissolved into the water and later released form the water. After the biogas arrives at the upgrade site, the gas is pressurised to 6-10 bars at an energy need of 0.10-0.15 kWh/Nm^3. For the water pump, the energy need is around 0.05-0.1 kWh/Nm^3, and 0.022 l of water per kWh biomethane, for the cooling system the energy need is circa 0.01-0.05 kWh/Nm^3 (Bauer et al. 2013; Starr et al. 2014). The methane recovery is 99%, and with a total methane content of 98% in the biomethane (Akervold 2014; Malmberg 2014).

Pressure swing adsorption. The pressure swing adsorption is a technique that utilises the physical properties of the gases separated. In basics the biogas is pressurised and fed into adsorption columns where only the methane goes through, when the columns are full they are emptied, thus making room for continues filling of carbon dioxide, and the methane concentration is assumed to be 98%. The process inputs required for the process is by industries and literature set to 0.15-0.3 kWh/Nm^3 (Bauer et al. 2013; Starr et al. 2014).

Membrane separation. This technique uses a membrane, which is a thick filter that captures the CO_2 and lets the CH_4 true. Most guaranties on methane recovery is at 95%, and an energy input of 0.2-0.3 kWh/Nm^3 (Bauer et al. 2013; Starr et al. 2014).

2.2.4. Biogas utilisation

Heat

For heating, the biogas is combusted in a boiler, thus warming up water. This can be used onsite in a building, or be sent to a local district heating net, the boiler works the same as a boiler made for liquid fuels, or other solids, but are made specifically for gas. The purpose of heat generation is best served for farm use or small plants where the end-used is located onsite or close by; the biogas does not need as much treatment as other uses need, but still needs removal of contaminants (Svenskt Gastekniskt Center AB 2012).

Combined heat and power

For direct utilisation for the purpose of heat, electricity or combined heat and power, CHP, the biogas needs no upgrade, but it needs some removal of water and hydrogen sulphide because of corrosion and other possible damages. After cleaning, utilisation of biogas in stationary engines or gas turbines is possible. Up to 40% of the biogas is converted to electricity and the rest as heat, at most the efficiency can reach as high as 85% (Svenskt Gastekniskt Center AB 2012).

Biomethane for transport or gas injection

Further uses of biogas are the use of vehicle fuel or injection into a natural gas grid. However, to do so, the biogas has to go through an upgrade; this upgrade will remove carbon dioxide form the biogas and leave the biogas at a methane level of around 98%, now biomethane.

Biogas, when upgraded to biomethane can then be utilised as replacement for natural gas used as fuel for vehicles, as CNG (Compressed Natural Gas) LNG (Liquefied Natural Gas), and it can also be fed into existing gas grid (Seadi et al. 2008).

2.3. Feedstock substrates

When it comes to the substrates there are regulations to the use, disposal, and use of the bioresidual. The regulations are set by "Regulation on animal by-products not intended for human consumption" (Forskrift om animalske biprodukter 2007), which regulates the categories the substrates are listed under. These regulations are set due to risk of spreading of deceases to humans and animals, the animal by-products are categorised into three categories. The categories define the level of treatment they need, the first category means destruction and/or landfilling, the second category demands pretreatment through hygienisation at 130 degrees Celsius for 20 minutes and category three demands hygienization at 70 degrees Celsius for one hour. While for some substrates in this category the hygienisation is not a demand if anaerobic digestion follows (Vann & Norge 2009), however for most substrates if thermophilic digestion follows than there would not be a need for hygienisation, while as mentioned in chapter 2.2.1 “Pretreatment”, there is a benefit of doing so.

2.3.1. Sewage sludge

Sewage sludge. The theoretical potential of biogas from sewage sludge in Norway was 2007 circa 266 GWh/year (Raadal et al. 2008). The sewage sludge is the pretreated material from the wastewater treatment plants, and consists of all the masses taken out during the cleaning processes at the WWTPs. This is a highly organic mass well suited for biogas production, and also since there are still costs related to the end-of-life treatment of the pretreated sewage sludge, utilising it in co-digestion with e.g. manure will cut down the costs related with the biogas production from the manure and/or other substrates (Meld. St. 21 (2011–2012) 2012). The HHV is assumed to be 25.7 MJ/kg as given by Trinh et al. (2013). The DM content of the sewage sludge ranges from 25-30%, where biological sludge has a DM of 25% and the chemical sludge has a DM of 30%. The VS content of the biological sludge is 70% (Purac AB 2011) while for chemical sludge the VS content is assumed to be 76.9% as given by (Paulsrud 2014).

The biogas potential for sewage sludge varies anywhere from 0.75 – 1.12 Nm^3 per kg of VS destroyed, with a typical value of 0.95 Nm^3/kg (Junne 2014), however a number of 0.9 Nm^3/kg VS destroyed is reported by Sande et al. (2008).

The nutrient content of the sewage sludge varies from the type of treatment it undergoes, according to Yara (2011) the biological sewage sludge has a nutrient content of 0.6% for P and a N content of 2.9% of the DM. While for chemical sludge a nutrient level of 1.4% for P and an N content of 0.7%, the same assumes for septic.

2.3.2. Wet organic waste

Organic Municipal Waste (OMW). In Norway, the annual contribution of OMW per capita was at circa 147 kg in 2014 (relies upon unchanged waste numbers since 2012) (SSB 2014a) (SSB 2014b). The theoretical potential for wet organic waste for Norway from households was in 2008, 644 GWh/year. Sorted food waste has in general a DM content of 30-35% with a VS content of 85% (Carlsson et al. 2009).

Commercial food waste. While for commercial food waste the theoretical potential is 149 GWh/year (Raadal et al. 2008). The DM content of the commercial food waste is around 25%, with a VS content at 85% (Purac AB 2011; Sande & Seim 2011). The HHV of commercial food waste is 18.5 MJ/kg waste (Wirsenius, 2000), and a biogas potential for organic solid waste is given at 0.38 – 0.42 Nm^3 per kg of VS added at a single-stage process, while at two-stage process the potential can be up to 0.6 Nm^3 per kg VS added (Junne 2014). Sande et al. (2008) reports a biogas potential of 0.9 Nm^3/kg VS destroyed, which would be the equivalent of 0.53 Nm^3/kg VS added.

The commercial food waste is generated generally by restaurants, and according to Rogoff & Screve (2011) the generated waste has much of the same properties to food waste generated in the household sector. Therefore similar nutrient levels to household food waste is assumed as according by Modahl et al. (2015) at 3.8 kg P per ton DM and 21.8 kg N per ton DM.

2.3.3. Cooking oil

Cooking oil defines as the leftover from use of vegetable oils for cooking; here examples can rapeseed oil and olive oil. The DM content of the cooking oil is around 95%, with a VS content at 90% (Purac AB 2011; Sande & Seim 2011). The HHV of the vegetable oil is 39.3 MJ/kg (Wirsenius 2000) and the biogas production is assumed 0.9 Nm^3/kg of VS destroyed (Purac AB 2011; Sande & Seim 2011).

2.3.4. Glycol

Propylene glycol is an odourless and colourless liquid, utilised to defreeze airplanes before take-off, and as preventing treatment of airplanes on the ground (Avinor 2013). The utilisation of glycol happens in a manner to minimise the off-run of glycol and prevent any damage on nature. The HHV assumed for glycol is 18 MJ/kg waste (Wirsenius 2000) this is assumed for non-eatable stimulants, this assumption is done on the basis of lack of information, however according to Sande et al. (2008) the biogas potential of glycol is 100 Nm^3/ton input, here assumed with a glycol content of 10%, used as DM content. Furthermore, the glycol is reduced to nothing, thus not contributing to mass in the bioresidual (Akervold 2015a).

2.3.5. Grease waste

Grease trap sludge. Grease waste from grease separators at wastewater treatment plants. The DM content of the grease is around 10%, with a VS content at 60% (Purac AB 2011; Sande & Seim 2011). The HHV of grease is 37.3 MJ/kg waste (Wirsenius 2000), furthermore the biogas production from grease waste is 0.9 Nm^3/kg VS destroyed (Purac AB 2011; Sande & Seim 2011). The grease waste contains some nutrients as according to Modahl et al. (2015) is at 3.8 kg P per ton DM and 16 kg N per ton DM.

2.3.6. Manure

Animal manure has possible the largest theoretical potential when it comes to biogas production in Norway, it has a theoretical potential of circa 2.5 TWh, which is just under half of the total theoretical potential for Norway (Raadal et al. 2008). Animal manure is a great substance to stabilise the process around the anaerobic digestion, it also contains allot of valuable nutrients for the biofertiliser product, these nutrients come from the feed they are given and it is important to recover and reuse them, manure is often called the “black gold” of the farmers (Carlsson et al. 2009).

2.3.7. Other feedstock substrates

Of other feedstock substrates, energy crops and crops residues can be mentioned (Normak et al. 2011). As for energy crops it is meant as energy crops grown specifically for the purpose of biogas production, or dedicated energy crops (DEC, Seadi et al. 2008). Examples here can be grass, maize, raps even wood crops, which would then need some extra treatment, in for of delignification, before the anaerobic digestion process.

2.3.8. Co-digestion

The speed of downgrading of material can vary allot, this depends much on the different substances used in anaerobic digestion process. How much pretreatment in form of separation and splitting of pieces has a lot to say, the biogas output could be increased by co-digestion, thusly called positive co-digestion effect (Carlsson et al. 2009).

Co-digestion is a good way to increase the biogas yield of the biogas process, there can be several combinations, and not all will give an increase. As reported by Silvestre et al. (2011) the use of grease waste might give an increase of up to 138% when the grease waste was 23% of the total VS. Other benefits in biogas yield can be found with a thermophilic process, as suggested by Cavinato et al. (2013), would be the best for treating a mix of sewage sludge and bio-waste, where improvements of 45-50% were identified.

2.4. Emissions

Compost

During compost of organic waste, there are some related emissions from conversion of N, here the same values assumes for sewage sludge that undergoes compost. Bernstad & la Cour Jansen (2011) informs, according to Chung (2007), which during compost there is a total loss of N at 42%, whereof 96% turns into NH_3, 1.4% turns into N_2O and lastly 2.6% turns into N_2. When it comes to CH4 emissions, conditions informed by Amon et al. (2006) is assumed, which gives a total of 1344.6 g CH4/m3 compost.

Storage of bioresidual

During the post-treatment of the bioresidual it is important to store the residues due to methane emissions from this stage, and the control of this can also increase the biogas efficiency of the overall plant (Normak et al. 2011). The bioresidual should also be stored in covered tanks in order to minimise the release of ammonia through evaporation. The higher the temperature in storage tank is, the higher is the risk of nitrogen in the bioresidual to be lost as ammonia, thus contributing to harmful emissions and reducing the important levels of nitrogen in the bioresidual if to be used as fertiliser.

Emissions regarding N are assumed to be the same as in **Compost**, with the same loss and separation between the emissions, and further as given by Amon et al. (2006), the separation between storage and application is assumed, where storage has 4%, 91% and 99.9% of the emissions from NH_3, N_2O and N_2 respectively.

According to Bernstad & la Cour Jansen (2011), by Hansen et al. (2007), it is informed in a study that there is a methane loss of 0.08 Nm^3 of methane per ton digested food waste, similar is assumed for other feedstock as well and for open storage conditions. Further, as informed by Normak et al. (2011) there is a 65% reduction in methane loss from storage if stored in a closed tank. Thus, ending up with an emission of 0.028 Nm^3 CH4/ton digested waste from closed storage tanks. However, Amon et al. (2006) informs of a CH_4 emission of 1344.6 g CH_4/m3 bioresidual, similar emission is assumed, with a separation of 99.9% of the emission coming from storage.

Application of bioresidual

Amon et al. (2006) informs of an CH_4 emissions of 2 mg CH_4/L of applied bioresidual, further it is informed by Dieterich et al. (2012) that total CH_4 emissions from application of bioresidual varies from 7.3 – 11.5 mg CH_4/L applied bioresidual. Dieterich et al. (2012) further argues that another emission level of around 4 mg CH_4/L applied bioresidual, from Wulf et al. (2002), was found and that it is not clear if the full extent of the emissions are taken into account.

However as mentioned in **Storage of bioresidual** by Amon et al. (2006), with an emission of 1344.6 g CH_4/m3 bioresidual, similar conditions are assumed and thusly the total CH_4 emission from application will be 0.1% of the total methane emission from storage and application. Further for emissions regarding N, as mentioned in **Storage of bioresidual**, the emission separation is 96%, 9% and 0.001% for NH_3, N_2O and N_2 respectively.

Upgrading emission

Emissions related to the upgrading technologies varies as stated in chapter 2.1.3 Post-treatments, where the emissions of methane from upgrading varies from 0.06 to a couple of percent (Bauer et al. 2013; Normak et al. 2011). Further details about the emissions from different upgrading technologies are found in chapter 2.1.3 Post-Treatments, Upgrade of biogas to biomethane.

2.5. End-product use and benefits

According to the background report for increase of biogas-utilisation by Sletten & Maass (2013) there are three ways that production and use of biogas will reduce the emissions of climate gases. The first is that the anaerobic process and use of the produced biogas reduces the emissions from the aerobic process it replaces. The second is reduction in emissions from regular fuels when replaced by upgraded biogas. Thirdly, reduction of emissions from production and use of artificial fertiliser when replaced by the bioresidual.

2.5.1. Biogas and biomethane

For replacement of conventional fossil fuels, the best places are where the concentration of feedstock is large; this would mainly be concentrated around the larger cities around Norway. Today there are use of buses running on gas in Bergen, Fredrikstad, Oslo, Stavanger and Trondheim. Oslo and Fredrikstad are the only one that runs on biomethane, with Bergen in development (Sande et al. 2008). The replacement of the natural gas would not give the largest emission reductions considering similar properties; while when considering the emissions from biomethane are bionic CO_2 it would still represent a significant reduction. On the other hand, if one were to replace regular diesel buses there can possibly be a bonus added to the equation, the replacement of the diesel would represent a significant drop, but also reduction of emissions from animal manure, if in use. Thus representing a negative emission situation from the replacement of diesel, as represented in the figure below.

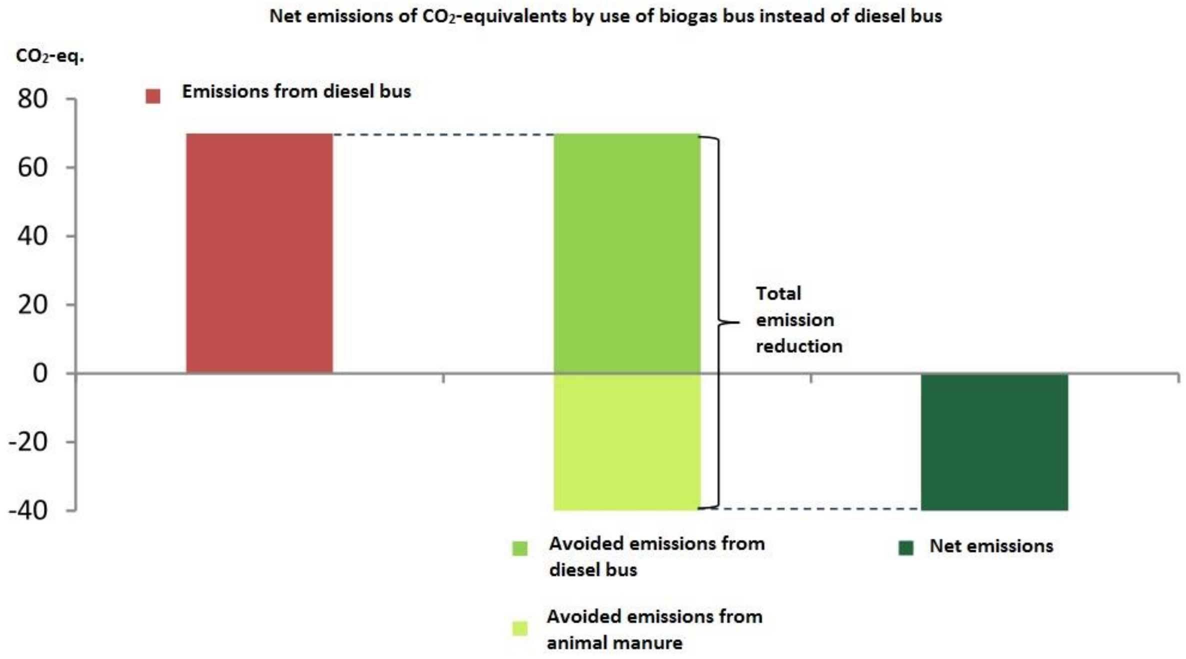


Figure 2: Example of how much emission is reduced by replacing diesel with biomethane (Sletten & Maass 2013).

Similar emission reduction as above could occur if utilising food waste for biogas production rather than open compost where there would be direct methane emissions from the compost site. However, it is more common that food waste goes to incineration with other organic waste and thusly biogas production from food waste does not alone contribute to reduction in emissions (Sletten & Maass 2013).

For Norway, as the electricity mix is more than 95% hydropower (NVE et al. n.d.), it would not be beneficial to utilise biogas for the production of electricity as there is per today no special price for such production. Most heating in homes happens via electricity or wood burning, and in several cities, there are municipal incineration plants delivering heat for industry and private/commercial buildings via heating grids. Most reports on biogas potential in Norway have concluded that because there is not much created per today that the best place to utilise the produced gas is in the transport sector, then for large vehicles such as buses in the public transport (Seadi et al. 2008; HOG Energi 2012). There are two cities today that utilises biomethane for fuel in the public transport, and that is Oslo and Fredrikstad, with Bergen now constructing a biogas plant with the purpose of producing their own fuel for the buses in the city (HOG Energi 2012; Sande et al. 2008; Svenskt Gastekniskt Center AB 2012).

2.5.2. Bioresidual

The leftovers from the biogas production is a nutrition rich mass called bioresidual. The use of this bioresidual will increase the overall efficiency and add to the emission reduction potential of the biogas utilisation.

The bioresidual, as mentioned, represent a potential source to reduce the use of chemical fertiliser, which production is energy intense, and reducing the demand will represent a reduction in energy consumption and emissions related. The use of bioresidual will mean some increase of transport and storage considering a lower nutrient concentration than chemical fertiliser does, however, in cases where manure applies directly, the farmer will have a more concentrated, and easier substance to transport with less runoff and emissions related to application. A potential emission reduction of ammonia of up to 62% can take place if manure is applied after anaerobic digestion (Tormod et al. 2010). Centralised biogas plants around farmlands would help the farmer do exactly so, and is what Greve Biogass in Vestfold, Norway is doing, and will be the plant in Scandinavia with the highest emission reduction per FU and will also upgrade the produced biogas to vehicle standard. Greve Biogass can possible get an emission reduction potential as the one shown in figure 2, and the plant will be done constructed sometime in the year 2015 (Greve Biogass n.d.).

An example for use of bioresidual is as upgraded biofertiliser, one producer of this is IVAR (n.d.), which is an inter-municipal water, sewage and renovation company for several municipals in Rogaland county. They have started production of a pellet type of biofertiliser from the bioresidual from their mesophilic anaerobic digestion process, where the bioresidual dries at 100°C for half an hour before turned into pellets. The biofertiliser produced contain 100% bioresidual from sewage sludge and stays within class 2 of heavy metal content (Forskrift om organisk gjødsel 2003; Grønn vekst n.d.). By the use of this method it is possible to increase the DM content to around 90%, which would mean that transport related to the biofertiliser is that much less compared to example 30% DM. Also informed is that even though the nutrient level is lower than chemical fertiliser, the organic content makes it attractive for areas that lack natural fertiliser (IVAR 2011).

Even though there are good potential uses for bioresidual as fertiliser or upgraded to biofertiliser, there are restrictions related to the heavy metal content and if sewage sludge is in the incoming feedstock. This means that, even though the bioresidual is a stabilised and homogenous product, restrictions fall upon it if containing sewage sludge.

First, according to § 25. Special demand for use of products containing sewage sludge (Forskrift om organisk gjødsel 2003), no products containing sewage sludge can be used for areas growing berries, fruit, vegetables or potatoes.

Table 2: Maximum values of heavy metals, according to § 10. Quality demand (Forskrift om organisk gjødsel 2003).

Quality classes (mg/kg DM)	**0**	**1**	**2**	**3**
Cadmium (Cd)	0	1	2	5
Lead (Pb)	40	60	80	200
Mercury (Hg)	0	1	3	5
Nickel (Ni)	20	30	50	80
Zinc (Zn)	150	400	800	1 500
Copper (Cu)	50	150	650	1 000
Chromium (Cr)	50	60	100	150

Further the level of heavy metals also limit the use of, see table above, § 27. Quality classes and areas for use (Forskrift om organisk gjødsel 2003) informs that class 0 can be used without restrictions for the use as fertiliser, while class 1 and 2 can be used only every 10 year and with limit on the amount used and the thickness of the layer, while class 3 cannot be used for agriculture. A problem around the bioresidual can arise when the main source is sewage sludge, meaning that the heavy metal levels of the bioresidual has to be by a certain standard.

2.6. State of the art utilisation in Norway

2.6.1. Present situation

Today there are still in use several biogas collection plants from landfills, where capturing of biogas produced from the decomposing waste is utilised. This seems as a good alternative for utilising existing landfills, but the utilisation percentage is low. According to "Underlagsmaterialet til tverrsektoriell biogass-strategi" by Sletten & Maass (2013), the utilisation rate in 2010 was circa 50 %, the reasons for this low percentage is that a lot of the gas is combusted directly and therefore gives no useful energy. Despite this low utilisation rate, it was still per 2010 the largest single production sector of biogas, even though it is not active production (Sletten & Maass 2013). For the active biogas production, it seems as most of the present plants are utilising sewage sludge for inputs, and most produce mainly heat, but also some electricity. Today around 60% of the energy produced via biogas is used internally as process energy, and the rest is used externally, either for heat, electricity, or transport, or by torching (Sletten & Maass 2013).

2.6.2. Future plans

The plans for biogas in the future focus mainly on manure and municipal solid wastes; it is a political goal that 30% percent of all animal manure in Norway to go through anaerobic digestion by 2020. This is a part of the Klimakur 2020, which is a document written by the Environment department in Norway with means to reach the emission goals for 2020, it also suggest a co-digestion with municipal solid waste (Klima- og Forurensingsdirektoratet 2010).

The total biogas production was per 2010 at 497 GWh, allocated among biogas production from sewage sludge, solid wastes (household and industry) and landfills. There are per 2012, 34 biogas plants in Norway, which also includes farm plant utilising animal manure. There are also 18 plants planned, where these plants represent more than a doubling of the 2012 capacity of biogas production (Sletten & Maass 2013), some of this potential is already realised as some of those plants are already built.

For use in transport, it is only Oslo and Fredrikstad that utilises upgraded biogas, biomethane, as fuel in the public transport sector; Bergen is soon to follow with its new biogas plant to be finished constructed in 2016 after some delays. Stavanger is today the only major city in Norway with a gas grid for both natural gas and biogas, the grid distributes gas for all purposes, such as heating and transport. The general trend is that biogas utilisation happens around larger cities, where it is also easier to get hold of larger amounts of raw material (Sletten & Maass 2013).

2.6.3. Means for increase in biogas utilisation

In the background study by Sletten & Maass (2013) for an increase in biogas-utilisation several means for increase in biogas use was identified. The means for increase divides into three categories and takes on wet organic waste and animal manure; the first measure is how to increase the access to the raw materials, the second is how to increase the biogas production and the last one is how to increase the biogas utilisation. A summary of the measures is shown in the below table.

Table 3: Summary of measures for increase of biogas-utilisation (Sletten & Maass 2013).

Increase the access of substrates	Legal means	Wet organic waste ▪ Sorting out of waste ▪ Ban on incineration ▪ Reduce exports
		Animal manure ▪ Forced delivery of manure to biogas plants ▪ Stricter demand for more environmental friendly storage and spreading of animal manure ▪ Demand of a certain mix of animal manure in biogas plants ▪ Put a roof on emissions from animal manure

	Economic means	Wet organic waste ▪ Tax on incineration if wet organic waste is not sorted
		Animal manure ▪ Pay farmers for delivering manure to biogas plants ▪ Support for separation of dry and liquid part of manure, if dry part goes to biogas plants ▪ Reward farmers for reduction in emissions from manure
	Informative means	Wet organic waste ▪ National goal of treatment
		Animal manure ▪ Inform farmers about biogas production and the positive effects
Increase the production of biogas	Economic means	▪ Investment support for biogas plants ▪ Subsidy on produced energy (NOK/kWh) ▪ Combination of investment and subsidy support ▪ Investments support for pretreatment facilities for wet organic waste ▪ Investment support for both biogas plants and pretreatment facilities ▪ Simplify the application procedure for economical support (Enova/Innovasjon Norge)
Increase the utilisation of biogas	Legal means	▪ Develop standards for biogas ▪ Demand of biogas sold to transport sector ▪ Make gas companies receive biogas if available ▪ Demand mixing of biomethane and natural gas ▪ Public stock of gas driven vehicles ▪ Demand collection of landfill gas ▪ Demand utilisation of landfill gas
	Economic means	▪ Increase the CO_2 tax on fossil fuels ▪ Consider exception of road tax on biomethane and perhaps natural gas ▪ Investment support for purchase of gas vehicles (private and/or taxi), fleet operation (e.g. transport company) and/or buses ▪ Investment support for construction of filling stations ▪ Investment support for exchanging oil burner for gas burner ▪ Feed-in tariff for biomethane at gas stations ▪ Taxes on natural gas unless a certain percentage of biomethane

3. Method

Answering of the master thesis is done by the use of a literature study on biogas production and relevant technologies, and by applying both LCA and MFA methodology on a specific case, Rådalen biogas plant, for the predicted situation of the year 2020. Further description of the case is found in chapter 3.7 “Case: Rådalen Biogas Plant”.

3.1. Literature study

Through the literature study, information about technologies and processes, etc. about biogas production has been found and listed in chapter 2 ”Theory”, with all the corresponding sources. Information bases mainly on international journal articles, reports done by science institutes in Norway and Sweden, and books on the subject. For Norwegian conditions, literature from Norway is utilised as far as possible.

3.2. Quantitative methods

3.2.1. Material flow analysis

Material flow analysis, MFA, is an assessment to measure flows and stocks of material, within a system defined in space and time (Brunner & Rechberger 2004b). MFA utilises the law of preservation - meaning there is a mass balance in the system - making it possible to see what a slight change in a flow within the system can do to the balance of the system. A MFA system gives a complete overview of all flows and stocks within the system; in a waste management system, all the flows of waste, water, and energy needs become visible, thus making it possible to identify their origin (Brunner & Rechberger 2004).

In MFA, there is a methodology, or common language, which one can build up the system upon. The first is material, which by definition stands for both the substance and the good, where substance is the type of matter and the good the substances with an economic value assigned to it. A process defines as where something is happening, production of a good, transport, etc. In the processes there are flows going in and out, which also links all the processes, here in mass per time. In the processes there are also a stock, this is a reservoir of material and is defined in mass unit, here kg.

The above definitions are confined in the system boundary that define the system; the system boundary can be anything from a country to a single house, as long as the system boundary is defined in all aspects. Below follows a simplification of a MFA system, with system boundary and with internal flows, and imports and export flows.

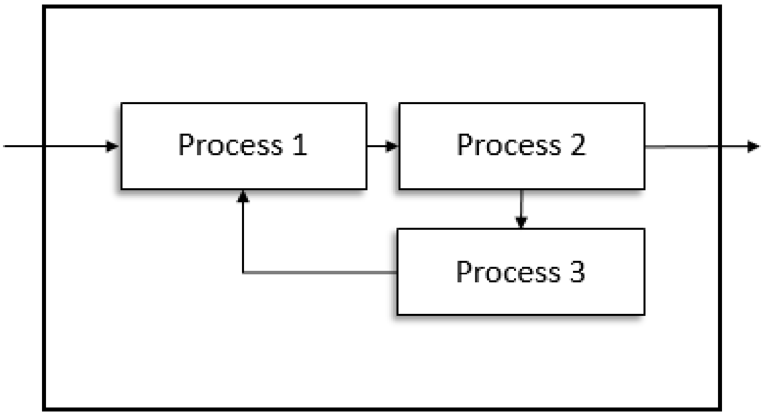


Figure 3: Simplified MFA system.

3.2.1.1. MFA general system

As stated in the description of the project assignment a quantifiable model for the value chain of the future biogas plant being constructed in Rådalen, Bergen. Based on MFA methodology and the theory in chapter 2, a general system for Bergen were made, see Figure 4. This gives a simplified overview of the system; as the plant is in construction, simplifications were made, and does not represent all aspects of the plant.

In the general system. The system definition includes the transportation of the substrates, waste from different processes as well as the bioresidual and the biogas. There are five main processes identified, they are as following:

- 6. Pretreatment
- 7. Hygienisation
- 8. Anaerobic digestion
- 9. Biogas upgrading
- 11. Bioresidual and reject

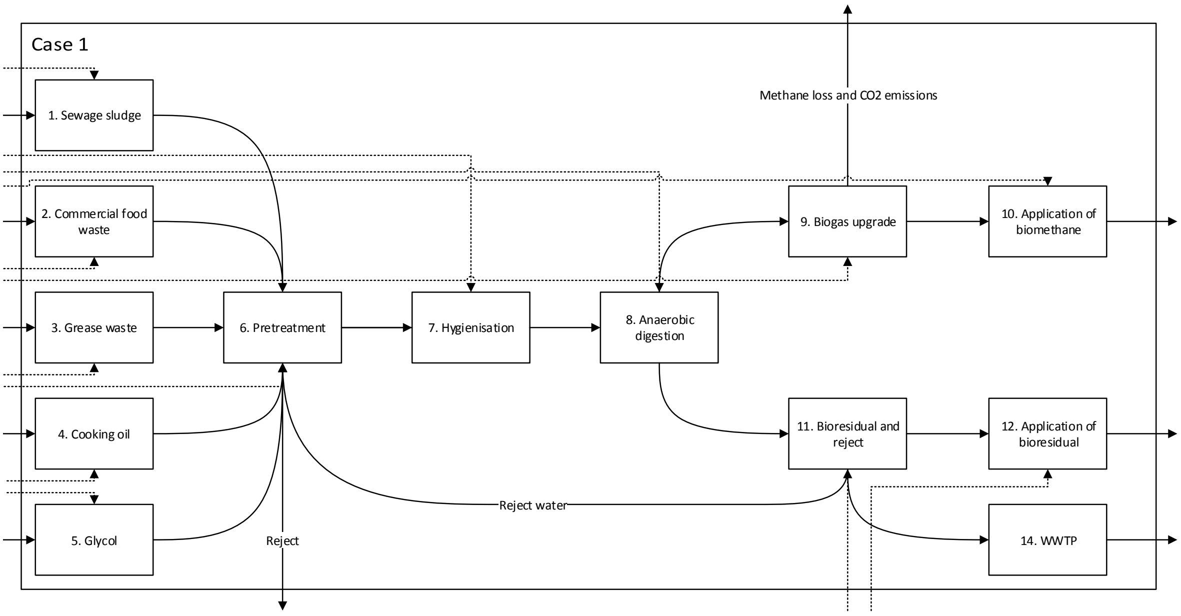


Figure 4: System of RBP for Case 1, whole lines are mass (dry and wet) and the dotted line is energy inputs (transport and process).

The calculations for the figure utilises DM feedstock and the DM percentage of each feedstock types in order to calculate the flows, further to be able to calculate the amounts of substrates going in to biogas production or to the bioresidual, parameters given for the DM and VS contents were utilised to find how much w.as able to be used in the biogas production (Sande et al. 2008; Purac AB 2011).

3.2.1.2. Resource- and energy efficiencies.

Based on the MFA system, the energy and resource efficiency, can be calculated through the formulas for energy efficiency and material rate of recovery, and shown in the basic formulas (1) and (2), and the nutrient efficiency

The energy efficiency, the nominator is all energy produced by the system, is calculated by outgoing energy divided by the denominator, all the input energies from the feedstock, transport and process.

$$\eta=\frac{E_{\text{fuel}}+E_{\text{Heat}}+E_{\text{el.}}}{\sum E_{\text{feedstock}}+\sum E_{\text{transport}}+\sum E_{\text{process}}} \qquad (1)$$

Material rate of recovery. The material rate of recovery defines as the outgoing mass in the numerator and the incoming mass in the denominator. The output mass refers to the bioresidual applied or the bottom- or fly ash.

$$\text{RR}=\frac{\text{Output Mass}}{\text{Input Mass}} \qquad (2)$$

Nutrient efficiency. The nutrient efficiency defines by the amount of plant available nutrient after spreading, can be defined much as the RR, and redefines as nutrient rate of recovery, NRR, as shown in formula (3).

$$\text{NRR}=\frac{\text{Output Nutrient}}{\text{Input Nutrient}} \qquad (3)$$

3.2.2. Life cycle assessment

LCA, life cycle assessment, or by another name "from cradle to grave", gives information about the environmental consequences and the consumption related to the products or systems looked at (Hauschild & Barlaz 2011). "The objective of a Life Cycle Assessment is generally to perform consistent comparisons of technological systems with respect to their environmental impacts" (Strømman 2010).

While LCA normally focus on the production and use phase with waste as a output from the system, while the primary focus for the waste management system is the end-of-life (Hauschild & Barlaz 2011). Two types, attributional- and consequential LCA, normally classify LCA. The attributional LCA seek to understand the environmental impacts directly connected to the products. While the consequential LCA seeks to describe the consequences from a change in the system, then aiming to support or not, a change to the system (Hauschild & Barlaz 2011).

The LCA procedure divides into four main phases; they are goal and scope definition, inventory analysis, impact assessment, and interpretation (Baumann & Tillman 2004).

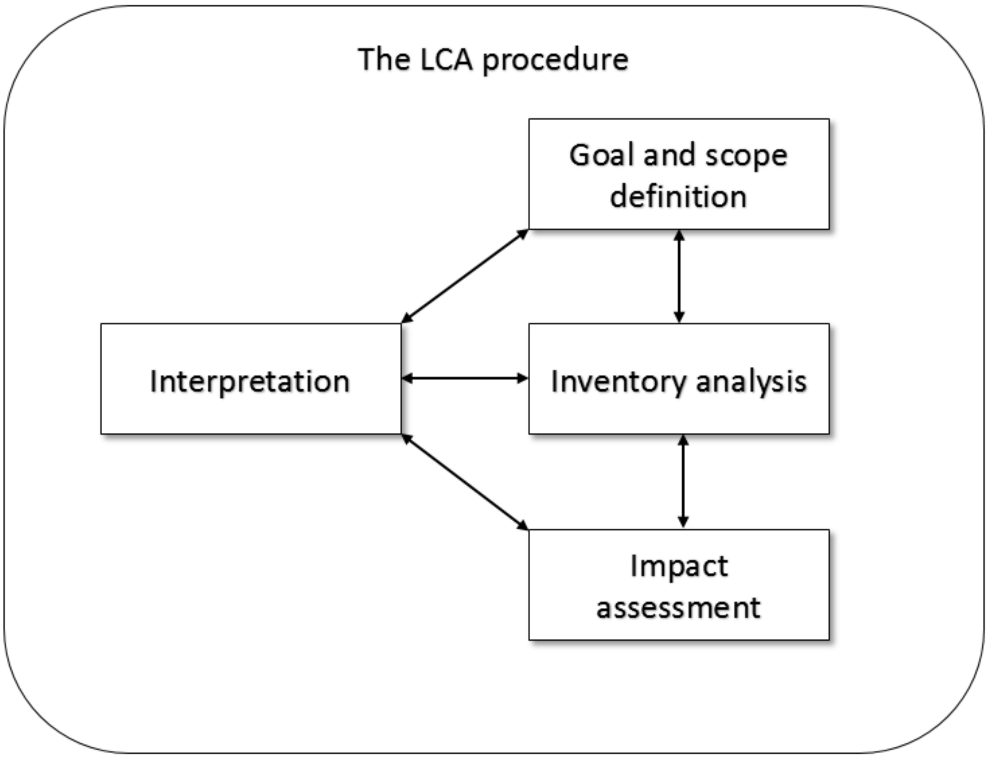


Figure 5: The procedure of LCA (Baumann & Tillman 2004).

Definition of the goal and scope. Goal defines the purpose of the study, for waste management the goal can be to compare different end-of-life treatments, hereunder biogas- and bio-soil production, and replacement of chemical fertiliser and natural gas (Hauschild & Barlaz 2011). Scope defines the object of the study hereunder the functional unit, other issues includes the boundaries of the system, timescale, technologies of the system, etc. (Hauschild & Barlaz 2011; Baumann & Tillman 2004).

Inventory analysis. The inventory is in basics a list of all the inputs and outputs going in and out of processes in the system defined (Hauschild & Barlaz 2011; Baumann & Tillman 2004).

Impact assessment. Any life cycle assessment is bound to have impacts related to its inputs and emissions. By doing the impact assessment one can interpret what the emissions related to the assessment have to say e.g. for human health, or the natural environment (Hauschild & Barlaz 2011; Baumann & Tillman 2004).

Interpretation. In this part, all the results are interpreted in consideration to the defined goal and definitions of the study, in this part the sensitivity analysis, the limitation of the study, and external review must be considered (Hauschild & Barlaz 2011; Baumann & Tillman 2004).

Functional Unit. The functional unit defines as function of a system, here the treatment of one ton DM content of organic matter. The main focus will then be the 1 ton DM of organic matter and everything related to the FU, however it is important that the FU is relevant for the system, and that it allows for comparison. Comparing different FU can be difficult as they might not have equal properties and so on, however this should not be an issue with the FU defined for the thesis (Baumann & Tillman 2004).

3.2.2.1. LCA general system

The system builds upon several assumption of how the system is set up, here especially the distances travelled for each of the substrates types, also as much information is lacking because the biogas plant is still under construction, thus much of the information assumed bases upon literature on the subject.

As mentioned in chapter 3.2.2 the goal defines the purpose of the study, and for waste management the end-of-life is the focus. The purpose of the LCA study is to discover the environmental impacts of the biogas plant under construction in Rådalen, Bergen. Hereunder the biogas production with upgrading and the use of the bioresidual, this is also compared to two other scenarios, which will be described further later in the chapter.

The first thing begun was to make an inventory list, here making a list of all the inputs and outputs going into and out of the processes defined for the system. The amounts of the different substrates are defined for year 2020.

Transport coefficients. The first to be calculated was the transport of the substances, here are a general setup for the transport of sewage sludge was already made, and used for the calculations, the average of the distances from the different WWTPs was used as the distance of the Septic's. The glycol had a set distance from Bergen Airport, while the other substances were unknown; here the distance assumed for commercial food waste and cooking oil are the distance from downtown Bergen and the biogas plant. Lastly, the septic and the grease trap waste comes from various locations, thereby the average of the sewage sludge collection it utilised. Retracing the premade calculations for transport were necessary for the proceeding work, the calculations bases on the amount of substrate moved each trip, how far and how many trips in a year. The transport coefficients are calculated in tkm, or ton kilometre, which defines the weight of the substance in question multiplied with the number of kilometre transported.

For the biomethane, a location was chosen 10 kilometre from the plant, here there are both a bus depot and a filling station for natural gas, which makes the location ideal. Distance for the bioresidual was chosen to be the distance to downtown Bergen where the assumed location for the use of the bioresidual.

Parameters. As many parameters as was given or could be made was taken from either the pre-project for the biogas plant, or the application to Energy fund (Sande et al. 2008; Sande & Seim 2011). Other parameters such as the energy needs or emissions in the different processes were taken from literature relevant to the study.

3.2.2.2. SimaPro

The LCA is being run in the program SimaPro Classroom 8.0.3.14 Multi user, this is a tool to collect, analyse and assess the environmental performance of a defined system, products or services. SimaPro utilises ecoinvent v3.01 and was compiled in October 2013, this was made into SimaPro format and thusly not all information from the ecoinvent v3 is available.

Via the SimaPro program Life Cycle Assessment is to be run, and by the use of ReCiPe Midpoint (H) method, where the H stands for the hierarchist version, and normalised for Europe.

In the SimaPro the systems defined for the master thesis was defined in the "Inventory", and separated into the "Processes" and "Parameters". In "Processes" the different processes is defined with the overall system of "Rådalen Biogas Plant" as a system under the category "Processing", here it was possible to define the different cases and the all the underlying processes needed for the different defined cases, where most parameters are written down and calculated in "Parameter" thus making it easy to fix and change parameters underway, see Appendix 8 for the entire parameter list from SimaPro, note that most of the parameters are the same as utilised in the MFA, however several calculations were made to be able to utilise the parameters and thusly not all the parameters are recognisable for the different methods.

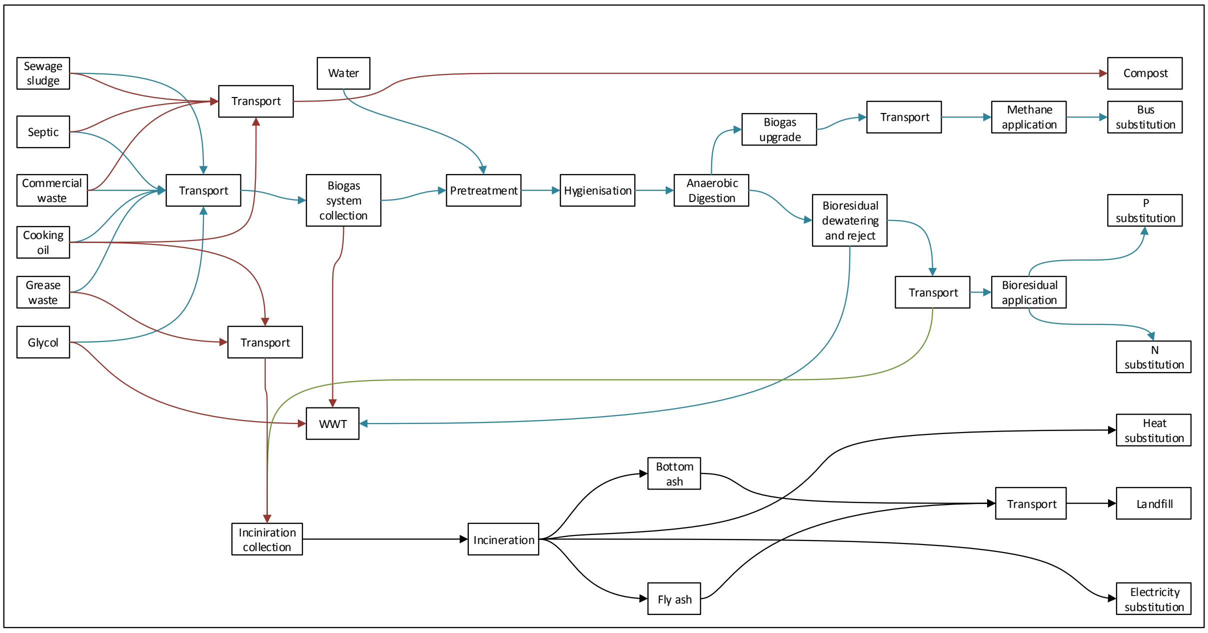


Figure 6: Basic LCA chart for all cases.

Above is the basic flowchart for the life cycle assessment used for all the cases, where different colours defines different cases; blue represent Case 1 and 3, and green the use of bioresidual for Case 2 and 4, red is Case 0 and the black is the incineration step for cases 0, 2 and 4.

3.2.3. Uncertainties

Uncertainties will always play a role for data used in analysis. The uncertainties can be connected to the collection of data, unavailable data or the models them self. Data related to specific cases realized is regarded as less uncertain, while for unrealized specific cases the data is regarded uncertain. This has to do with predictions done in the early planning stages of such projects, which based on empirical data, such as expected population growth to calculate the future output form WWTPs. Even before data is collected or received, it would be beneficial to evaluate the data, in order to evaluate the affects it might have on the result if changed. This then makes it possible to find more accuracy for the data with the highest impacts on the results. It is also desirable to approach the model as close to the actual case as possible in order to minimise uncertainties related.

3.3. Case: Rådalen Biogas Plant

The case study Rådalen biogas plant is located in Bergen, Norway. A simplification of the value chain is shown in figure 4. The Rådalen biogas plant is the newest addition in renewable energy production situated in Bergen, this biogas plant will mainly utilise treated sewage sludge from the city’s WWT plants, and this will represent the majority of the feedstock inputs. Other inputs are commercial food waste, grease waste, cooking oil and glycol.

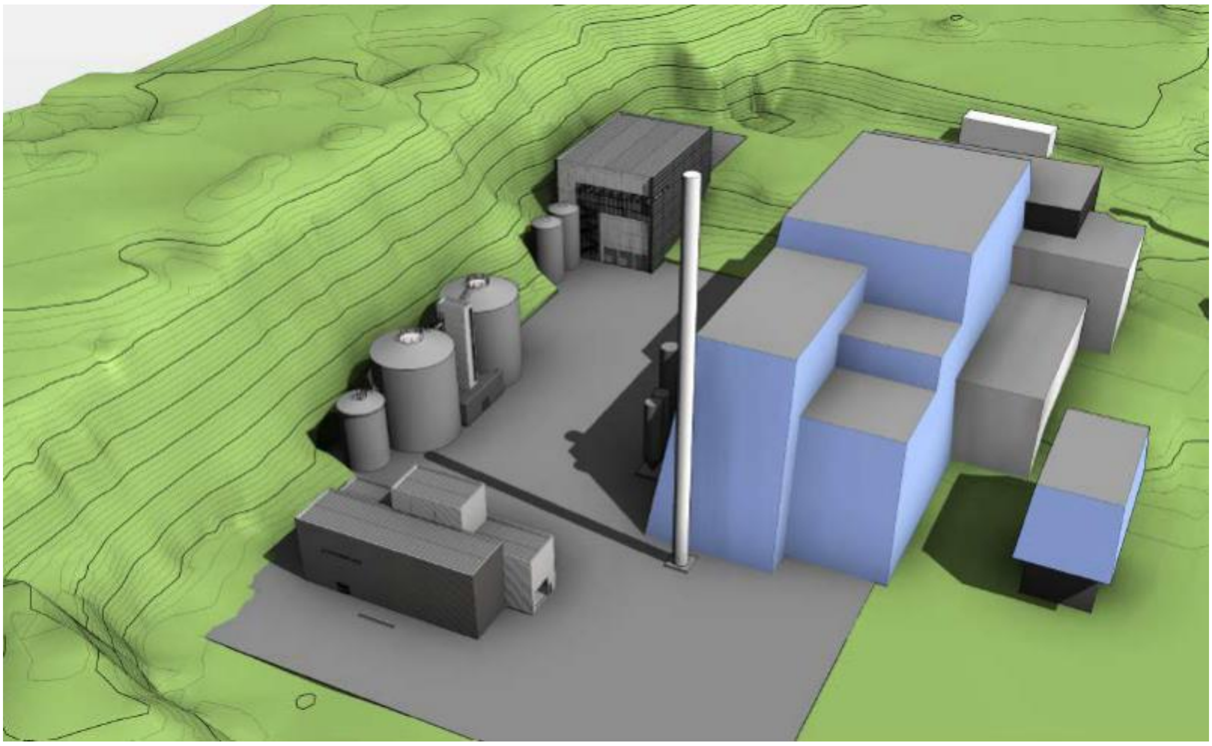


Figure 7: Rådalen Biogas Plant (left) and the Municipal Incineration Plant (right) (Akervold 2013).

Table 4: Assumed inputs for different years (Sande & Seim 2011).

Location/Feedstock	**Sewage type**	**2014** ton DM/year	**2015** ton DM/year	**2020** ton DM/year	**2025** ton DM/year	**2030** ton DM/year
Kvernevik	Biological	200	909	961	1 015	1 072
Ytre Sandviken	Biological	773	781	825	872	921
Flesland	Biological	-	2 623	2 771	2 927	3 092
Holen	Biological	-	1 606	1 696	1 792	1 893
Garnes	Biological	-	-	369	385	408
Knappen	Chemical	1 333	1 333	1 422	1 511	1 600
Septic		107	107	89	74	59
Commercial waste		750	750	813	875	938
Cooking oil		143	143	152	163	174
Grease waste		6	6	8	9	9
Total		**3 312**	**8 258**	**9 106**	**9 623**	**10 166**
Glycol (m3/year)		80	85	90	95	100

The table above shows the expected inputs of different feedstock over intervals of five years and lastly the assumed 100% capacity of the plant, as it will be constructed in round one, in year 2030. To be able to calculate the amounts of substrates going into biogas production or to the bioresidual, parameters given for the DM and VS contents were utilised to find how much w.as able to be used in the biogas production (Sande et al. 2008; Purac AB 2011).

The basing of the case is a biogas plant under construction in Rådalen, Bergen. The purpose of the plant is to produce upgraded biogas for local transport and preferably create bioresidual for the use as fertiliser. The location in Rådalen was chosen for its closeness to the municipal incineration plant that will deliver the process heat required, and to a treatment plant for septic, and the inputs for the year of 2020 is utilised.

3.3.1. Collection

Collection of all the substrates happens from several locations around the city, where collection of sewage sludge happens from all the upgraded sewage plants. Collection of biological sludge happens at Kvernevik, Ytre Sandviken, Flesland, Holen, and Garnes. Chemical sludge from Knappen and lastly septic is collected from various off-grid locations around Bergen. Commercial food waste and cooking oils assumes collected from downtown Bergen, glycol comes from the airport and grease waste collected from all the sewage sludge locations.

The plant receives mainly unstabilised sewage sludge, which consist of approximately 88% of the inputs while the other feedstock covers the rest. The plant however, designed to receive most types of feedstock, while it does not separate plastic, packaging, and foods such as hard vegetables.

Collection of the sewage sludge feedstock happens via two pockets for receiving, while the receiving of OIW, fats and cooking oil happens in a tank for liquid feedstock and lastly the receiving of glycol happens at a separated tank, where it can be fed either directly into the buffer tank or the bioresidual tank. For simplicity of calculations, the glycol assumes fed with the other substrates and the water content is used to water out the other incoming feedstock in the mixing tank. For septic, the feedstock is treated for non-organics such as sand before entering with the rest of the sewage sludge, the separation is uncertain, however 10% of the DM assumes to be separated out (Akervold 2015b).

Table 5: Feedstock, DM content, VS content and rate of destruction of matter (Sande & Seim 2011; Sande et al. 2008; Akervold 2015a).

Fraction	Feedstock [tons]	DM content [%]	VS [%]	AD efficiency [%]
Kvernevik [bio]	3 844	25 %	70 %	60 %
Ytre Sandviken [bio]	3 300	25 %	70 %	60 %
Flesland [bio]	11 084	25 %	70 %	60 %
Holen [bio]	6 784	25 %	70 %	60 %
Garnes [bio]	1 476	25 %	70 %	60 %
Knappen [Chem]	4 740	30 %	77 %	60 %
Septic	3 560	3 %	65 %	60 %
Commercial waste	3 252	25 %	85 %	60 %
Cooking oil	160	95 %	90 %	60 %
Grease waste	80	10 %	60 %	60 %
Glycol	900	10 %	100 %	100 %

To calculate the amount of substrates going to either biogas production or bioresidual, parameters for the DM- and VS contents and lastly the decomposition rate of the individual substrates were utilised in the system. To be able to calculate the amounts of substrates going in to biogas production or to the bioresidual, parameters given for the DM and VS contents were utilised to find how much w.as able to be used in the biogas production (Sande et al. 2008; Purac AB 2011).

3.3.2. Pretreatment

After collection of all incoming feedstock are through the collection process, the feedstock is lead into the buffer tank where mixing of all the feedstock happens. After the completion of the mixing, the mix is transferred to the pretreatment tank where the mix is diluted with reject water and preheated up to a temperature of 52 degrees Celsius, where the feedstock temperature is assumed 15 degrees Celsius and heat is recovered from the downstream processes until the temperature is reached.

After the homogenisation of the feedstock is completed, a step of hygienisation is done, where the feedstock is heated to 70 degrees Celsius for one hour. This is done to further break down the cell walls of the feedstock and to take care of any pathogens that might be in the feedstock, also the hygienisation takes care of any bacteria’s that might disrupt the balance of the culture in the digestion chambers.

3.3.3. Anaerobic digestion

After completion of the hygienisation step, the feedstock is transferred into the digestion chambers that run on parallel, with an expected efficiency of 60% decomposition of the VS content in the feedstock. However, the glycol assumes a complete decomposition of the VS, meaning that 100% of the DM is turned into biogas as the VS is assumed 100%. By doing, the hygienisation step before the AD process, any bacteria’s that might disturb the culture in the digestion chambers are taken care of, which also makes it possible to reduce the containment time in the chambers. Over time, it might also reduce the culture’s sensitivity to nitrogen inhibition and thus the reuse of reject water can increase.

3.3.4. Post-treatment and upgrade

The post treatment at the plant consist of two main processes; dewatering of bioresidual and the upgrade of biogas.

Bioresidual

The sludge form the anaerobic process is pumped via heat exchangers and cooled, and ending in a bioresidual buffer where it is stirred to keep sedimentation from happen. The dewatering of the bioresidual happens with the assist of centrifuges, which, expected, to manage a DM of 30%, and with a polymer need of 5 kg per ton DM entering the dewatering process. After dewatering of the bioresidual, a third party is supposed to collect the bioresidual continuously for further use. The third party is still unknown and thusly the transport distance for bioresidual to application assumes the average of transport distance for the feedstock, and no further treatment than the dewatering is included.

However, the plant supplier gives information about the storage of dewatered bioresidual; this is assumed process energy, only dislocated from Rådalen to wherever the bioresidual is going.

Further, from literature information is given on the spreading of bioresidual on farmland, here an electricity consumption at 3.18 kWh/ton DM and 0.73 kg diesel/ton DM (Hospido et al. 2005). As explained in chapter 2.4 about emissions from storage and application, the same parameters assumed here for the application of bioresidual and storage.

As mentioned before the bioresidual is nutrient rich and thus good as fertiliser or general soil-improvement. However, since the soil in western Norway is already nutrient rich and the agriculture bases mainly on animal husbandry and any necessary fertilising usually suffice by the use of manure. Which means that possible areas for the use of the bioresidual are most likely grain producers in the east of Norway or other locations, for example Europe. however, the requirements for the content of heavy metals may vary from country to country, so will the demand for bioresidual (Sande et al. 2008).

As mentioned in chapter 2.5.2 Bioresidual, IVAR is producing organic fertiliser from the sewage sludge from the WWT plant in Stavanger, which also could be a possibility for the party ending up with the bioresidual from the biogas production system.

Biomethane

According to the pre-project for the biogas plant in Rådalen by Sande et al. (2008), the use of the potential energy produced has been the main argument for the choice of anaerobic digestion as the waste treatment for the city's sewage sludge and other degradable organic matter intended for the plant.

Upgrading of biogas to biomethane happens onsite in Rådalen, and the chosen technology is water scrubber and the upgrade system deliverer is Malmberg (Akervold 2014), and the quality of the biomethane is 98±0.5% and maximum loss of 1%, as further described in chapter 2.2.3 Post-treatments.

Per today, there is around 80 buses running on natural gas, and there are filling stations around Bergen for CNG at the nearest bus depot for the public buses, as the biomethane has the same qualities it can replace or mix with the natural gas. Today GASNOR AS provide 2 million Nm^3 of natural gas each year, Sande et al. (2008) further predicts 2.4 million Nm^3 biomethane at yearly production, which might lead to an increase in the use of gas buses, the potential is based on predictions for year 2030.

3.3.5. Inventory

In this chapter follows the explanations around the inventory list used for the MFA and LCA done for the master thesis, with calculations and explanations. This chapter will show all the main calculations done, with reference to the parameter list shown in the appendix and all the inventory lists for the different cases.

Process energy

Process energy is defined by the process supplier, Purac AB, and was given by Kanders (2015) at Purac AB. In the information supplied the process energy, some processes were aggregated and also the information was defined for the year of 2030. This required some adjustments for the use of different machinery, thusly, process energy per machine calculates as following, as instructed by Kanders (2015) at Purac AB. The effect factor is defined at 80% and the usage of this factor is defined at 90% as the capacity factor, which is the feedstock capacity used of the total feedstock capacity of the plant. Further, the amount of hours each type of machine runs varies and defines from the calculations of hours, where the amount of days in use is multiplied with the daily use in hours to get the annual use. working hours used are; 8,400h, 6,000h, 2,000h, 1,000h and 250h. Below follows the basic calculation done for all processes, the Y is usually defines to 90%, however there are some processes that run on 50% of the X.

$$\text{Process} = ((kW*X)*Y)*h/year = kWh/year \tag{4}$$

kW = power of the machine
X = factor for the effect use [%]
Y = max use of X [%]
h/year = predefined use, max 8,400 h/year

In the following table shows the energy required in kWh per m3/ton or kg. This table however does not include all the process data included for the different cases, as some of the cases include incineration and so on.

Table 6: Process data.

Process energy		
Reject water to WWTP [sewage pipes]	0,36	[kWh/m3]
Commercial waste	8,59	[kWh/m3]
Glycol	5,64	[kWh/m3]
Grease waste and cooking oil	53,40	[kWh/m3]
Sludge	2,62	[kWh/m3]
Septic	6,64	[kWh/m3]
Heat [from Hygienisation]	57,20	[MJ/ton]
Heat [from AD]	105,60	[MJ/ton]
Heat [from Incineration plant]	79,20	[MJ/ton]
Hygienisation [aggregatet]	3,09	[kWh/m3]
Anaerobic digestion	1,55	[kWh/m3]
Bioresidual and reject	1,40	[kWh/m3]
Polymer	0,19	[kWh/kg]
Biogas system; biogas from AD to Biogas upgrading	0,01	[kWh/Nm3]
Biogas upgrading [corrected for per Nm3]	0,23	[kWh/Nm3]
Biomethane compression	0,22	[kWh/Nm3]
Biomethane tanking	0,11	[kWh/Nm3]
WWTP	1,10	[kWh/m3]

Reject water to WWTP. The energy required for sending water to WWTP are calculated by dividing the annual energy needed by the annual flow of water, which in the case of MFA will be, however for the LCA as described earlier, there cannot be a flow of reject to pretreatment as it would be looked at as a stock.

$$\text{Reject water to WWTP} = \frac{14{,}520\ \text{kWh/year}}{40{,}511.56\ \text{m}^3\text{/year}} = 0.36\ \text{kWh/m}^3 \qquad (5)$$

Thusly, the process of WWTP is utilised for all water separated from the dewatering process, and the water needed comes from tap water.

Pretreatment. This process includes all the process energy related to the input feedstock as shown in the following calculations.

$$\text{Commercial Food Waste} = \frac{27{,}936 \text{ kWh/year}}{3{,}252 \text{ m}^3\text{/year}} = 8.59 \text{ kWh/m}^3$$

$$\text{Glycol} = \frac{5.076 \text{ kWh/year}}{900 \text{ m}^3\text{/year}} = 5.64 \text{ kWh/m}^3$$

$$\text{Grease Waste and Cooking Oil} = \frac{12{,}816 \text{ kWh/year}}{240 \text{ m}^3\text{/year}} = 53.4 \text{ kWh/m}^3 \tag{6}$$

$$\text{Sewage Sludge} = \frac{81{,}900 \text{ kWh/year}}{31{,}228 \text{ m}^3\text{/year}} = 2.62 \text{ kWh/m}^3$$

$$\text{Septic} = \frac{23{,}652 \text{ kWh/year}}{3{,}560 \text{ m}^3\text{/year}} = 6.64 \text{ kWh/m}^3$$

This gives the individual energy demand, however, in the LCA the average of theses energy demands are used, where the annual energy demand is added together and divided by the total feedstock wet weight, thus giving 3.86 kWh/m^3 input into Pretreatment.

Heating of feedstock. The extra heating needed at the plant is supplied via the local incineration plant situated next door to the biogas plant, where the specific heating capacity of water is utilised to find the amount of energy needed, here calculated at 4.4 MJ/°C/ton (95% efficiency, Coultry et al. 2013). With this energy content it is possible to calculate the energy flows being reused from other processes and what is needed to cover the rest, this is done by multiplying the specific heating value by the amount of degrees reused or needed heating. Since the plant utilises heat exchangers, there is a limited amount of degrees having to be heated extra, by heat exchangers 37°C is preheated and with the assumed incoming temperature of 15°C, the feedstock is preheated to 42°C, and only 18°C is needed to be imported.

Hygienisation. The hygienisation energy is calculated with the total incoming wet feedstock, giving the following calculation

$$\text{Hygienisation} = \frac{473{,}558 \text{ kWh/year}}{153{,}118 \text{ m}^3\text{/year}} = 3.09 \text{ kWh/m}^3 \tag{7}$$

Anaerobic Digestion. The anaerobic digestion same as hygienisation uses the total wet feedstock, giving the following calculation

$$\text{Anaerbic Digestion} = \frac{237{,}082 \text{ kWh/year}}{153{,}118 \text{ m}^3\text{/year}} = 1.55 \text{ kWh/m}^3 \tag{8}$$

Bioresidual and reject. This process includes several processes aggregated, such as the dewatering, storage of wet and dry bioresidual and return of reject water into pretreatment.

$$\text{Bioresidual and Reject} = \frac{208{,}368 \text{ kWh/year}}{149{,}026 \text{ m}^3\text{/year}} = 1.40 \text{ kWh/m}^3 \tag{9}$$

Polymer. The polymer energy need calculates from the annual electricity requirement and divided by the annual use of polymer; this means that for the requirement of 5 kg polymer/ton DM the electricity need is 0.95 kWh in total for those 5 kg of polymer.

$$\text{Polymer} = \frac{4{,}848 \text{ kWh/year}}{25{,}594 \text{ kg/year}} = 0.19 \text{ kWh/kg} \tag{10}$$

Biogas system; biogas from AD to biogas upgrading. In this category is the transfer of biogas from the gas collection tank into the biogas upgrade process, and this process demands the following.

$$\text{Biogas System} = \frac{33{,}624 \text{ kWh/year}}{3{,}661{,}362 \text{ Nm}^3\text{/year}} = 0.01 \text{ Nm}^3\text{/year} \tag{11}$$

Biogas Upgrade, Compression and Tanking. The biogas upgrade uses water scrubbing, and the electricity demand per Nm^3 upgraded biogas is calculated via the averages of the different needs in the process, ending up with a need of 0.23 kWh/Nm^3 upgraded biogas and further the average water need per upgraded Nm^3 is utilised giving a need of 0.22 L/Nm^3 upgraded biogas.

The compression is the average of information supplied by Bauer et al. (2013), which adds up to 0.22 kWh/Nm^3 compressed biomethane to 200 bar pressure, and further the tanking is given at 0.11 kWh/Nm^3 as informed by Hung & Solli (2011).

Other energy inputs needed for processes. For the incineration process information from Suh & Rousseaux (2002) has been used, informed is that the incineration process demands 265 kWh/ton DM treated and that all of DM not VS is turned into bottom ash, further informed by Boesch et al. (2014) is that 10% of the matter turned into ash is fly ash.

The compost process has the following inputs as defined by Suh & Rousseaux (2002), with an electricity consumption of 30 kWh/ton DM for the storage process, and 8.4 kg diesel/ton DM for the spreading of the compost matter. For the land application of bioresidual however, as informed by Bernstad & la Cour Jansen (2011) there is a diesel consumption of 0.73 kg/ton DM and a electricity consumption of 3.18 kWh/ton DM.

Transport

For the transport parameters real distances are utilised as far as possible, this means the exact distances from all the WWT plants to the future biogas plant with the use of Google Maps, while for septic and grease waste the average distance of all the WWT plants are used. Glycol only comes from the airport, and lastly for cooking oil and commercial food waste the distance between Bergen downtown and Rådalen is used.

Transport energy is calculated through information about diesel consumption from SimaPro 8 about the type of transport chosen, given in diesel consumption per tkm, and the energy consumption is further calculated via the energy content per kg of diesel, where the LHV of diesel has been utilised.

The transport calculates into tkm for use in SimaPro and into MJ for the use in the MFA calculations, below is an example of the calculations done in order to find the mass of fuel needed for each distance, the calculation below is annual transport for the WWT plant Kvernevik.

$$\text{Location} = \text{WW*km} = \text{tkm * ton D/tkm} = \text{ton D * MJ/ton} = \text{MJ/year} \qquad (12)$$

WW = the transported weight of feedstock
km = the distances for different locations
ton D/tkm = the amount of diesel used per tkm
MJ/ton = the MJ content of 1 ton Diesel

For the situation today where sewage sludge is sent to compost, the distances varies, for the ease of calculation each location sends its waste 50/50 between the two locations, Sløvåg and Odda. The distance is drawn from each individual location; except for septic as the assumption that is still goes to Rådalen for dewatering before further transport, applies.

For the comparison cases situated in Sweden, the distances are longer, same method is applied, drawing the distance from each location til Gothenburg, Sweden. Septic and grease waste are still calculated as the average distance of the WWT plants, while cooking oil and commercial food waste is the distance between Bergen and Gothenburg. Glycol has the same distance as sewage sludge from the WWT plant located at Flesland.

For incineration cases, it is necessary with landfills for the bottom ash and the fly ash, as for fly ash there is a fixed location for hazardous waste, and that is Langøya in the Oslo fjord. Bottom ash also needs to be landfilled, here two locations are chosen; Mjeldstad Miljø for Bergen (BIR.no n.d.) and Tagene for Gothenburg (Richards 2011).

For transport of biomethane, a location for filling of natural gas situated at a local bus depot, and thusly this location were chosen for this transport distance, while for transport of bioresidual the distance between Rådalen and Bergen downtown was picked. The same assumptions of distance are used in the Gothenburg cases.

Bioresidual

The bioresidual from the biogas plant comes from mainly sewage sludge, which means there are potential of high levels of heavy metals in the bioresidual, the calculation of the bioresidual is done by subtracting the destroyed mass from the DM content. As shown in the following formula.

$$\text{Bioresidual}=\text{DM}_{\text{feedstock}}-(\text{VS}_{\text{content}}*\text{AD}_{\text{efficiency}}) \tag{13}$$

Further, the same formula assumes for all feedstock, where the VS content varies from feedstock to feedstock and the AD efficiency is the same all over. See Appendix 9 for further calculations in order to get the bioresidual.

Heavy metals

The heavy metal concentration goes through a similar formula, as the heavy metal is only in the organic mass, the concentration of heavy metal will increase with the destruction of matter. As shown in the following formula.

$$\text{New Concentration}=\text{Old Concentration}*(1-(\text{VS}_{\text{content}}*\text{AD}_{\text{efficiency}})) \tag{14}$$

This applies for all the feedstock with a heavy metal content, this will vary depending on it goes through the anaerobic digestion process or not, as the concentration will increase with reduction of the VS content (Paulsrud 2014). See appendix 10 for further description of the calculations.

Biogas and biomethane

The biogas production calculates via biogas production in Nm^3 per kg-destroyed matter, and the destroyed matter calculates via the efficiency of the AD process. As given by the system deliverer, 60% destruction of VS of all substances except glycol, which is 100% destroyed in the AD process.

Further to calculate the biomethane the average methane content of all substances has been utilised in order for this calculation, where the methane content has been multiplied with the percentage of the that feedstock of the total feedstock.

$$\text{Methane}_{\text{feedstock, tot}} = \sum_{\text{i = n feedstock}} \frac{\text{Methane}_{\text{feedstock, i}}*\text{DM}_{\text{feedstock, i}}}{\text{DM}_{\text{feedstock, tot}}} \text{ where,} \tag{15}$$

$\text{Methane}_{\text{feedstock, i}}$ = methane content of n feedstock
$\text{DM}_{\text{feedstock, i}}$ = DM content of n feedstock

When utilising the calculated methane content of the biogas produced, this will give a number in 100% methane, as the upgrade process gives 98% purity and 1% methane loss, the 1% loss subtracts from the total methane production and the remaining multiplies with 98% to get the correct purity. The biomethane production further multiplies with the energy content of pure methane, giving the total energy potential of the system. See Appendix 9 for the biogas production (same as for the bioresidual).

3.4. Sensitivity analysis

The purpose of a sensitivity analysis is to test what different parameters of the system has to say on the results, thusly testing the different assumptions and variations made for the different cases and also for the input values given.

A common method, and the chosen method of doing sensitivity analysis is to change one parameter at a time. Meaning that when one parameter is changed from original value, the other remain original, and thusly it is possible to see how a change in one parameter can affect the system results (Baumann & Tillman 2004).

3.4.1. MFA

For the MFA parameters looked into is the incoming substance, this is predictions made for every five year, meaning that the information given for the inputs are given in annual ton DM input, and thusly the input parameter will be tested, here including all the different locations of sewage sludge, as the amount of sludge from each location varies. The variation is set to ±15% from the original value, also included are the production of biogas and the bioresidual as this includes in the results related to the MFA, here also is the transport distances and the process energy. For the biogas production the efficiency of the AD process is analysed, because this will also affect the production of bioresidual, and further the need for transport of biomethane and bioresidual, here with a change in value of also ±15% from the original value. Transport will be tested for Bioresidual and Biomethane at +50%, while for Cooking oil and Commercial waste at +30%, as the probability of these distances being shorter are low.

3.4.2. LCA

For the parameters used in the LCA some are chosen, they are the purity of the biomethane and the loss of methane from upgrade and the efficiency of the AD process. Transport distances tested in the MFA will also be the same for the LCA sensitivity analysis, also added for testing is the bus substitution, which is handled as personkm, with a +50% variation on the original value. The main impact category looked at is the GWP, and the main focus of testing of the parameters are made for the testing of the GWP of the system, however the other impact categories chosen will be looked at due to expected sensitivity.

4. Results

4.1. Material flow analysis

4.1.1. Quantitative results

For the determinations of the mass flows in the MFA system, the flows are found via mass balance and equations for the different flows. This is done for the system defined in the methodology, chapter 3.2.1.1, only flows for the DM contents are considered, however there are some flows that are included for the mass balance of the wet system. The MFA takes on the main processes at sight, meaning the collection, pretreatment, hygienisation, AD process, dewatering and the upgrade of the biogas. Focus of the MFA results will be Case 1, with upgrade of biogas and utilisation of the bioresidual.

In the figure above follows the flows of mass from Case 1, which is the case most representative to the system of the future. It includes only the flows of mass and water, including the mass from "Emission to air", here methane and carbon dioxide from upgrade.

The following figures shows the flows for mass, both the DM and for the wet flows and the last shows the energy flows. In the tables below, follows the mass balance and the energy balance of Case 1. In the first table, the mass balance, the flows shown in tons/year, which includes water content and emissions from nutrients, methane and carbon dioxide, and a second column with the same flows in only DM content of tons/year. Table 7 shows the flows used to calculate the RR for the system of RBP, more information about the flows can be seen in the inventory for Case 1 in Appendix 3.

Table 7: Mass and DM flows of the RBP system.

Flow	Mass flow	Total mass (ton/year)	DM flow	Total DM (ton/year)
Sewage sludge to pretreatment	X_1,6	34 788	DM_1,6	8 124
Commercial food waste to pretreatment	X_2,6	3 252	DM_2,6	813
Grease waste to pretreatment	X_3,6	160	DM_3,6	152
Cooking oil to pretreatment	X_4,6	80	DM_4,6	8
Glycol to pretreatment	X_5,6	900	DM_5,6	90
		22 461		
Pretreatment to hygienisation	X_6,7	39 180	DM_6,7	9 187
Hygienisation anaerobic digestion	X_7,8	153 118	DM_7,8	9 187
Anaerobic digestion to N&P loss	X_8,0	34	DM_8,8	34
Anaerobic digestion to biogas upgrade	X_8,9	4 058	DM_8,9	
Anaerobic digestion to bioresidual and recject	X_8,11	149 026	DM_8,11	5 095
Biogas upgrade to methane loss and CO2 emissions	X_9,0	2 329	DM_9,0	
Biogas upgrade to application of biomethane	X_9,10	1 729	DM_9,10	
Bioresidual and reject to pretreatment	X_11,6	91 478	DM_11,14	
Bioresidual and reject to application of bioresidual	X_11,12	17 006	DM_11,12	5 038
Application of bioresidual to emissions of N and CH4	X_12,0	57	DM_12,0	57
Bioresidual and reject to WWTP	X_11,14	40 486	DM_11,6	

The largest single flow that also includes DM content is the Sewage sludge, and together with the other incoming feedstock water via reject and tap water is added to dilute the mix to the largest flow of (X_7,8) at 153,118 tons, this is the incoming feedstock with a DM content at 6%.

Table 9 shows all the energy flows given in MJ per year, and relates to feedstock energy content in the HHV, all the process energy, both electricity and heat, and the transport energy related to all transport needed for Case 1. Information given in the table are aggregated and might not be recognisable. The HHV used for the feedstock is defined in the table below.

Table 8: HHV utilised.

Feedstock	MJ/ton DM	
Sewage sludge	25 700	[1]
Commercial waste	18 500	[2]
Cooking oil	39 300	[2]
Grease waste	37 300	[2]
Glycol	18 000	[2]

[1] Trinh et al. (2013)

[2] Wirsenius (2000)

Table 9: Energy flows of Case 1.

Flow	Energy flow	Total energy (MJ/year)
Feedstock transport into pretreatment	E_0,6	583 964
Process energy for collection of feedstock [aggregated]	E_0,6	544 968
Sewage sludge to pretreatment	E_1,6	208 789 370
Commercial food waste to pretreatment	E_2,6	15 040 500
Grease waste to pretreatment	E_3,6	5 973 600
Cooking oil to pretreatment	E_4,6	298 400
Glycol to pretreatment	E_5,6	1 620 000
Process energy for pretreatment [aggregated]	E_0,6	11 399 354
Pretreatment to hygienisation	E_6,7	231 721 870
Process energy for hygienisation	E_0,7	1 704 810
Hygienisation to anaerobic digestion	E_7,8	231 721 870
Process energy for anaerobic digestion	E_0,8	853 494
Anaerobic digestion to biogas upgrade	E_8,9	85 848 894
Process energy for biogas upgrade	E_0,9	121 046
Biogas upgrade to methane loss and CO2 emissions	E_9,0	4 240 935
Biogas upgrade to application of biomethane	E_9,10	81 607 959
Process energy for application of biomethane	E_0,10	3 031 608
Biomethane transport to application of biomethane	E_9,10	15 928
Process energy for bioresidual and reject	E_0,11	750 296
Process energy for WWTP	E_0,11	52 272
Anaerobic digestion to bioresidual and recject	E_9,11	141 632 040
Process energy for application of bioresidual	E_0,12	195 720
Bioresidual transport to application of bioresidual	E_0,12	305 801
Bioresidual and reject to application of bioresidual	E_11,12	141 632 040

The energy efficiency of the system is calculated via these flows and provides an estimate of how well the system perform with regard to energy. The table includes all process and transport flows, which are included as flow from 0 to the process it is going to, this will be further used for the energy efficiency of the system.

4.1.2. Energy- and resource efficiencies

When including the specific energy flows from the MFA system of the different cases, the following two versions of the energy efficiency is given.

$$\eta=\frac{E\_methane}{E\_feedstock+E\_transport+E\_process} \tag{16}$$

$$\eta=\frac{E\_methane+E\_heat+E\_el.}{E\_feedstock+E\_transport+E\_process} \tag{17}$$

When including the specific flow of DM in the MFA system based on the different cases, two main versions of the formula identifies.

$$RR=\frac{DM_{digestate}}{DM_{feedstock}} \tag{18}$$

$$RR=\frac{DM_{bottom\ ash}+DM_{fly\ ash}}{DM_{feedstock}} \tag{19}$$

Following below is the numbers used for the RR and η for Case 1, where there is a recovery rate of 54.21% of the incoming DM content, this means that 44.79% is turned into biogas or lost to the surroundings when treated in the system.

Table 10: RR calculations for Case 1.

Material rate of recovery		
Flow name	**DM_i.j**	**ton DM/year**
Kvernevik [bio]	DM_1,6	961
Ytre Sandviken [bio]	DM_1,6	825
Flesland [bio]	DM_1,6	2 771
Holen [bio]	DM_1,6	1 696
Garnes [bio]	DM_1,6	369
Knappen [Chem]	DM_1,6	1 422
Septic	DM_1,6	80
Commercial waste	DM_2,6	813
Cooking oil	DM_3,6	152
Grease waste	DM_4,6	8
Glycol	DM_5,6	90
Bioresidual	DM_11,12	4 980
Material rate of recovery	**RR**	**54,21 %**

While for the energy efficiency 32.23% is recovered as usable energy, the rest is lost or bound in the bioresidual, and not available for energy usage. Several of the energy flows are aggregated in the table, thus the # sign is used for this purpose.

Table 11: η calculations for Case 1.

Energy efficiency		
Flow name	**E_i.j**	**MJ/year**
Substrate flow	DM_#,6	231 721 870
Transport flow	DM_#,#	903 856
Process flow	DM_#,#	18 653 567
Biomethane	E_9,6	80 984 747
Energy efficiency	**η**	**32,23 %**

The results of energy- and resource efficiency for all cases are shown below, for energy efficiency the higher the better, while for resource efficiency, depending on the qualities of the output mass, the lower the better.

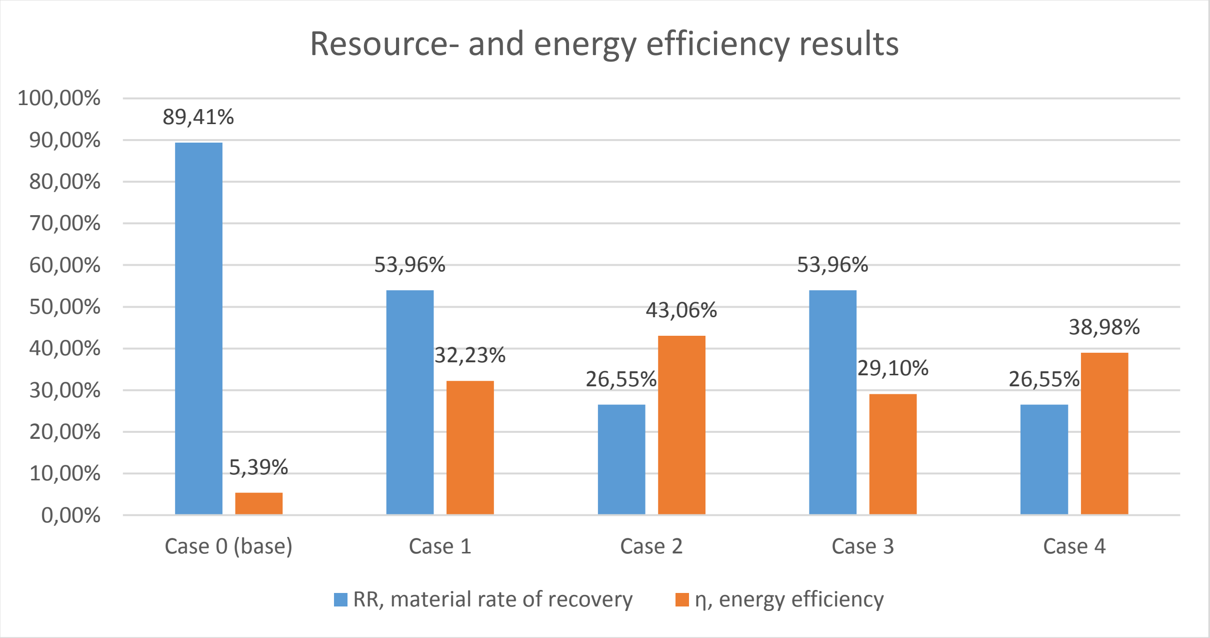


Figure 8: Efficiency rates.

Case 0 assumes compost of the sewage sludge, as this is the main input the material recovery rate is high, because no matter is reduced, and still in circulation. Case 1 and 3 has the same utilisation of the organic matter and since biogas is produced the RR is somewhat lower. Cases 2 and 4 has the lowest RR, here biogas is produced and the bioresidual is incinerated and thus the RR is further reduced.

The energy efficiency is another matter, Case 0 has the lowest efficiency due to the fact it only utilises a small fraction of feedstock available for energy purpose and still needs a lot of energy. Energy efficiency is highest in cases 2 and 4, and sees in connection with the energy utilisation of the bioresidual, case 4 is somewhat lower due to much larger transport distances. Lastly, cases 1 and 3 are among the lowest, where case 3 is lowest due to the much larger transport distances. Overall, Case 2 performs the best in both RR and energy efficiency.

4.1.3. Nutrient efficiency

In the following formulas are the variations of the NRR formula, here separated into both nitrogen and phosphorus.

$$\mathrm{NR} = \frac{\mathrm{N}_{\mathrm{feedstock}}}{\mathrm{N}_{\mathrm{bioresidual,\ platnavailable}}} \tag{8}$$

$$\mathrm{PR} = \frac{\mathrm{P}_{\mathrm{feedstock}}}{\mathrm{P}_{\mathrm{bioresidual,\ platnavailable}}} \tag{9}$$

In the figure below the results for nutrient recovery are shown, some cases does not have any recovery of nutrients, this is because in situations of incineration the nutrients are considered lost as they will follow the bottom- and fly ash to landfill. In Case 0, the sewage sludge goes to compost, where it will later be used for example as filling for roads and similar, and does not available for utilisation.

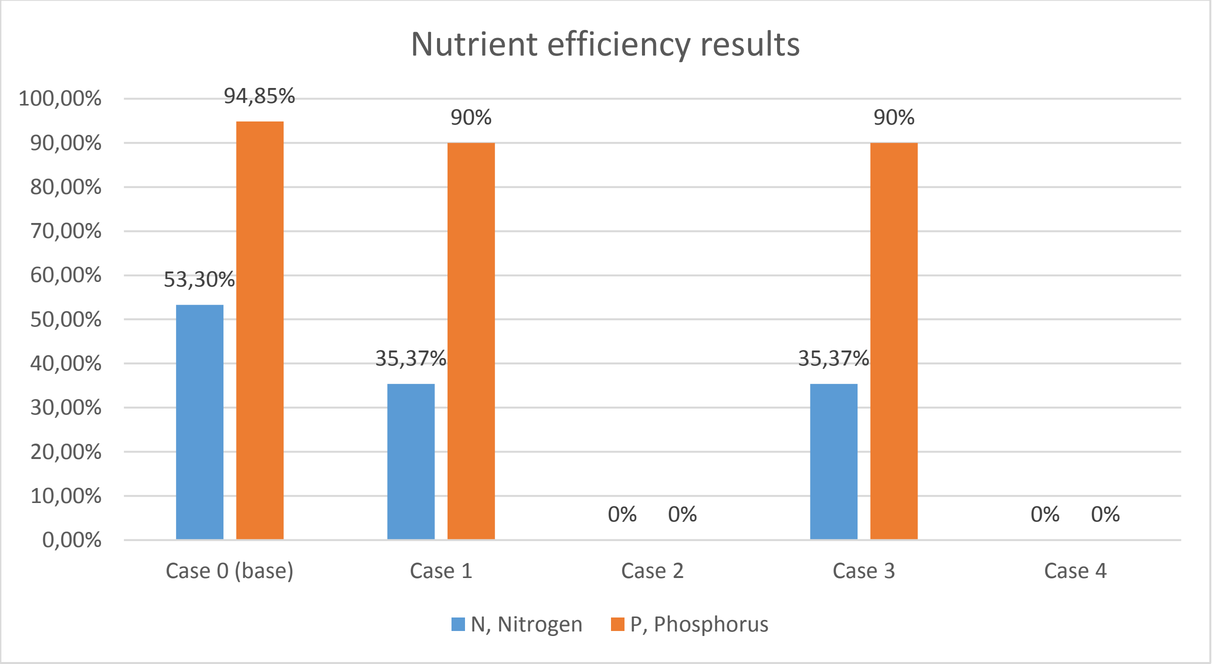


Figure 9: Recovery rates for nutrients.

The reason for the difference in the amount if nutrients are the different loss parameters utilised for the results, take phosphorus, there is only reported of one loss, from the anaerobic digestion, where 10% is lost, further losses are not given, and since phosphorus is a mineral it follows the mass throughout. The nitrogen however, has several losses, the first is in the anaerobic digestion process, where 13% assumes lost, some of the nitrogen is separated with the reject water going either to pretreatment or to WWTP, then further in the storage and application process where circa 42% is lost as emissions to air, further this efficiency does not account for what is plant available. From the table its shows that Case 0 has the highest recovery rates and Cases 1 and 3 have the same, Case 0 does not utilise the nutrients for agriculture application and thusly assumes zero recovery rate, cases 1 and 3 has the same process system and use of bioresidual and thus the same rates. Lastly, cases 2 and 4 assumes the same system as 1 and 3, however as the bioresidual is incinerated and the nutrients assumes lost in this process the recovery rates are defined as zero. Overall, cases 1 and 3 perform the same and best for nutrient recovery.

4.2. Life cycle assessment

4.2.1. Quantitative flows

For the system of treating the FU of 1-ton DM sewage sludge and organic waste, five cases identified to be of interest. There are in basic three cases, where all are compared to the “Business as usual 2020” while there are two cases per location in order to compare different substitution effects of the system.

Table 12: Process comparison between cases.

Process	Variations analysed				
	Case 0 (base)	Case 1	Case 2	Case 3	Case 4
Transport feedstock	x	x	x	x	x
Compost	x				
Pretreatment		x	x	x	x
Hygienisation		x	x	x	x
Anaerobic Digestion		x	x	x	x
Methane <98% CH4		x	x	x	x
Transport Biomethane		x	x	x	x
Dry bioresidual		x		x	
Transport Bioresidual		x		x	
Incineration	x		x		x
Bottom ash	x		x		x
Fly ash	x		x		x
Transport Ash	x		x		x
WWTP	x	x	x	x	x
P2O5 substitution		x		x	
Nitrogen substitution		x		x	
Bus substitution		x	x	x	x
Heat substitution	x		x		x
Electricity substitution	x		x		x

Business as usual 2020

Case 0 is the continuation of the system of today, this means that the upgrades for all the WWT plants are completed and sewage sludge is still delivered for compost at either Sløvåg or Odda, were a 50/50 separation from each delivery site is assumed. Glycol from defrosting of airplanes are collected after use and sent true the local WWT plant situated at Flesland, while the other organic industrial waste including commercial food waste are collected for incineration at the municipal incineration plant in Rådalen. This case produces some heat and electricity from the incineration of the feedstock going through the incineration process, and thusly some substitution of heat and electricity takes place, see Appendix 2.

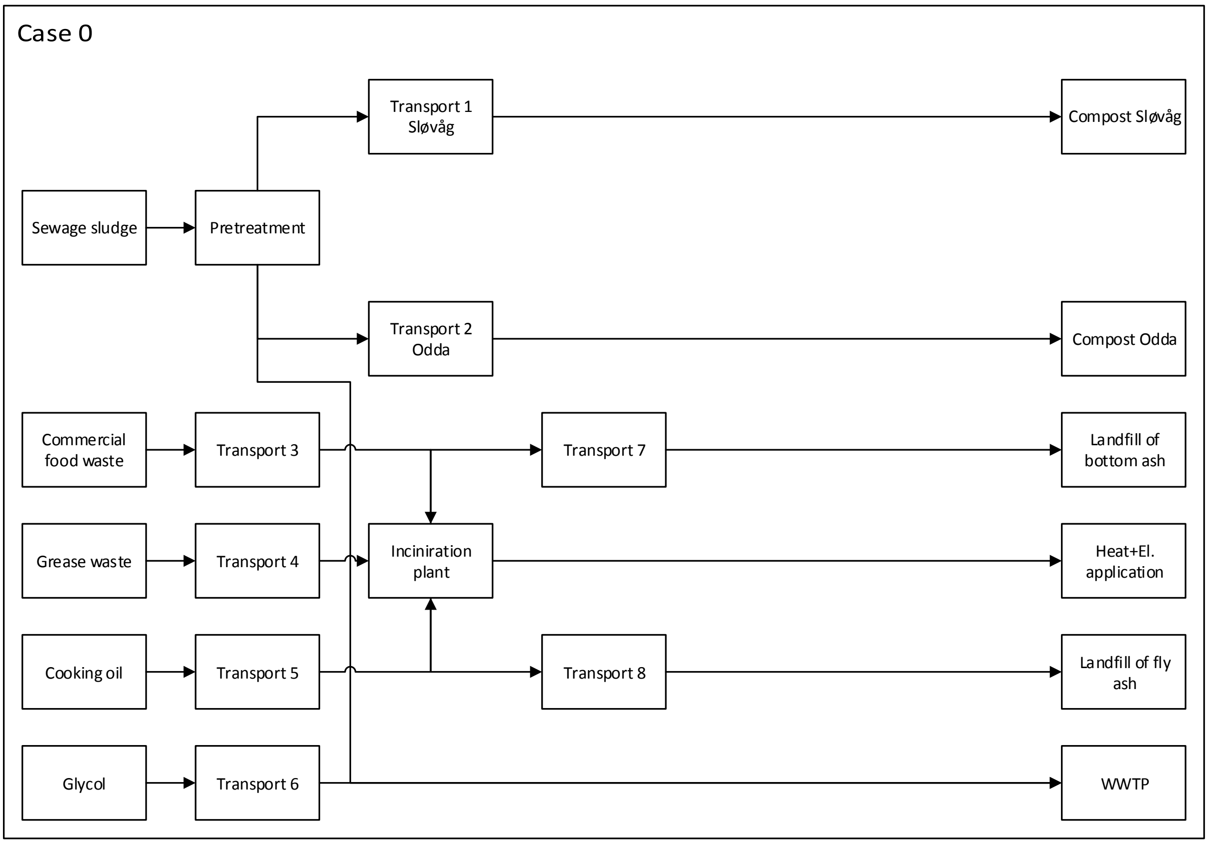


Figure 10: Simplified flow chart of case 0.

Situation of 2020 Bergen, Norway

Case 1 represent the system currently under construction, where a biogas plant will get what would normally go to compost, incineration and WWT in Case 0, this case assumes that all upgrades related to WWT has been completed. The new system will produce biogas, and upgrade it to fuel standard. This means that there is possibilities for substitution of fuel, either from natural gas in use or diesel, if engines or vehicles are changed. Further substitution is possible via the bioresidual as it contains a lot of nutrient that can replace chemical fertiliser and energy utilised in such production. This case produces biomethane for substituting natural gas or diesel and bioresidual for substituting chemical fertiliser, see Appendix 3.

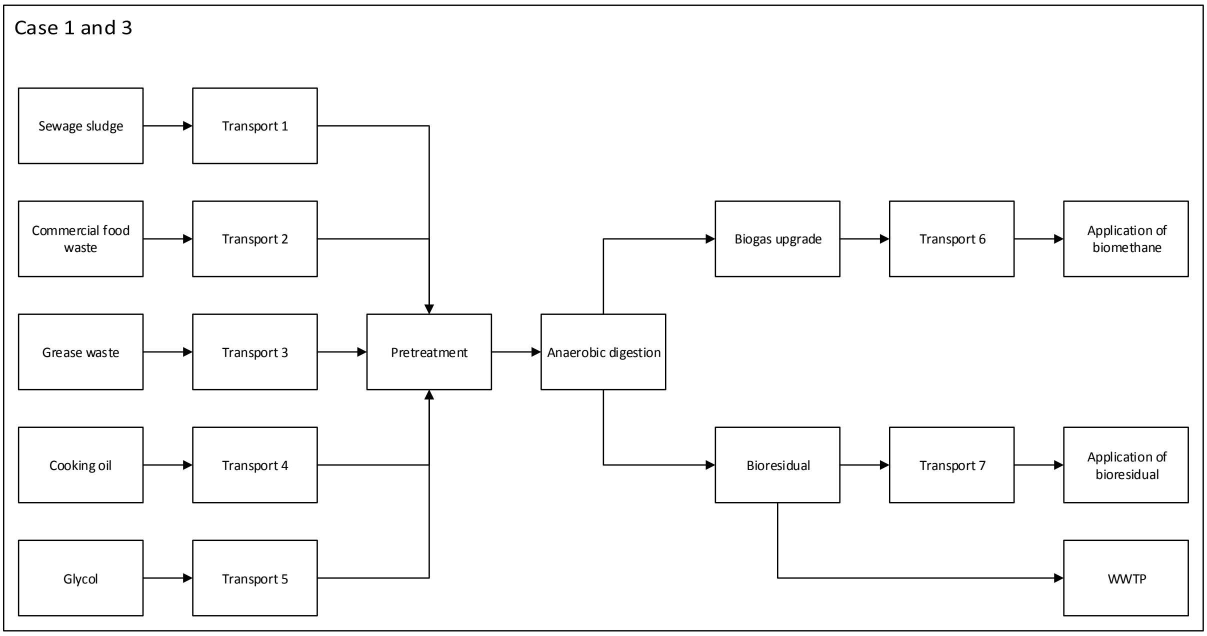


Figure 11: Simplified flow chart for cases 1 and 3.

Case 2 assumes the same situation as Case 1, where the biogas plant is constructed and production of biomethane for the use of fuel; however, the incineration of bioresidual takes place, the reason can be both to high levels of heavy metals or that the city does not have a recipient for the bioresidual, and thusly incineration is the sound choice. Further, no replacement of chemical fertiliser can take place, however as a bi-product of the end-of-life treatment of the bioresidual is heat and electricity. This case produces biomethane for substituting natural gas or diesel and substitute's heat and electricity from incineration of the bioresidual, see Appendix 4.

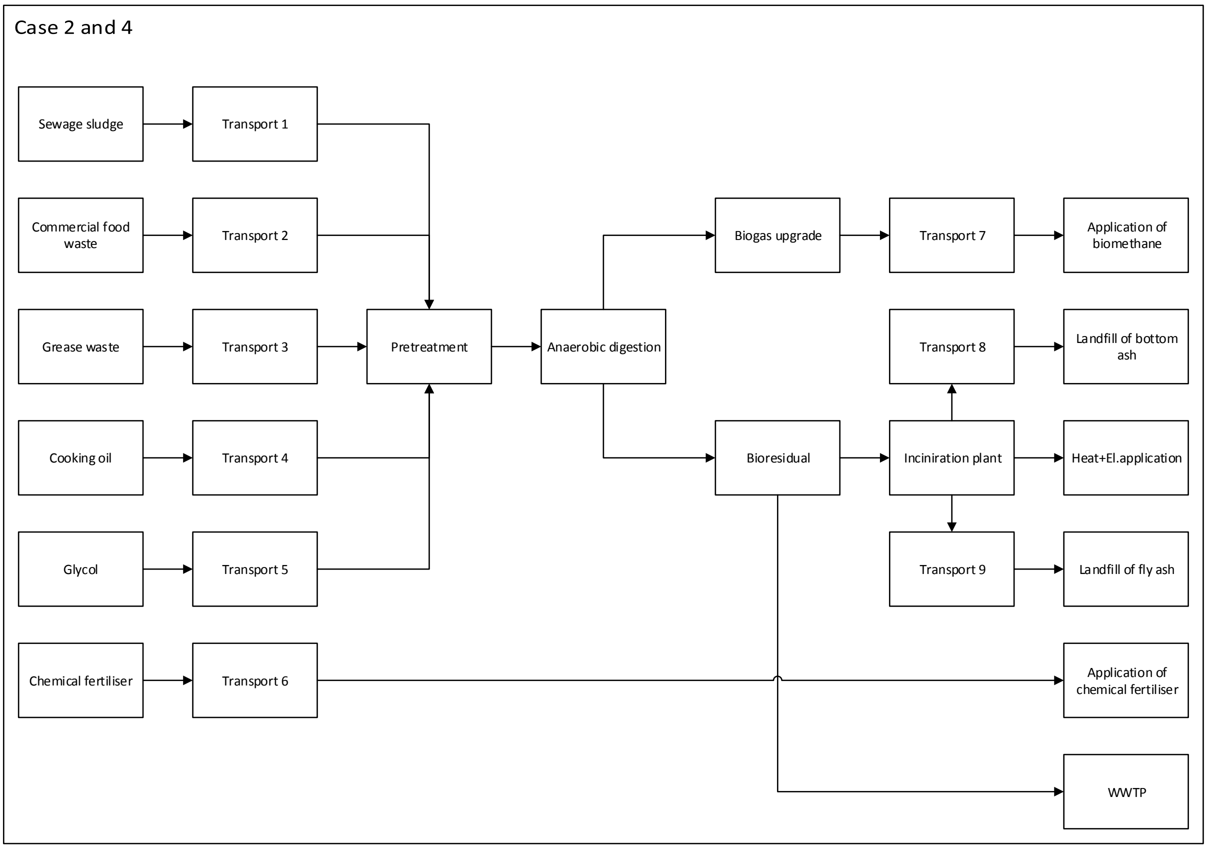


Figure 12: Simplified flow chart for cases 2 and 4.

Situation of 2020 Gothenburg, Sweden

Case 3, this case assumes a situation with a decision to not build a biogas plant and rather send it all to Sweden, where the location chosen is Gothenburg. This will mean the same settings of the system as Case 1, but with drastic changes to the distances for the individual feedstock. This case produces biomethane for substituting natural gas or diesel and bioresidual for substituting chemical fertiliser, se Appendix 5.

Case 4, the last case is a similar case to Case 2, where the bioresidual has either to high levels of heavy metals for use as biofertiliser or no receiver for the bioresidual and thusly incinerated. However, as the location is in Gothenburg, Sweden and some changes in the distances for the bottom ash and the fly ash. This case produces biomethane for substituting natural gas or diesel and substitute’s heat and electricity from incineration of the bioresidual, see Appendix 6.

The following tables show the results from all the variations of the FU in the different cases looked at, and for the chosen impact categories, following the setup shown in table 12; Global warming potential, terrestrial acidification potential, human toxicity potential and fossil depletion potential.

Table 13: GWP results on tested variations of the FU.

Process	Global Warming Potential (kg CO2-eq.)				
	Case 0 (base)	Case 1	Case 2	Case 3	Case 4
Transport feedstock	4,23E+01	7,48E+00	7,48E+00	3,54E+02	3,54E+02
Compost	1,42E+02				
Pretreatment		3,50E-01	3,50E-01	3,50E-01	3,50E-01
Hygienisation		9,82E-01	9,82E-01	1,59E+01	1,59E+01
Anaerobic Digestion		3,30E+00	3,30E+00	4,14E+00	4,14E+00
Methane <98% CH4		4,20E+01	4,20E+01	4,55E+01	4,55E+01
Transport Biomethane		2,70E+00	2,70E+00	2,70E+00	2,70E+00
Dry bioresidual		8,69E+01		8,79E+01	
Transport Bioresidual		3,95E+00		3,95E+00	
Incineration	2,41E+00		1,20E+01		1,81E+01
Bottom ash	6,92E+00		1,22E+02		1,22E+02
Fly ash	3,92E-01		6,93E+00		6,93E+00
Transport Ash	1,42E-01		2,52E+00		1,05E+00
WWTP	9,52E-12	4,28E-10	4,28E-10	4,28E-10	4,28E-10
P2O5 substitution		-3,03E+01		-3,03E+01	
Nitrogen substitution		-7,24E+01		-7,24E+01	
Bus substitution		-4,54E+02	-4,54E+02	-4,54E+02	-4,54E+02
Heat substitution	-8,39E+00		-1,71E+01		-4,98E+01
Electricity substitution	-1,12E+00		-2,28E+00		-6,64E+00

Table 14: TAP results on tested variations of the FU.

Process	Terrestrial Acidification Potential (kg SO2-eq.)				
	Case 0 (base)	Case 1	Case 2	Case 3	Case 4
Transport feedstock	1,38E-01	2,45E-02	2,45E-02	1,16E+00	1,16E+00
Compost	2,10E+01				
Pretreatment		1,23E-03	1,23E-03	1,23E-03	1,23E-03
Hygienisation		6,23E-03	6,23E-03	1,01E-01	1,01E-01
Anaerobic Digestion		1,31E-02	1,31E-02	1,68E-02	1,68E-02
Methane <98% CH4		6,41E-03	6,41E-03	2,15E-02	2,15E-02
Transport Biomethane		8,84E-03	8,84E-03	8,84E-03	8,84E-03
Dry bioresidual		1,45E+01		1,45E+01	
Transport Bioresidual		1,29E-02		1,29E-02	
Incineration	8,77E-03		4,37E-02		6,99E-02
Bottom ash	2,23E-03		2,89E-02		2,89E-02
Fly ash	5,20E-02		2,73E-02		2,73E-02
Transport Ash	8,41E-02		8,24E-03		3,43E-03
WWTP	1,63E-03	3,51E-12	3,51E-12	3,51E-12	3,51E-12
P2O5 substitution		-2,50E-01		-2,50E-01	
Nitrogen substitution		-5,95E-01		-5,95E-01	
Bus substitution		-2,78E-01	-2,78E-01	-2,78E-01	-2,78E-01
Heat substitution	-2,94E-02		-6,00E-02		-2,01E-01
Electricity substitution	-3,92E-03		-7,99E-03		-2,68E-02

Table 15: HTP results on tested variations of the FU.

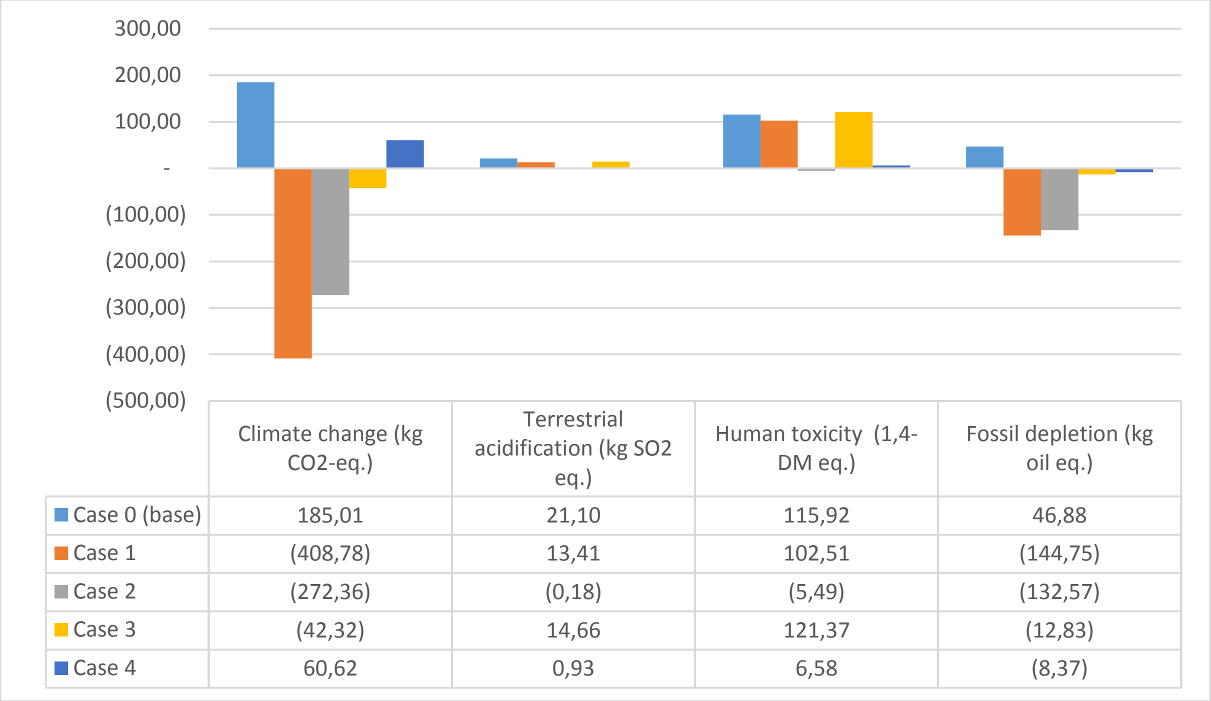
Process	Human Toxicity Potential (kg 1,4-DB eq.)				
	Case 0 (base)	Case 1	Case 2	Case 3	Case 4
Transport feedstock	1,73E+00	3,05E-01	3,05E-01	1,44E+01	1,44E+01
Compost	1,16E+02				
Pretreatment		6,63E-02	6,63E-02	6,63E-02	6,63E-02
Hygienisation		2,37E-01	2,37E-01	3,83E+00	3,83E+00
Anaerobic Digestion		2,84E-01	2,84E-01	4,60E-01	4,60E-01
Methane <98% CH4		3,46E-01	3,46E-01	1,08E+00	1,08E+00
Transport Biomethane		1,10E-01	1,10E-01	1,10E-01	1,10E-01
Dry bioresidual		1,15E+02		1,15E+02	
Transport Bioresidual		1,61E-01		1,61E-01	
Incineration	2,79E-01		1,41E+00		2,69E+00
Bottom ash	5,41E-02		9,57E-01		9,57E-01
Fly ash	2,81E-02		4,97E-01		4,97E-01
Transport Ash	5,81E-03		1,03E-01		4,28E-02
WWTP	2,22E-12	9,95E-11	9,95E-11	9,95E-11	9,95E-11
P2O5 substitution		-2,35E+00		-2,35E+00	
Nitrogen substitution		-5,61E+00		-5,61E+00	
Bus substitution		-6,14E+00	-6,14E+00	-6,14E+00	-6,14E+00
Heat substitution	-1,59E+00		-3,23E+00		-1,01E+01
Electricity substitution	-2,12E-01		-4,31E-01		-1,35E+00

Table 16: FDP results on tested variations of the FU.

Process	Fossil Depletion Potential (kg oil eq.)				
	Case 0 (base)	Case 1	Case 2	Case 3	Case 4
Transport feedstock	1,53E+01	2,71E+00	2,71E+00	1,28E+02	1,28E+02
Compost	3,26E+01				
Pretreatment		6,58E-02	6,58E-02	6,58E-02	6,58E-02
Hygienisation		3,56E-01	3,56E-01	5,77E+00	5,77E+00
Anaerobic Digestion		5,87E-01	5,87E-01	7,76E-01	7,76E-01
Methane <98% CH4		3,44E-01	3,44E-01	1,13E+00	1,13E+00
Transport Biomethane		9,78E-01	9,78E-01	9,78E-01	9,78E-01
Dry bioresidual		3,59E+00		3,82E+00	
Transport Bioresidual		1,43E+00		1,43E+00	
Incineration	5,12E-01		2,55E+00		3,91E+00
Bottom ash	8,84E-02		1,57E+00		1,57E+00
Fly ash	5,15E-02		1,56E+00		1,56E+00
Transport Ash	1,75E-12		9,12E-01		3,79E-01
WWTP	-2,10E-01	7,86E-11	7,86E-11	7,86E-11	7,86E-11
P2O5 substitution		-4,21E+00		-4,21E+00	
Nitrogen substitution		-1,00E+01		-1,00E+01	
Bus substitution		-1,41E+02	-1,41E+02	-1,41E+02	-1,41E+02
Heat substitution	-1,58E+00		-3,21E+00		-1,06E+01
Electricity substitution	-2,10E-01		-4,28E-01		-1,41E+00

4.2.2. Impact assessment

For the LCA part of the master thesis, five cases were run, and the impact categories chosen are global warming potential (GWP), human toxicity potential (HTP), eutrophication potential, photochemical oxidation formation, particular matter formation, and lastly fossil depletion potential.

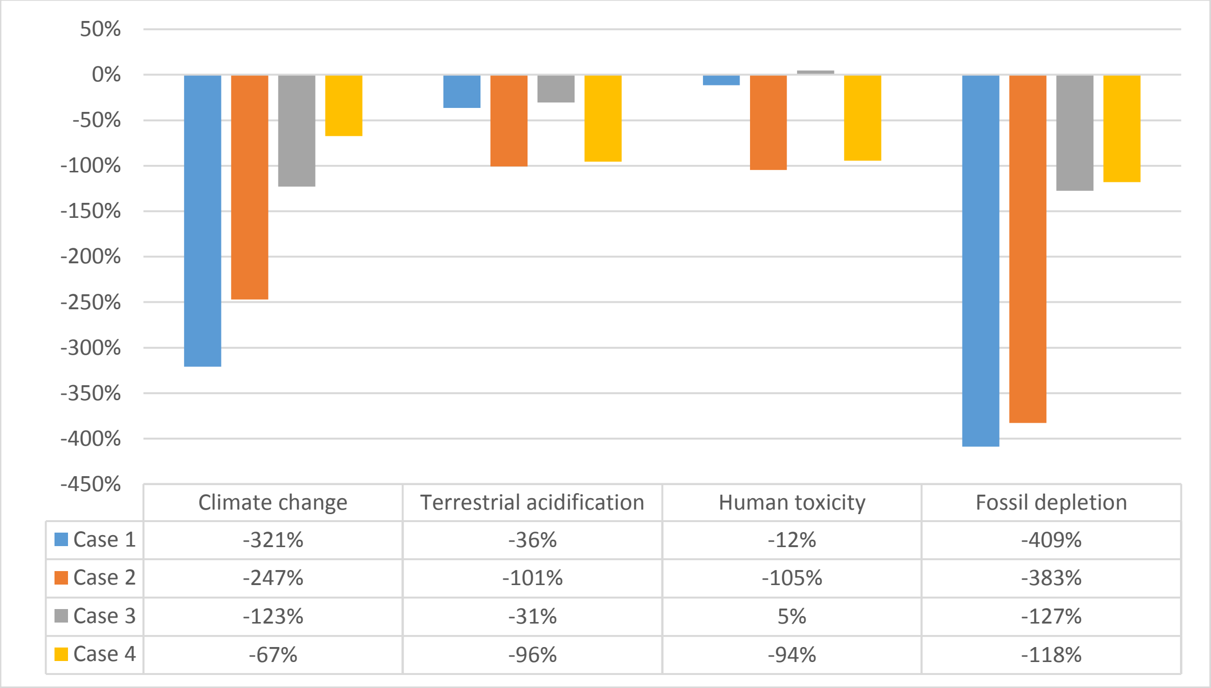


	Climate change (kg CO2-eq.)	Terrestrial acidification (kg SO2 eq.)	Human toxicity (1,4-DM eq.)	Fossil depletion (kg oil eq.)
🟦 Case 0 (base)	185,01	21,10	115,92	46,88
🟧 Case 1	(408,78)	13,41	102,51	(144,75)
⬜ Case 2	(272,36)	(0,18)	(5,49)	(132,57)
🟨 Case 3	(42,32)	14,66	121,37	(12,83)
🟦 Case 4	60,62	0,93	6,58	(8,37)

Figure 13: Emissions from chosen impact categories.

Figure 13 shows the LCA results for the impact categories looked at, the highest emissions are all found in the Case 0, the base case. Case 1 shows the largest impact reduction for GWP and FDP, while Case 2shows the largest impact reductions for TAP and HTP. The large reduction in GWP from cases are mostly seen in connection with substitution effect from bus, and nutrients or heat- and electricity production. Human toxicity potential is increasing in most cases due to heavy metal content in the sewage sludge.

The figure below shows reduction caused by the other cases in relevance to Case 0, in order to see the benefits of upgrading the use of the defined FU. As seen there is a reduction in all cases for the chosen impacts, except for HTP in Case 3, and most are seen in connection with the substitution for bus, here diesel as fuel. All differences are showed in percentage change relevant to Case 0, thus showing how much the different cases compare to today’s situation. Some of the cases have either very large reduction for the given impact category, this does not mean that the impact is very large, but represent the relationship between Case 0 and the case looked at.



	Climate change	Terrestrial acidification	Human toxicity	Fossil depletion
Case 1	-321%	-36%	-12%	-409%
Case 2	-247%	-101%	-105%	-383%
Case 3	-123%	-31%	5%	-127%
Case 4	-67%	-96%	-94%	-118%

Figure 14: Emission potential compared to Case 0.

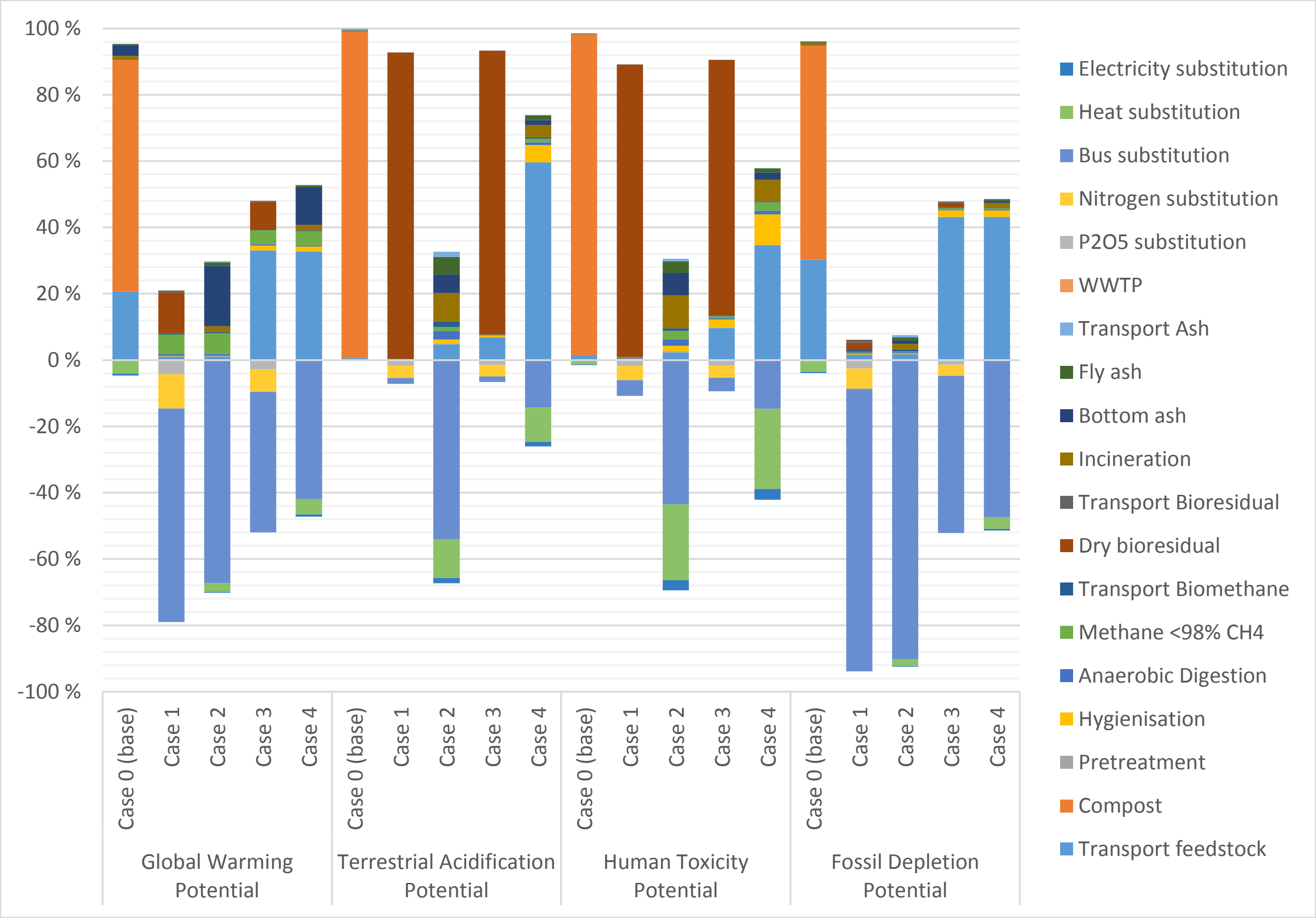


Figure 15: Normalised emission categories for the different cases.

Figure 15 shows all the impacts caused by the cases, for the impacts looked at, normalised in order to be comparable and to find the processes behind the largest impacts per process. The general trend for GWP is that Bus substitution represent the largest reduction, while Transport of feedstock represent the largest impact in Case 2 and 4, however in Case 1 and 2 Dry Bioresidual and Bottom Ash represent the largest GWP impact, respectively. Due to the large effect of Bus substitution, this process also contributes to a large reduction in Fossil Depletion Potential, where it represent the largest reduction except for the reference case, where Heat substitution represent the most reduction.

As shown in the previous figures (13 and 14) there are reductions in all categories looked at, however it varies which case reduce more, the tipping point is decided by the substitution effect for heat, as heat from electricity is more common in Norway, as explained earlier Case 1 is the preferred system of the future and thus chosen to look more into, as shown in figure 15.

Global Warming Potential (GWP). The first impact category looked at is the climate change, this shows the global warming potential for the cases chosen, and is measured in kg CO_2-equivalents. CO_2-equivalents measure a weighted average for all climate gases, were other climate gases are normalised to match CO_2. An example is CH_4, which has 23 times the global warming potential of CO_2, meaning 1 kg of CH_4 would be the same as 23 kg of CO_2-equivalents (Goedkoop & Huijbregts 2013).

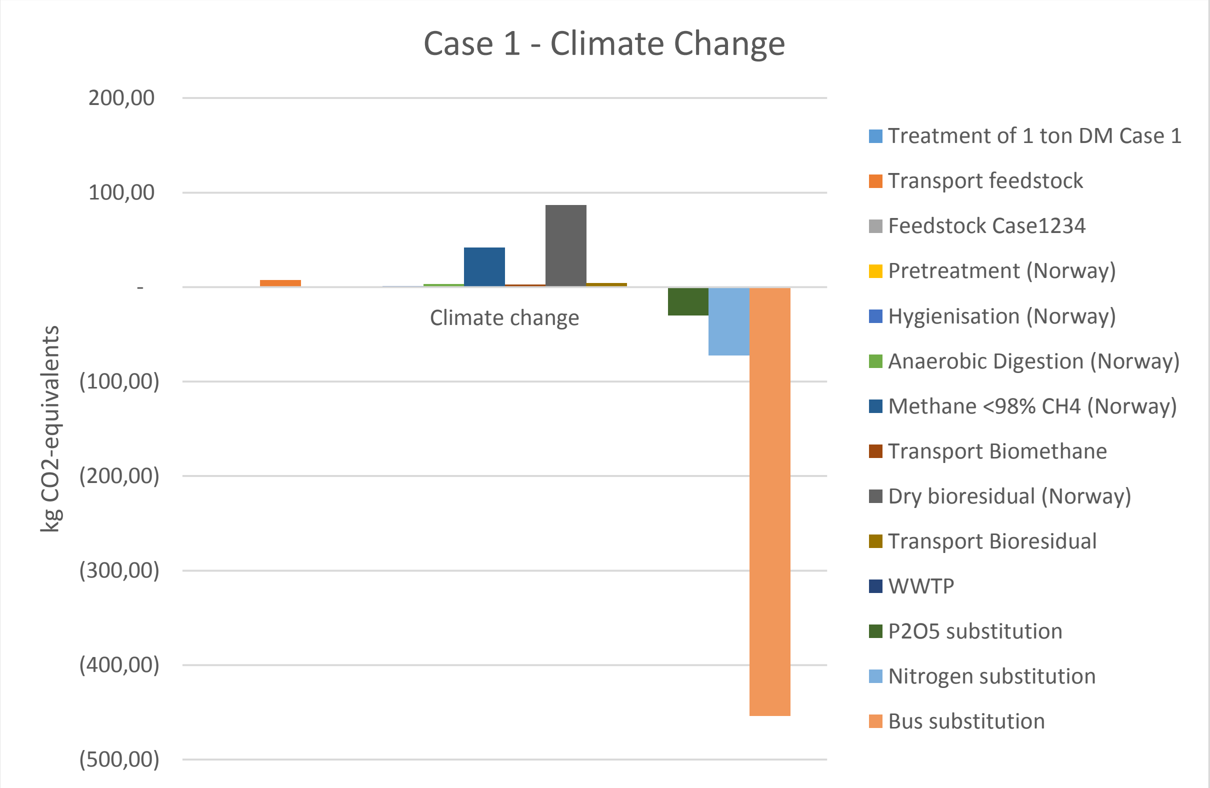


Figure 16: Global warming potential.

Above is the climate change impact from Case 1, as can be seen the largest reduction of climate change comes from mainly the process of Bus Substitution, and the largest impact is from Dry Bioresidual.

In total the positive impact from GWP sum up to 147.62 kg CO_2-equivalents before the substitution is added. The two main contributors to the positive emission is Dry Bioresidual at 86.86 kg CO_2-eq. and the second largest is Methane <98% CH_4 at 42 kg CO_2-eq.

The largest contribution to Dry Bioresidual is from the processes Bioresidual and reject and Spreading of bioresidual dry, with impacts at 78.6 and 2.36 kg CO2-eq. respectively. From Bioresidual and reject the main contributors to the process emission is from methane (CH_4) and dinitrogen monoxide (N_2O) with impacts of 55.6 and 23.1 kg CO_2-eq. respectively.

The largest contribution to Methane <98% CH_4 is the process of Water Scrubbing which is the upgrading of biogas to biomethane at 41.4 kg CO_2-eq., where the loss of methane stands for 97% of this, or 40.2 kg CO2-eq.

In the negative impacts for the GWP, that in total stands for -556.4 kg CO_2-eq., where the main contributors are Bus substitution and Nitrogen substitution at -454 and -72.4 CO_2-eq. respectively.

The largest reduction from Bus substitution comes from the change of fuel, from diesel in use to biomethane, where this process has a total reduction of -441 kg CO_2-eq. from CO_2 emissions alone, where the use of the methane contribute to 57 kg CO_2-eq. and the substitution of diesel contributes to -497 kg CO_2-eq.

The largest reduction from Nitrogen substitution comes from the production and application of nitrogen fertiliser, with total separated reductions at -15.7 and -56.6 kg CO_2-eq. respectively, where the largest contributor for both reductions are reduction of CO_2 emissions at -14.7 kg CO_2-eq. each.

Terrestrial Acidification Potential (TAP). The second impact category looked at is the terrestrial acidification potential that measures the atmospheric deposition of emitted pollution, such as NO_X, NH_3 and SO_2, and is measured in kg SO_2-equivalents (Goedkoop & Huijbregts 2013).

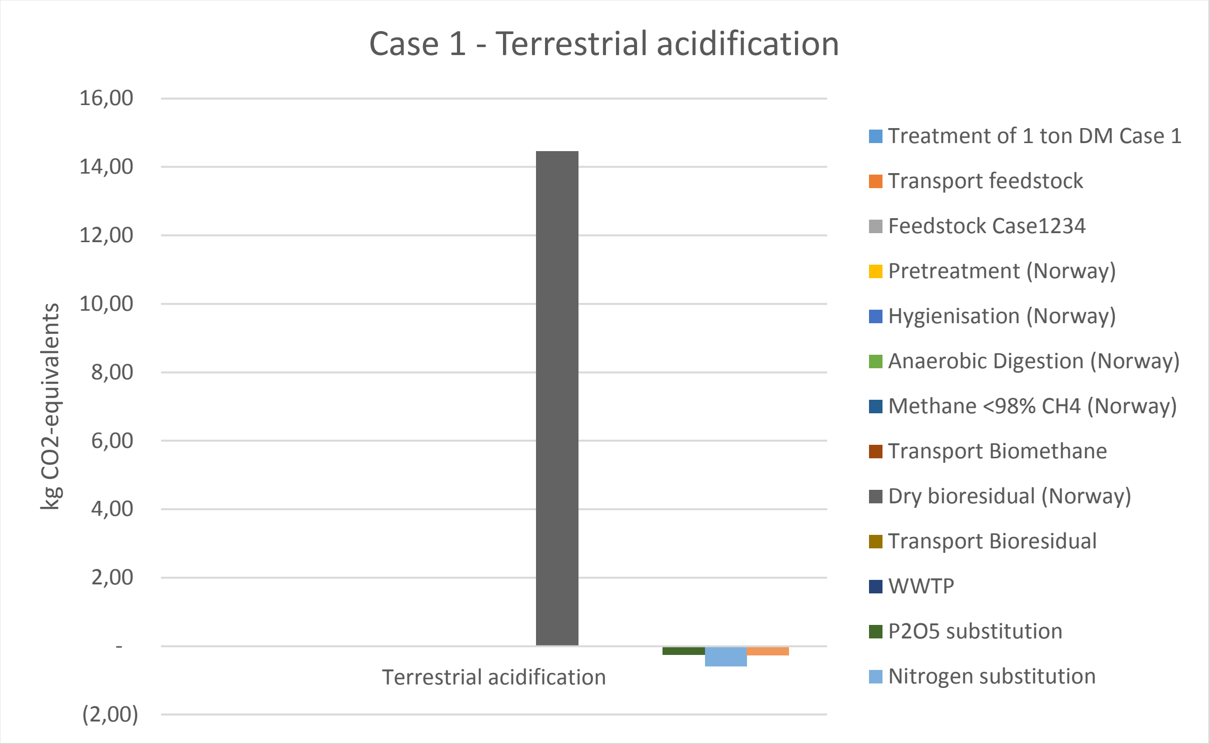


Figure 17: Terrestrial Acidification Potential.

Figure 15 shows the terrestrial acidification potential for Case 1, as seen the largest impact comes from the process of Dry bioresidual and the largest reduction from Nitrogen substitution.

The total positive emissions amount up to 14.53 kg SO_2-eq. where the largest contribution to this positive impact is as mentioned the Dry bioresidual with 14.46 kg SO_2-eq. alone, where this impact can be traced back to the sub-process of Spreading of bioresidual dry that stands for 95% or 13.8 kg SO_2-eq., contributing to this impact is mainly the emission of ammonia (NH3) that stands for close to 100% of the impact from spreading, this is due to the conversion of nitrogen into ammonia that is mainly happening in the spreading, with 96% of the conversion released in this process.

The total negative impact amount to -1.12 kg SO_2-eq. where the largest contribution to this reduction comes from as mentioned the Nitrogen substitution at 0.6 kg SO_2-eq. alone, this reduction can further be broken down to the sub-processes of production and application of nitrogen fertiliser with -0.123 and -0.472 kg SO_2-eq. respectively, where this reduction can be traced back to the reduction of sulphur dioxide (SO_2) at -0.0675 kg SO_2-eq. for production of nitrogen fertiliser and reduction of ammonia (NH_3) at -0.348 kg SO_2-eq. for the spreading of nitrogen fertiliser.

Human Toxicity Potential (HTP). The third impact category looked at is the human toxicity potential, this accounts for the persistence, accumulation and toxicity of a chemical, and is measured in kg 1,4-DB equivalents. The 1,4-DM stands for the chemical 1,4-dichlorobenzene, which is the reference unit for the toxicity (Goedkoop & Huijbregts 2013).

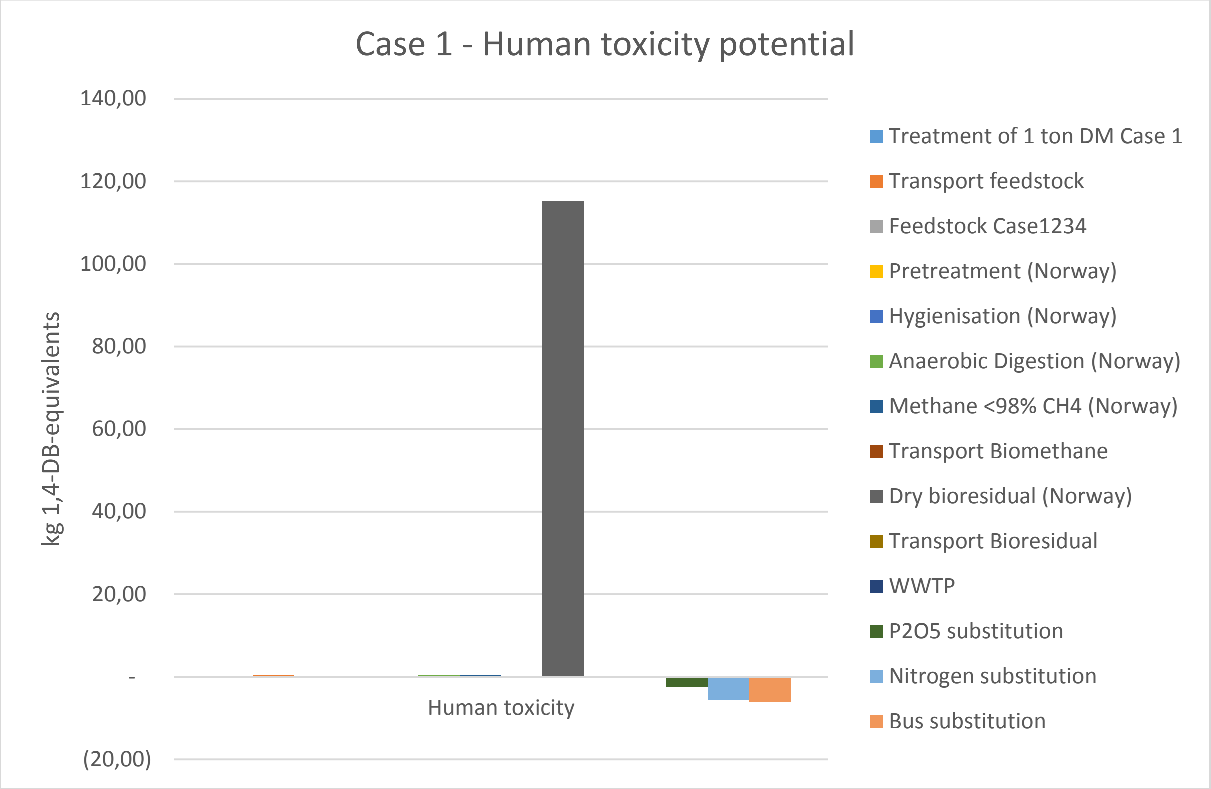


Figure 18: Human toxicity potential.

Same as for terrestrial acidification potential; Dry bioresidual represent the largest impact for human toxicity potential, while the largest impact reductions are represented mainly by Bus substitution and from Nitrogen substitution.

The total positive impact amounts to 116.61 kg 1,4-DB eq. where the largest contributor is Dry bioresidual at 99% or 115.1 kg 1,4-DB eq. alone, this impact can further be traced back to the sub-process of Heavy metals that represent 99% or 114 kg 1,4-DB eq. of the Dry bioresidual process. The Heavy metal impact is mainly caused by the heavy metal zinc that represent 74% of this impact, and is due to the high concentration of zinc in the bioresidual, at 342.22 mg/kg DM of bioresidual.

The total negative impact amount to -14.1 kg 1,4-DB eq. where Bus substitution represent -6.14 kg 1,4-DB eq. and Nitrogen substitution represent -5.61 kg 1,4-DB eq.

The process of Bus substitution can be broken down to the use of biomethane as fuel for buses at 7.23 kg 1,4-DB eq. and the substitution effect of replacing diesel as fuel at -13.2 kg 1,4-DB eq. From the substitution effect the largest impact reduction is from formaldehyde (CH_2O) with -3.17 kg 1,4-DB eq. and for the use of biomethane as fuel the largest impact comes from arsenic (As) at 2.54 kg 1,4-DB eq.

The process of Nitrogen substitution is broken down into the sub-processes of production and application with impact reduction at -4.38 and -1.22 kg 1,4-DB eq. respectively. For the impact reduction, reduction of mercury (Hg) emission represent the largest impact reduction of 1.13

kg 1,4-DB eq., while for application, arsenic (As) represents the largest impact reduction with -0.0239 kg 1,4-DB eq.

Fossil depletion Potential. Defines the use of a non-renewable resource, here defined for all fossil fuels, not uranium as it is a metal, and is measured in kg oil equivalents (Goedkoop & Huijbregts 2013).

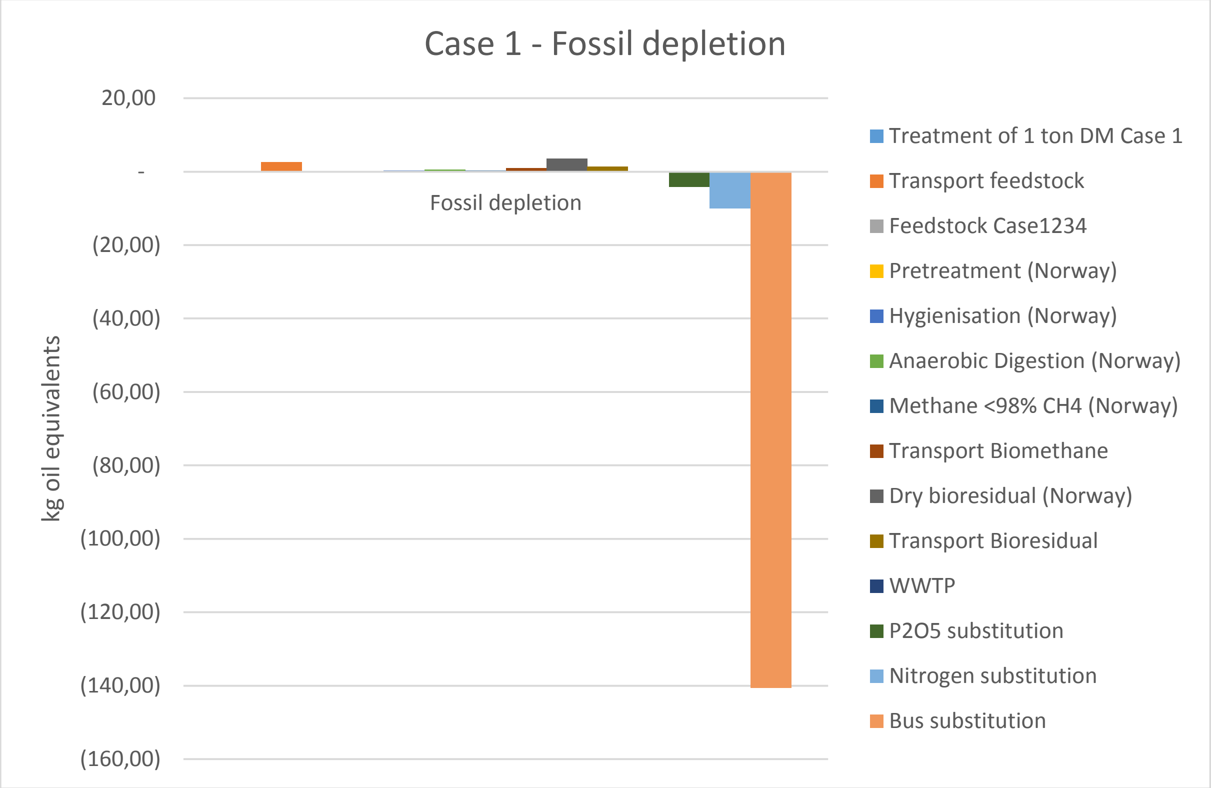


Figure 19: Fossil Depletion Potential.

The last impact category looked at is the fossil depletion potential, where the largest impact is found in Dry bioresidual and Transport feedstock, while the impact reduction is mainly represented by Bus substitution.

The total positive impact represent 10.05 kg oil eq., where Dry bioresidual and Transport feedstock represent the largest impacts at 3.59 and 2.71 kg oil eq. respectively, together they represent 63 % of the total positive impact. From the Dry bioresidual process the impacts can be traced back to the use of natural gas and crude oil at respectively 1.47 and 1.45 kg oil eq., while for Transport feedstock the impact is traced back to mainly crude oil at 1.76 kg oil eq.

The total negative impact is mainly represented by Bus substation, with 91% of the impact reduction or -140.56 kg oil eq., where the use of biomethane as fuel represent 24.6 kg oil eq. and the substitution of diesel as fuel represent -165 kg oil eq. These impacts are both represented by crude oil as the major contributor, where the substitution represent -110 kg oil eq. and the use of biomethane represent 11.4kg oil eq.

4.3. Sensitivity analysis

Here follows the results of the sensitivity analysis performed on the MFA and LCA systems.

4.3.1. MFA

In the table below the sensitivity analysis of the MFA is shown. As mentioned in the methodology not all parameters are tested.

Table 17: Sensitivity for the MFA.

Input variable	Unit	Initial value	% change in initial value	% change of results			
				RR	NR	PR	η
Kvernevik [bio]	ton DM	961	15 %	-	-	-	-
	-	-	-15 %	-0,06 %	-0,15 %	-	0,08 %
Ytre Sandviken [bio]	ton DM	825	15 %	0,05 %	0,12 %	-	-0,07 %
	-	-	-15 %	-0,05 %	-0,13 %	-	0,07 %
Flesland [bio]	ton DM	2 771	15 %	0,15 %	0,39 %	-	-0,21 %
	-	-	-15 %	-0,17 %	-0,44 %	-	0,23 %
Holen [bio]	ton DM	1 696	15 %	0,10 %	0,25 %	-	-0,13 %
	-	-	-15 %	-0,10 %	-0,26 %	-	0,14 %
Garnes [bio]	ton DM	369	15 %	0,02 %	0,05 %	-	-0,03 %
	-	-	-15 %	-0,02 %	-0,06 %	-	0,03 %
Knappen [Chem]	ton DM	1 422	15 %	-0,05 %	-0,71 %	-	0,10 %
	-	-	-15 %	0,05 %	0,72 %	-	-0,10 %
Septic	ton DM	89	15 %	0,01 %	-0,04 %	-	-0,02 %
	-	-	-15 %	-0,01 %	0,04 %	-	0,02 %
Commercial waste	ton DM	813	15 %	-0,16 %	-0,06 %	-	0,50 %
	-	-	-15 %	0,17 %	0,06 %	0,00 %	-0,51 %
Cooking oil	ton DM	152	15 %	-0,04 %	-0,11 %	-	-0,07 %
	-	-	-15 %	0,04 %	0,11 %	-	0,07 %
Grease waste	ton DM	8	15 %	0,00 %	0,00 %	-	-0,01 %
	-	-	-15 %	0,00 %	0,00 %	0,00 %	0,01 %
Glycol	ton DM	90	15 %	-0,15 %	-0,07 %	-	0,26 %
	-	-	-15 %	0,15 %	0,07 %	-	-0,26 %
AD efficiency	-	60 %	15 %	-11,96 %	-0,45 %	-	14,45 %
	-	-	-15 %	11,96 %	0,45 %	-	-14,50 %
Biomethane purity	-	98 %	0,5 %	-	-	-	1,01 %
	-	-	-0,5 %	-	-	-	-1,00 %
Methane loss	-	1 %	15 %	-	-	-	-0,15 %
	-	-	-15 %	-	-	-	0,15 %
Biogas production potential BioSludge	Nm3/kg	0,9	15 %	-	-	-	10,12 %
	-	-	-15 %	-	-	-	-10,14 %
Biogas production potential ChemSludge	Nm3/kg	0,9	15 %	-	-	-	2,39 %
	-	-	-15 %	-	-	-	-2,39 %
Biogas production potential Septic	Nm3/kg	0,9	15 %	-	-	-	0,11 %
	-	-	-15 %	-	-	-	-0,11 %
Biogas production potential Commercial food waste	Nm3/kg	0,9	15 %	-	-	-	1,51 %
	-	-	-15 %	-	-	-	-1,51 %
Biogas production potential Cooking oil	Nm3/kg	0,9	15 %	-	-	-	0,30 %
	-	-	-15 %	-	-	-	-0,30 %
Biogas production potential Grease waste	Nm3/kg	0,9	15 %	-	-	-	0,01 %
	-	-	-15 %	-	-	-	-0,01 %
Biogas production potential Glycol	Nm3/ton	100	15 %	-	-	-	0,36 %
	-	-	-15 %	-	-	-	-0,36 %

As shown in the sensitivity analysis there are generally not any mayor effect on the results by changing different parameters, however the largest change is found in the efficiency of the AD process, a 15% increase of this process gives a total increase of 14.45% in the energy efficiency and a decrease of -11.96% in the material rate of recovery. A -15% change to the parameter gives a reduction of -14.5% to the energy efficiency and an increase of 11.96% to the material rate of recovery.

The AD efficiency also affect the nitrogen recovery, -0.45% reduced with the increase in the parameter and 0.45% increase with a decrease in the parameter. However the parameter with the largest effect on nitrogen recovery is the feedstock parameter of chemical sewage sludge, where a ±15% change of this parameter gives a -0.71% and 0.72% change respectively.

The second largest change in the sensitivity is from the biogas production factor for the biological sewage sludge, because this accounts for the majority of the input this parameter naturally has a large effect. With a 15% increase of this parameter, only the energy efficiency change, it changes with 11.12% while a decrease of -15% gives a decrease of -11.14% in the energy efficiency.

Table 18: Sensitivity of process and transport energy.

Input variable	Unit	Initial value	% change in initial value	% change of results			
				RR	NR	PR	η
Reject water to WWTP [sewage pipes]	kWh/year	14 520	15 %	-	-	-	-0,003 %
Commercial waste	kWh/year	27 936	15 %	-	-	-	-0,006 %
Glycol	kWh/year	5 076	15 %	-	-	-	-0,001 %
Grease waste and cooking oil	kWh/year	12 816	15 %	-	-	-	-0,003 %
Sludge	kWh/year	81 900	15 %	-	-	-	-0,018 %
Septic	kWh/year	23 652	15 %	-	-	-	-0,005 %
Hygienisation [aggregatet]	kWh/year	473 558	15 %	-	-	-	-0,102 %
Anaerobic digestion	kWh/year	237 082	15 %	-	-	-	-0,051 %
Bioresidual and reject	kWh/year	208 368	15 %	-	-	-	-0,045 %
Polymer	kWh/year	4 848	15 %	-	-	-	-0,001 %
Biogas system; biogas from AD to Biogas upgrading	kWh/year	33 624	15 %	-	-	-	-0,007 %
Total process energy from internal machinery	kWh/year	1 123 380	15 %	-	-	-	-0,241 %
Distance, Kvernevik [bio]	km	25	15 %	-	-	-	-0,009 %
Distance, Ytre Sandviken [bio]	km	19	15 %	-	-	-	-0,006 %
Distance, Flesland [bio]	km	9	15 %	-	-	-	-0,007 %
Distance, Holen [bio]	km	14	15 %	-	-	-	-0,007 %
Distance, Garnes [bio]	km	47	15 %	-	-	-	-0,011 %
Distance, Knappen [Chem]	km	13	15 %	-	-	-	-0,005 %
Distance, Septic	km	21	50 %	-	-	-	-0,020 %
Distance, Commercial waste	km	16	30 %	-	-	-	-0,009 %
Distance, Cooking oil	km	16	30 %	-	-	-	-0,003 %
Distance, Grease waste	km	21	30 %	-	-	-	-0,004 %
Distance, Glycol	km	9	15 %	-	-	-	-0,001 %
Distance, Biomethane	km	10	50 %	-	-	-	-0,003 %
Distance, Bioresidual	km	19	50 %	-	-	-	-0,060 %

As seen in the sensitivity results for the transport distances and the process energy supplied from Purac AB by Kanders (2015), there are no major changes for any of the parameters tested, the largest change found is if the total energy input is tested, which only adds up to -0.241% change to the overall energy efficiency. However, as this result include the HHV content of the incoming feedstock the picture would be different if this was not included.

4.3.2. LCA

Table 19: Sensitivity for the LCA.

Input variable	Unit	Initial value	% change in initial value	% change of results			
				GWP	TAP	HTP	FDP
AD efficiency	-	60 %	10 %	-0,13 %	-0,33 %	-8,65 %	-0,15 %
	-	-	-10 %	0,13 %	0,33 %	8,65 %	0,15 %
Biomethane purity	-	98 %	0,5 %	0,056 %	0,001 %	0,002 %	0,005 %
	-	-	-0,5 %	-0,056 %	-0,001 %	-0,002 %	-0,005 %
Methane loss from upgrade	-	1 %	10 %	0,9706 %	-0,0001 %	-0,0005 %	-0,0009 %
	-	-	-10 %	-0,9726 %	0,0001 %	0,0004 %	0,0009 %
People per bus	-	12,0	10 %	-11,07 %	-0,21 %	-0,58 %	-9,70 %
	-	-	-10 %	11,07 %	0,21 %	0,58 %	9,70 %
	-	13 %	10 %	0,24 %	-0,07 %	0,10 %	0,14 %
Nitrogen loss from anaerobic digestion	-	-	-10 %	-0,24 %	0,07 %	-0,10 %	-0,14 %
Nitrogen loss from storage and application	-	42 %	10 %	1,90 %	11,08 %	0,40 %	0,50 %
	-	-	-10 %	-1,90 %	-11,08 %	-0,40 %	-0,50 %
Phosphorus loss from anaerobic digestion	-	10 %	10 %	0,08 %	0,02 %	0,02 %	0,03 %
	-	-	-10 %	-0,08 %	-0,02 %	-0,02 %	-0,03 %
Methane emission from storage and applicaiton	mg CH4/m3	1344,6	10 %	1,36 %	-	-	-
	-	-	-10 %	-1,36 %	-	-	-
	Nm3/kg	0,9	10 %	0,75 %	0,01 %	0,03 %	0,06 %
Biogas production potential BioSludge	-	-	-10 %	-0,75 %	-0,01 %	-0,03 %	-0,06 %
	Nm3/kg	0,9	10 %	0,176 %	0,002 %	0,007 %	0,015 %
Biogas production potential ChemSludge	-	-	-10 %	-0,176 %	-0,002 %	-0,007 %	-0,015 %
Distance, Kvernevik [bio]	km	25,00	50 %	0,24 %	0,02 %	0,04 %	0,24 %
Distance, Ytre Sandviken [bio]	km	19,00	50 %	0,17 %	0,02 %	0,03 %	0,17 %
Distance, Flesland [bio]	km	9,00	50 %	0,18 %	0,02 %	0,03 %	0,19 %
Distance, Holen [bio]	km	14,00	50 %	0,20 %	0,02 %	0,03 %	0,20 %
Distance, Garnes [bio]	km	47,00	50 %	0,29 %	0,03 %	0,05 %	0,29 %
Distance, Knappen [Chem]	km	13,00	50 %	0,14 %	0,01 %	0,02 %	0,14 %
Distance, Septic	km	21,17	50 %	0,15 %	0,01 %	0,02 %	0,15 %
Distance, Commercial waste	km	16,00	50 %	0,11 %	0,01 %	0,02 %	0,12 %
Distance, Cooking oil	km	16,00	50 %	0,04 %	0,00 %	0,01 %	0,04 %
Distance, Grease waste	km	21,17	50 %	0,05 %	0,01 %	0,01 %	0,05 %
Distance, Glycol	km	9,00	50 %	0,033 %	0,003 %	0,005 %	0,033 %
Distance, Biomethane	km	10,40	50 %	0,33 %	0,03 %	0,05 %	0,34 %
Distance, Bioresidual	km	19,12	50 %	0,48 %	0,05 %	0,08 %	0,49 %

Above follows the results from the sensitivity run on the SimaPro results, the main changes that can be taken out are from the following parameters; AD efficiency, People per bus, Nitrogen loss from storage and application, Methane emission from storage and application and lastly Transport.

AD efficiency. The AD efficiency does not represent a significant change in the impacts above, besides the HTP, where the ±10% causes a change of -8.65% and 8.65% relative to the changes to the parameter. This however shows a weakness to the model, because the heavy metals consist during the AD process, thusly the HTP should not differentiate due to a change in this parameter.

People per bus. A change to this parameter causes the largest changes to the GWP and the FDP, a ±10% change causes the -11.07% for the GWP and -9.7% for the FDP, and 11.07% to the GWP and 9.7% to the FDP, relative to the change of the parameter. Increasing the amount of people each bus carry on average will increase the substitution effect of the change to biomethane as fuel for buses, and thusly this will reduce the FDP due to less use for diesel as fuel in other buses.

Nitrogen loss from storage and application. The parameter regarding loss of nitrogen in the storage and application, represent the conversion of nitrogen into NH_3, N_2O and N_2. The ±10% change to the parameter leads to a 1.9% and -1.9% change to the GWP, and more importantly 11.08% and -11.08% in the TAP relative to the changes induced.

Methane emission from storage and application. This parameter represent the loss of methane from the bioresidual in both storage and application, and is tested for ±10% which results in variations of 1.36% and -1.36% relative to the changes.

Transport. For the transport, all distances for the chosen case were tested, as seen in the table, changing the individual distance with 50% does not change the impact categories much, together they might. However, the sum of changes for the GWP for transport only adds up to around 2.4% change, meaning for the chosen case the transport does not represent significant uncertainty to the results.

The sensitivity analysis of the LCA shows that the most sensitive parameters are related to the use of the produced biomethane and from loss of nitrogen in the processes of storage and application. Further seen in the table is that the parameter of nitrogen loss also is the parameter with the most effect in the overall impact categories looked at and thusly is considered very important for the system.

5. Discussion

5.1. Findings

MFA findings

In the results of the MFA, the material rate of recovery (RR) were found to be 89.41% (Case 0), 53.96% (Case 1 and 3) and 26.55% (Case 2 and 4). The RR does not represent the amount of usable material per se, because it represent the amount of material that has not been reduced or used in the processes beforehand. In Case 0 most of the mass is sent to compost, meaning it is not utilised for any other purposes than for example landfilling in road construction. Cases 1 and 3 the RR represent the remaining masses from the biogas production system and is the bioresidual. Lastly, the cases 2 and 3 represent the bottom ash and the fly ash after incineration of the bioresidual and is considered not usable and will be landfilled.

The nutrient recovery (NR) was found to be 47.13% (Case 0), 35.37% (Case 1 and 3) while 0% (Case 2 and 4). The result for Case 0 only indicates how much of the nitrogen is sent to compost, and is not reusable. While the result for Case 2 and 4 are 0% because of incineration with bottom ash and fly ash as end-products that further will be landfilled. The phosphorus recovery (PR) was found to be 94.85% (Case 0), 90% (Case 1 and 3) while same for Case 2 and 4 the recovery of phosphorus is zero due to incineration and the by-products being landfilled.

The energy efficiencies were found to be 5.39% (Case 0), 32.23% (Case 1), 43.06% (Case 2), 29.1% (Case 3) and 38.98% (Case 4). Cases 2 and 4 incinerate the bioresidual for heat and electricity, thus more energy is produced and the efficiency increases. The low efficiency in Case 0 is due to only the industrial organic waste, glycol excluded, being incinerated for energy output, while for Cases 1 and 3 the biomethane is the only energy output. Variations from case to case, can be traced to the large differences in transport, between Cases 1 and 2 and the Cases 3 and 4, while further alternative application of the bioresidual add to the variations.

Due to the plant being built in Bergen and a wish of nutrient recovery through the use of the bioresidual, Case 1 is chosen. Sensitivity performed for this case, shows that there are mostly small to no change in the overall results. Parameters such as the AD efficiency and the biogas production shows sensitivity on the system, RR (-+11.96%) and EE (±14.5%). What this shows is that it is important to ensure a stable culture in the digestion chamber, thusly ensuring a stable efficiency rate, and further find a mix of input that ensure the best biogas yield for the system.

LCA findings

In the results of the LCA, it was found that the best cases for the system is Case 1 and Case 2. With Case 1 better on GWP and FDP, while Case 2 is better on TAP and HTP, the difference is found from the utilisation of the bioresidual. If it ends up with the goal of reducing the HTP Case 2 is preferred, because of this it can be argued that by incinerate the bioresidual the system will perform better, and there will be less transport required by the system. However, such incineration would require upgrade of today’s incineration plant, and it is further argued by Sakse & Hjelle (2010) that the bioresidual does not give energy output, and should only be considered destruction. This would mean that Case 1 is still the better option of the system of Rådalen biogas plant, as it gives the substitution possibility of nitrogen and phosphorus, while this all rest on the amount of heavy metals, as a too high level can make it uninteresting as biofertiliser.

Results from the LCA shows that the impacts in GWP for the chosen case is 147.62 kg CO_2-equivalents/FU and the substitution effect amounts to -556.4 kg CO_2-equivalents/FU, the total reduction in GWP shows a total reduction of -321% compared to the base case. The results shows reductions in all impact categories looked at. The largest contributor to the impacts was found to be the processes Dry bioresidual and Methane <98% CH4 that together contribute to 87% of the positive impact.

The largest substitution effect is found in Bus- and Nitrogen substitution respectively at -453.71 and -72.35 kg CO_2-equivalents/FU, it was further found that the Bus substitution is very sensitive, and a 10% increase in the parameter will reduce the total GWP with another 11.07%.

Further, it was identified that the greenhouse gas with the most impact on the GWP, is biological methane at a total of 55.32 kg CO_2-equivalents and further it was found that the most important impact reduction is represented by fossil carbon dioxide at -459.04 kg CO_2-equivalalents.

While the bus substitution represent the largest impact reduction, it represent substitution of diesel, however as Bergen utilise a good number of buses running on natural gas it is more likely that the produced biomethane will replace natural gas and not diesel. If natural gas and not diesel is replaced then the substitution effect is bound to be lower, however even if the total process of Bus substitution is reduced to 20% of original value, the net total impact of the chosen case is -45.81 kg CO2-equivalents and still represent a reduction of impacts caused by the system.

5.2. Comparison with literature

For the NR and PR there is not much literature on these calculations, however there are a couple of master thesis written here at NTNU that writes about such results; “Life Cycle Assessment of Biogas/Biofuel Production from Organic Waste” by Seldal (2014) and “Analysis of Sewage Sludge Recovery System in EU - in Perspectives of Nutrients and Energy Recovery Efficiency, and Environmental Impacts” by Xu (2014).

Seldal (2014) reports NR at 26.1% and PR at 7.8%, those numbers are for the biogas plant Romerike Biogas Plant (RBP) outside Oslo, further for the plant she informs of an energy efficiency of 26.1%.

Xu (2014) however, presents an estimated NR at 40%, and PR at 21%, this is for the scenario where anaerobic digestion is applied and the bioresidual is used as biofertiliser, further such a treatment method yields an energy efficiency around 30%.

When it comes to the NR, the results from the study correlates to the cases compared to, where the calculated number of 35.37%, somewhat higher than calculated by Seldal (2014) (26.1%), the real difference comes in terms of the PR. Which, for this report is calculated at 90% efficiency, this is rather high, however as this efficiency assumes no other losses than in the AD process it stands. Informed by Bernstad & la Cour Jansen (2011) is a loss of 19% from P from entering the process and to application, this is somewhat higher than what has been applied in this report, however it does not change drastically the gap between the results informed above.

Further similarities can be found in the energy efficiency calculated and with those informed, the calculated energy efficiency is 32.23%, which is very similar to the data presented by Xu (2014), at around 30%, and by Seldal (2014), at 26.1%. This makes the results found in this report close to and comparable to literature.

The process energy of the system including only what is needed for the plant directly in, amount to around 8% of the feedstock energy, calculated from the HHV content of each feedstock substrates, Berglund & Börjesson (2006) informs from their results that from large scale biogas that the energy needed for process and transport amount to approximately 20-40% of the biogas energy output. Furthermore, the process energy is to about 40-80% of the energy input required from both processing and transport. However, the estimated numbers shown above does not include the feedstock energy. From this report it is found that the energy inputs for process and transport amounts to approximately 24% of the biomethane energy output. This is well within what is informed by Berglund & Börjesson (2006). However, when looking at the process energy alone, this amounts to about 95% of the total process and transport energy. This is a lot more than the 40-80% used by Berglund & Börjesson (2006). However, the transport distances are to blame for this, for the case of RBP the distances are generally short because of being in a city and better defined because of a specific case.

As mentioned in chapter 2.1.1, Adelt et al. (2011) argues that a 80% reduciton in GHG can be expected, based in the experiences, if substituting natural gas, a reduciton of 145.5% takes place for the system chosen. Further, Hung & Solli (2012) shows results of 5% reduction in GWP when using biomethane in the system of Trondheim, however this is expected to be low as there is a large use of natural gas, hybrid buses and biodiesel.

5.3. Strength and weakness

Since this study utilises both MFA and LCA on the system of RBP, this can contribute to a more robust analysis, as the MFA can contribute and act beneficial for the life cycle inventory and thus the LCA done on the system. The MFA can be used to fill in the blanks in the LCA, blanks caused by uncertainties or lack of information.

By the use of MFA and tracing flows, the substitution effects of example nutrients were found, and transferred to the LCA, and by combining MFA and LCA it is possible to see how the system perform in terms of efficiencies and the environmental impact performances.

Common weaknesses.

Common weaknesses are due to using the MFA calculations as basis for both models, and further basic numbers are the same for both methods.

Feedstock inputs. Uncertainties around the incoming feedstock are relevant, as they will have a direct influence on the energy output from both biogas production and incineration. Sewage sludge represent the majority of the incoming feedstock, which limits the influence of the remaining feedstock on the biogas production. However, as commercial food waste consist of around 9% of the incoming feedstock it can be expected that this might affect the output to some extent.

Heavy metals. Heavy metals in the bioresidual is of some uncertainty, information about the heavy metal content is given from one plant, with a chemical process, according to (Akervold 2015a) a somewhat lower heavy metal content can be expected from the other sludge, biological process, meaning that the uncertainty about reaching class 2 (see chapter …) is low. However, as this could change the human toxicity potential a lot, removal of bioresidual via incineration was included as separate cases.

Nitrogen related-, and methane emissions from storage and application. Emissions related to Nitrogen have a certain uncertainty associated to them, this is also for methane loss, both from storage and application of bioresidual. This is because the emissions related to nitrogen can vary a lot, depending on the type of soil, the amount of rainfall, and so on. Also the total loss of N is based on the average of two values from Bernstad & la Cour Jansen (2011) and then the separation between storage and application as according to Amon et al. (2006).

The methane loss is calculated by finding a transfer coefficient that will give the same methane loss as Amon et al. (2006), meaning there is a uncertainty related here as the loss is based on someone else’s calculations. However, the potential biogas left in the bioresidual calculates with the same method as calculating the biogas potential, the potential not realised by the AD efficiency. Similar biogas quality is assumed in order to achieve the same methane content. Then further, the separation of the methane loss between storage and application assumes the same relationship as given by Amon et al. (2006), thus reducing the uncertainty about the actual loss. Emissions from storage and application is something that is uncertain because the conditions of storage and application varies, open storage, closed storage, compost of bioresidual, or application as fertiliser, what is the type of soil, how much rainfall is there, etc.

These are all parameters that will affect the emissions, and then some, and thusly it is important to do actual measurement from location to location in order to get the correct emission for the individual system.

Weaknesses in the MFA.

Since the LCA bases itself on the calculations performed in the MFA, any mistakes in the MFA will then be performed in the LCA as well, something that makes it very important to perform the MFA very thorough. The MFA model does not illustrate losses in different processes well, and as some processes are aggregated the visual level drops. As the calculations are done with the use of MFA methodology and not performed as a proper MFA, there are some weaknesses related. This does not necessary create mistakes, although it makes the overview of calculations somewhat messy.

Weaknesses in the LCA.

Shown in the sensitivity for the LCA, when running the sensitivity on the AD efficiency the HTP changes -8.65% and 8.65% due to the +-10% change done on the parameter. In reality this is wrong, because the amount of heavy metals are not changed due to this parameter, however the concentration is, since this is not implemented in the SimaPro model, the changes to the concentration has to be manually implemented from the Excel model.

The same goes for the process of Bus substitution, where the amount of kilometre a bus is able to drive from the produced biomethane has to be imported from Excel. Further, the parameter of People per bus has to be changed manually, further reducing the flexibility of the model. The AD efficiency can be used as example here as well, where this parameter affects the biogas produced, and thus the biomethane for use. This was not made flexible for the amount of kilometre the bus could drive on the produced biomethane, meaning in reality this parameter should have a higher impact if changed on the GWP and other impact categories.

Aggregation of processes makes it easy to find the locations of impacts, however, the aggregation lower the visual performance of the system, for example the impact of the chosen system should be somewhat higher, but because the positive impact from bus use is aggregated in the bus substitution this is not shown. Similar aggregation are applied for several processes, which makes it somewhat harder to see the split down of the results, and require some further work in order to analyse.

Other weaknesses in the LCA model in SimaPro is rounding done by SimaPro when doing calculations in the program. That means that some detail is lost when re-doing calculations performed for the MFA in the LCA.

5.4. Further work

Further work of interest is to analyse the plant when completed in order to get actual operation data, rather than estimated process data, and further improve the system down to the actual flow of feedstock throughout the system, not just the FU defined. In addition to this, one could improve the general model for this purpose and also improve the SimaPro model to be less dependent on excel, and thereby have everything in the model and to make sure flexibility is in order for all flows.

Supplementing and further develop the model with more information related to emission from different stages, and implementing more processes, this is essential steps to improve the model, achieving the necessary accuracy. Upgrade parameter calculations to be more flexible, meaning they will be more dependent on other calculations included for the parameters needing upgrading. Examples of such parameters are heavy metal levels and numbers of kilometre possible to drive a bus with the produced biomethane.

Furthermore, another work of interest would be to collect more information related to nutrients, as there is lack of information regarding losses; it would be interesting to get new information here, especially from Norwegian conditions in order to get the most accurate results.

6. Conclusion

As mentioned in chapter 2.6, the main focus on biogas utilisation for the future is on manure and food waste, separate or in co-digestion. However, most biogas plants today utilise sewage sludge as main or as sole input.

From the MFA the results for the MR, NR and PR are the following, 53.96%, 35.37% and 90%, and lastly the energy efficiency at 32.23%. Compared to literature these results are in accordance with previous studies, these results bases on use of the bioresidual, if not used the MR would be reduced while the NR and PR would be inaccessible, this would in turn reduce the substitution effect.

The sensitivity analysis of the MFA system shows that the AD efficiency is the parameter with the largest effect on the RR and energy efficiency. However as mentioned the uncertainty is low due to process guarantee, the sensitivity shows that stability in the digestion chamber is one of the most important process parameters and should be measured carefully. The stability of the digestion process also affect the biogas production, as shown in the sensitivity, has large effect on the energy efficiency both ways, stability and the proper mix is thusly very important to ensure a high efficiency on the entire system, and should measure same as the AD efficiency.

Results from the LCA shows that the impacts in GWP for the chosen case is 147.62 kg CO_2-equivalents/FU and the substitution effect amounts to -556.4 kg CO_2-equivalents/FU. Total reduction in GWP shows a total reduction of -321% compared to the base case. Further, results show reductions in all impact categories looked at, with reductions at -36%, -12%, and -409% for TAP, HTP and FDP.

When looking at the combined results from both the MFA and the LCA, where Case 1 stands out with utilisation of the bioresidual as fertiliser substitute and biomethane to replace diesel as fuel for buses. However as the biomethane probably for starters will substitute natural gas in use, the substitution effect is thought to be lower, even so this would still favour the system defined for Case 1, which is also the preferred system by Bergen municipal when the construction of the biogas plant is completed.

This study is applicable as a system description of the projected biogas plant. It highlight substrate variations and how these will affect the overall biogas production and the resulting environmental performance, it further give indications of the overall system performances and show where uncertainties lie and where to ensure stability. The report should however not be directly applied as a given system rule as there is uncertainties concerning data.

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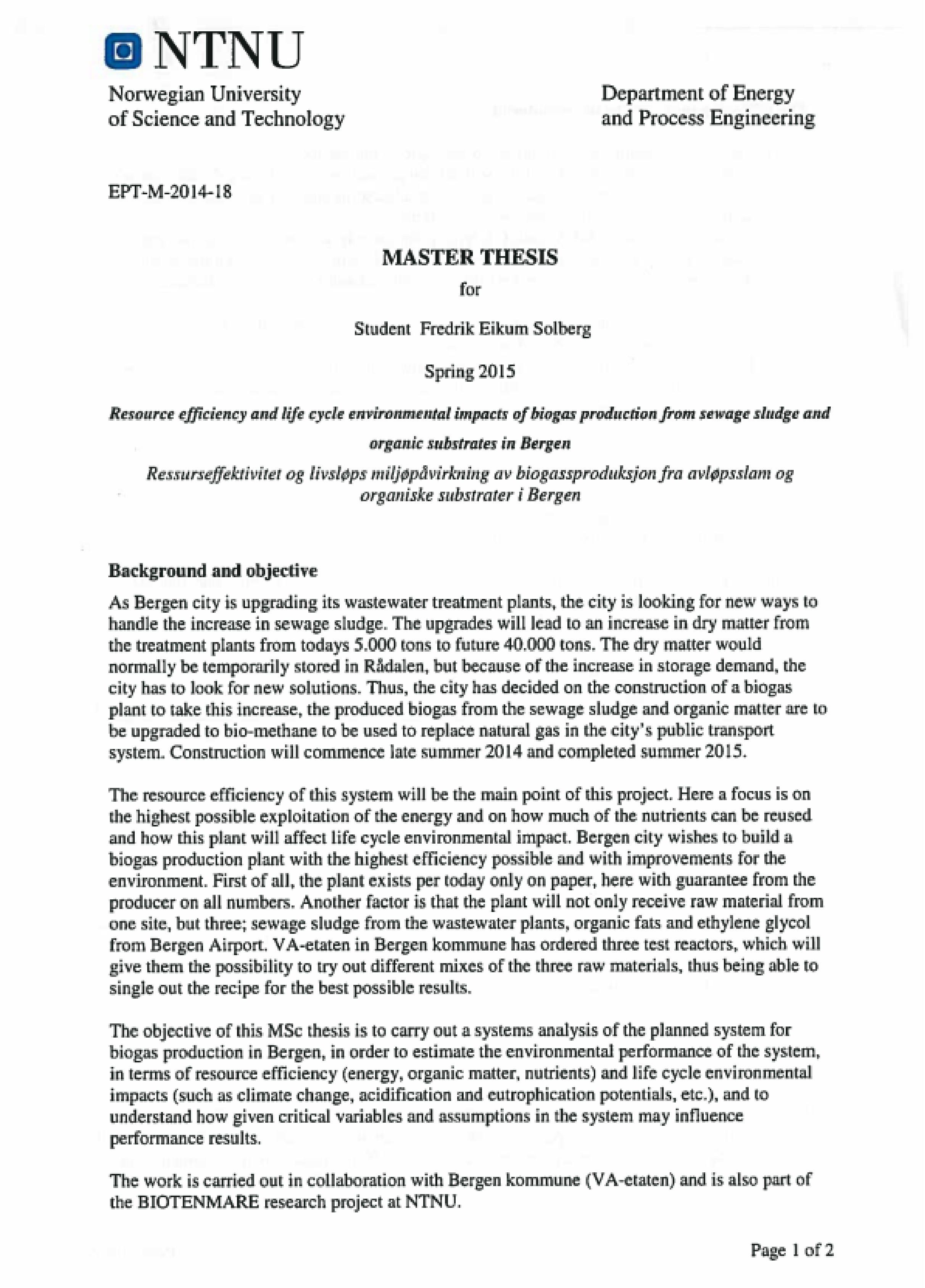
Appendix

Appendix 1 Master description



NTNU
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Department of Energy
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MASTER THESIS
for
Student Fredrik Eikum Solberg
Spring 2015

Resource efficiency and life cycle environmental impacts of biogas production from sewage sludge and organic substrates in Bergen

Ressurseffektivitet og livsløps miljøpåvirkning av biogassproduksjon fra avløpsslam og organiske substrater i Bergen

Background and objective

As Bergen city is upgrading its wastewater treatment plants, the city is looking for new ways to handle the increase in sewage sludge. The upgrades will lead to an increase in dry matter from the treatment plants from todays 5.000 tons to future 40.000 tons. The dry matter would normally be temporarily stored in Rådalen, but because of the increase in storage demand, the city has to look for new solutions. Thus, the city has decided on the construction of a biogas plant to take this increase, the produced biogas from the sewage sludge and organic matter are to be upgraded to bio-methane to be used to replace natural gas in the city's public transport system. Construction will commence late summer 2014 and completed summer 2015.

The resource efficiency of this system will be the main point of this project. Here a focus is on the highest possible exploitation of the energy and on how much of the nutrients can be reused and how this plant will affect life cycle environmental impact. Bergen city wishes to build a biogas production plant with the highest efficiency possible and with improvements for the environment. First of all, the plant exists per today only on paper, here with guarantee from the producer on all numbers. Another factor is that the plant will not only receive raw material from one site, but three; sewage sludge from the wastewater plants, organic fats and ethylene glycol from Bergen Airport. VA-etaten in Bergen kommune has ordered three test reactors, which will give them the possibility to try out different mixes of the three raw materials, thus being able to single out the recipe for the best possible results.

The objective of this MSc thesis is to carry out a systems analysis of the planned system for biogas production in Bergen, in order to estimate the environmental performance of the system, in terms of resource efficiency (energy, organic matter, nutrients) and life cycle environmental impacts (such as climate change, acidification and eutrophication potentials, etc.), and to understand how given critical variables and assumptions in the system may influence performance results.

The work is carried out in collaboration with Bergen kommune (VA-etaten) and is also part of the BIOTENMARE research project at NTNU.

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The work is carried out in collaboration with Bergen kommune (VA-etaten) and is also part of the BIOTENMARE research project at NTNU.

The following tasks are to be considered:

1) Carry out a literature study relevant to the topic of this project.
2) Provide a systems definition of the system you are analysing, including description of goal and scope, system boundaries and technical descriptions, for selected scenarios and/or configurations of technological solutions.
3) Develop quantitative MFA and LCA models for your system, with data so that you assuming the intended situation in 2020 and according to the relevant solutions within this system. Calculate the resource efficiency and potential life cycle environmental impacts of the system.
4) Document own assumptions and sources for your input variables and choices, and perform a sensitivity analysis of your system.
5) Discuss the overall findings of your work, agreement with literature, what are critical variables and assumption, strengths and weaknesses of your methods, and recommendations for further work.

-- " --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, that they are presented in tabular and/or graphic form in a clear manner, and that they are analysed carefully.

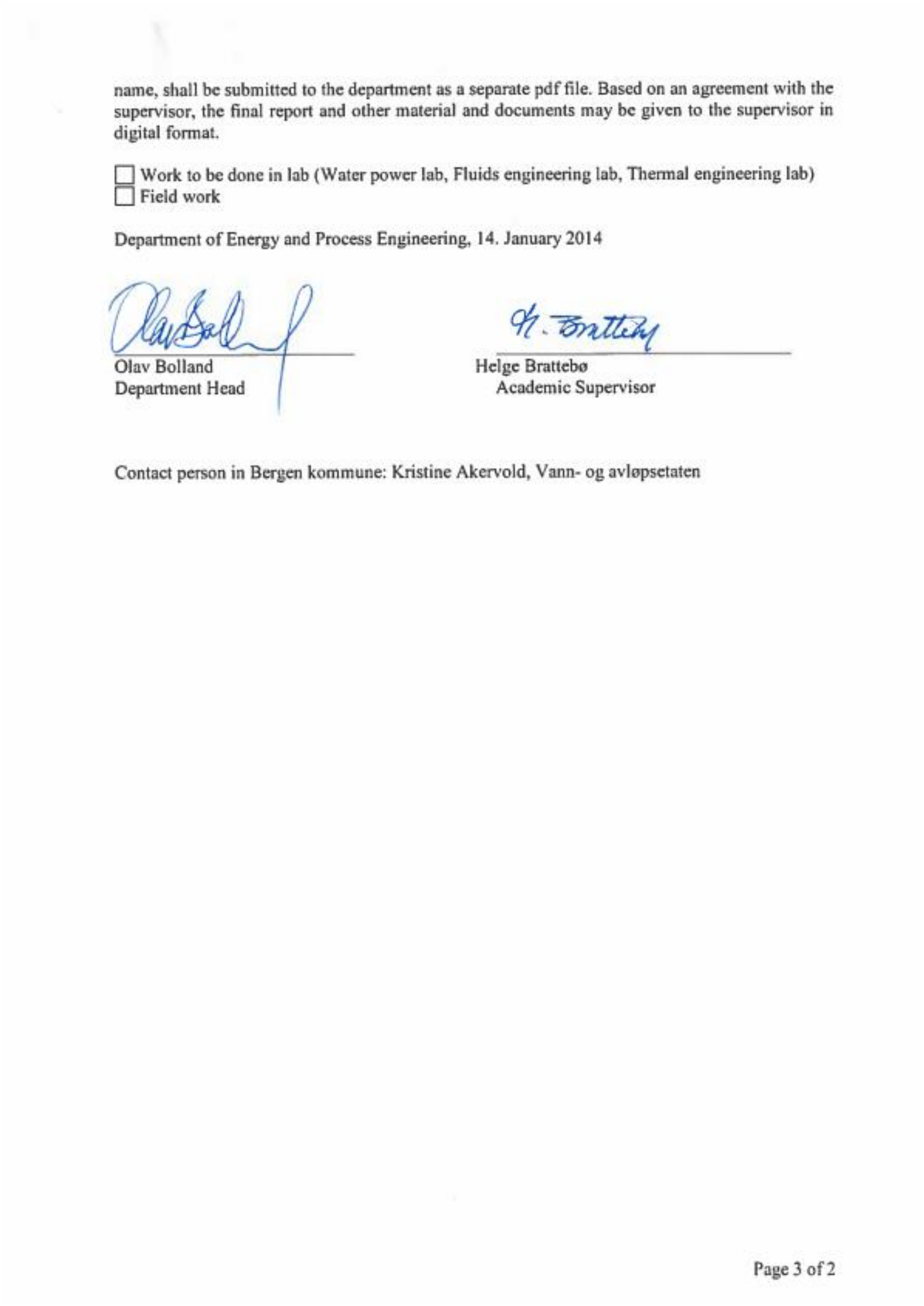
The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the



name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
Department Head

Helge Brattebø
Academic Supervisor

Contact person in Bergen kommune: Kristine Akervold, Vann- og avløpsetaten

Appendix 2 Inventory table Case 0

Case 0: Inventory for 9 196 tons DM			
Process	**Direction**	**Unit**	**Amount**
Septic dewatering process			
Electricity	input	kWh	4 978
Septic	input	m3	3 560
Transport	input	tkm	75 353
Transport (diesel)	input	tons	1,66
Water	output	m3	3 293
Septic (dewatered)	output	m3	267
Reject water [WWTP] process			
Electricity	input	kWh	1 180
Reject water [WWTP]	input	m3	3 293
Reject water [WWTP]	output	m3	3 293
Sløvåg collection process			
Kvernevik [bio]	input	m3	1 922
Ytre Sandviken [bio]	input	m3	1 650
Flesland [bio]	input	m3	5 542
Holen [bio]	input	m3	3 392
Garnes [bio]	input	m3	738
Knappen [Chem]	input	m3	2 370
Septic	input	m3	134
Transport	input	tkm	1 277 599
Transport (diesel)	input	tons	28
Mixed sludge	output	m3	15 748
Odda collection process			
Kvernevik [bio]	input	m3	1 922
Ytre Sandviken [bio]	input	m3	1 650
Flesland [bio]	input	m3	5 542
Holen [bio]	input	m3	3 392
Garnes [bio]	input	m3	738
Knappen [Chem]	input	m3	2 370
Septic	input	m3	134
Transport	input	tkm	2 084 818
Transport (diesel)	input	tons	46
Mixed sludge	output	m3	15 748
Incineration collection process			
Commercial food waste	input	m3	3 252
Cooking oil	input	m3	160
Grease waste	input	m3	80
Transport	input	tkm	56 285
Transport (diesel)	input	tons	1,24
Incineration feedstock	output	m3	3 492
WWT process			
Electricity	input	kWh	4 591
Glycol	input	m3	900
Reject water [WWTP]	input	m3	3 293
Compost process			

Electricity	input	kWh	243 723
Application [Diesel]	input	tons	68,24
Mixed sludge	input	m3	31 495
Nitrogen	input	tons	203
Phosphorus	input	tons	57
CH4 emissions	output	tons	42
NH3 emissions	output	tons	82
N2O emissions	output	tons	1
N2 emissions	output	tons	2
Nitrogen	output	tons	117
Phosphorus	output	tons	57
Incineration process			
Electricity	input	kWh	257 845
Incineration feedstock	input	m3	3 492
Bottom ash	output	tons	126
Fly ash	output	tons	14
Heat	output	MJ	12 623 266
Electricity	output	kWh	467 528
Bottom ash transport process			
Bottom ash	input	tons	126
Transport	input	tkm	1 693
Transport [diesel]	input	tons	0,04
Fly ash transport process			
Fly ash	input	tons	14
Transport	input	tkm	8 100
Transport [diesel]	input	tons	0,18

Appendix 3 Inventory table Case 1

Case 1: Inventory for 9 196 tons DM			
Process	**Direction**	**Unit**	**Amount**
Collection process			
Kvernevik [bio]	input	m3	3 844
Ytre Sandviken [bio]	input	m3	3 300
Flesland [bio]	input	m3	11 084
Holen [bio]	input	m3	6 784
Garnes [bio]	input	m3	1 476
Knappen [Chem]	input	m3	4 740
Septic	input	m3	3 560
Commercial food waste	input	m3	3 252
Cooking oil	input	m3	160
Grease waste	input	m3	80
Glycol	input	m3	900
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Transport	input	tkm	624 263
Transport [diesel]	input	tons	14
Electricity	input	kWh	151 380
Mixed sludge	output	m3	39 180
Water import process			
Electricity	input	kWh	8 050
Water	input	m3	22 461
Water	output	m3	22 461
Pretreatment process			
Heat	input	MJ	11 399 354
Water	input	m3	22 461
Reject water [pretreatment]	input	m3	91 478
Sludge	input	m3	39 180
Watered sludge	output	m3	153 118
Hygienisation process			
Electricity	input	kWh	473 558
Watered sludge	input	m3	153 118
Hygienisated sludge	output	m3	153 118
Anaerobic digestion process			
Electricity	input	kWh	237 082
Hygienisated sludge	input	m3	153 118
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Nitrogen loss	output	tons	27,9
Phosphorus loss	output	tons	6,1
Nitrogen	output	tons	192,5
Phosphorus	output	tons	54,5
Bioresidual [wet]	output	m3	149 026
Destroyed matter	output	tons	4 058
Bioresidual dewatering process			
Electricity	input	kWh	213 216

Bioresidual [wet]	input	m3	149 026
Polymer	input	tons	26
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP]	output	m3	40 486
Bioresidual [DM]	output	m3	5 095
Bioresidual [dry]	output	m3	17 062
Reject water [pretreatment] process			
Nitrogen	input	tons	40
Reject water [pretreatment]	input	m3	91 478
Nitrogen	output	tons	40
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP] process			
Electricity	input	kWh	14 511
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 486
Nitrogen	output	tons	18
Reject water [WWTP]	output	m3	40 511,56
WWT process			
Electricity	input	kWh	44 360
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 512
Bioresidual storage process			
Bioresidual [DM]	input	m3	5 037
Bioresidual [dry]	input	m3	17 004
Nitrogen	input	tons	134
Phosphorus	input	tons	55
CH4 emissions	output	tons	22,83
NH3 emissions	output	tons	2,3
N2O emissions	output	tons	0,7
N2 emissions	output	tons	0,7
Bioresidual [DM]	output	m3	5 010
Bioresidual [dry]	output	m3	16 978
Nitrogen	output	tons	131
Phosphorus	output	tons	55
Bioresidual application process			
Electricity	input	kWh	16 197
Transport	input	tkm	324 635
Transport [diesel]	input	ton	7
Application [Diesel]	input	ton	3,72
Bioresidual [DM]	input	m2	5 010
Bioresidual [dry]	input	m3	16 978
Nitrogen	input	tons	131
Phosphorus	input	tons	55
CH4 emissions	output	tons	0,03
NH3 emissions	output	tons	52
N2O emissions	output	tons	0
N2 emissions	output	tons	1
Total Nitrogen	output	tons	78
Plant available N	output	tons	66

Plant available P	output	tons	55
Bioresidual applied [DM]	output	tons	4 958
Bioresidual applied	output	tons	16 925
Biogas system process			
Electricity	input	kWh	33 624
Destroyed matter	input	tons	4 058
Biogas	input	Nm3	3 661 362
Destroyed matter	output	tons	4 058
Biogas	output	Nm3	3 661 362
Biogas upgrade process			
Electricity	input	kWh	842 113
Destroyed matter	input	tons	4 058
Biogas	input	Nm3	3 661 362
Water	input	m3	805
CH4 emissions	output	tons	17
CO2 emissions	output	tons	2 325
Water	output	m3	805
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane compression process			
Electricity	input	kWh	506 574
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane transport process			
Transport	input	tkm	16 897
Transport [diesel]	input	tons	0,37
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane tanking process			
Electricity	input	kWh	253 287
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane application process			
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608

Appendix 4 Inventory table Case 2

Case 2: Inventory for 9 196 tons DM			
Process	**Direction**	**Unit**	**Amount**
Collection process			
Kvernevik [bio]	input	m3	3 844
Ytre Sandviken [bio]	input	m3	3 300
Flesland [bio]	input	m3	11 084
Holen [bio]	input	m3	6 784
Garnes [bio]	input	m3	1 476
Knappen [Chem]	input	m3	4 740
Septic	input	m3	3 560
Commercial food waste	input	m3	3 252
Cooking oil	input	m3	160
Grease waste	input	m3	80
Glycol	input	m3	900
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Transport	input	tkm	624 263
Transport [diesel]	input	tons	14
Electricity	input	kWh	151 380
Mixed sludge	output	m3	39 180
Water import process			
Electricity	input	kWh	8 050
Water	input	m3	22 461
Water	output	m3	22 461
Pretreatment process			
Heat	input	MJ	11 399 354
Water	input	m3	22 461
Reject water [pretreatment]	input	m3	91 478
Sludge	input	m3	39 180
Watered sludge	output	m3	153 118
Hygienisation process			
Electricity	input	kWh	473 558
Watered sludge	input	m3	153 118
Hygienisated sludge	output	m3	153 118
Anaerobic digestion process			
Electricity	input	kWh	237 082
Hygienisated sludge	input	m3	153 118
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Nitrogen loss	output	tons	27,9
Phosphorus loss	output	tons	6,1
Nitrogen	output	tons	192,5
Phosphorus	output	tons	54,5
Bioresidual [wet]	output	m3	149 026
Destroyed matter	output	tons	4 058
Bioresidual dewatering process			
Electricity	input	kWh	213 216

Bioresidual [wet]	input	m3	149 026
Polymer	input	tons	26
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP]	output	m3	40 486
Bioresidual [dry]	output	m3	17 062
Reject water [pretreatment] process			
Nitrogen	input	tons	40
Reject water [pretreatment]	input	m3	91 478
Nitrogen	output	tons	40
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP] process			
Electricity	input	kWh	14 511
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 486
Nitrogen	output	tons	18
Reject water [WWTP]	output	m3	40 512
WWT process			
Electricity	input	kWh	44 360
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 512
Incineration process			
Electricity	input	kWh	1 351 845
Bioresidual [DM]	input	m2	5 037
Bioresidual [dry]	input	m3	17 004
Bottom ash	output	tons	2 195
Fly ash	output	tons	244
Heat	output	MJ	25 810 626
Electricity	output	kWh	955 949
Bottom ash transport process			
Bottom ash	input	tons	2 195
Transport	input	tkm	5 356
Transport [diesel]	input	tons	0,12
Fly ash transport process			
Fly ash	input	tons	244
Transport	input	tkm	6 386
Transport [diesel]	input	tons	0,14
Biogas system process			
Electricity	input	kWh	33 624
Destroyed matter	input	tons	153 118
Biogas	input	Nm3	3 661 362
Destroyed matter	output	tons	4 058
Biogas	output	Nm3	3 661 362
Biogas upgrade process			
Electricity	input	kWh	842 113
Destroyed matter	input	tons	4 058
Biogas	input	Nm3	3 661 362
Water	input	m3	805
CH4 emissions	output	tons	17
CO2 emissions	output	tons	2 325

Water	output	m3	805
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane compression process			
Electricity	input	kWh	506 574
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane transport process			
Transport	input	tkm	16 897
Transport [diesel]	input	tons	0,37
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane tanking process			
Electricity	input	kWh	253 287
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane application process			
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608

Appendix 5 Inventory table Case 3

Case 3: Inventory for 9 196 tons DM			
Process	**Direction**	**Unit**	**Amount**
Collection process			
Kvernevik [bio]	input	m3	3 844
Ytre Sandviken [bio]	input	m3	3 300
Flesland [bio]	input	m3	11 084
Holen [bio]	input	m3	6 784
Garnes [bio]	input	m3	1 476
Knappen [Chem]	input	m3	4 740
Septic	input	m3	3 560
Commercial food waste	input	m3	3 252
Cooking oil	input	m3	160
Grease waste	input	m3	80
Glycol	input	m3	900
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Transport	input	tkm	29 439 408
Transport [diesel]	input	tons	648
Electricity	input	kWh	151 380
Mixed sludge	output	m3	39 180
Water import process			
Electricity	input	kWh	8 050
Water	input	m3	22 461
Water	output	m3	22 461
Pretreatment process			
Heat	input	MJ	11 399 354
Water	input	m3	22 461
Reject water [pretreatment]	input	m3	91 478
Sludge	input	m3	39 180
Watered sludge	output	m3	153 118
Hygienisation process			
Electricity	input	kWh	473 558
Watered sludge	input	m3	153 118
Hygienisated sludge	output	m3	153 118
Anaerobic digestion process			
Electricity	input	kWh	237 082
Hygienisated sludge	input	m3	153 118
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Nitrogen loss	output	tons	27,9
Phosphorus loss	output	tons	6,1
Nitrogen	output	tons	192,5
Phosphorus	output	tons	54,5
Bioresidual [wet]	output	m3	149 026
Destroyed matter	output	tons	4 058
Bioresidual dewatering process			
Electricity	input	kWh	213 216

Bioresidual [wet]	input	m3	149 026
Polymer	input	tons	26
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP]	output	m3	40 486
Bioresidual [DM]	output	m3	5 095
Bioresidual [dry]	output	m3	17 062
Reject water [pretreatment] process			
Nitrogen	input	tons	40
Reject water [pretreatment]	input	m3	91 478
Nitrogen	output	tons	40
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP] process			
Electricity	input	kWh	14 511
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 486
Nitrogen	output	tons	18
Reject water [WWTP]	output	m3	40 512
WWT process			
Electricity	input	kWh	44 360
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 512
Bioresidual storage process			
Bioresidual [DM]	input	m3	5 037
Bioresidual [dry]	input	m3	17 004
Nitrogen	input	tons	134
Phosphorus	input	tons	55
CH4 emissions	output	tons	22,83
NH3 emissions	output	tons	2
N2O emissions	output	tons	1
N2 emissions	output	tons	1
Bioresidual [DM]	output	m3	5 010
Bioresidual [dry]	output	m3	16 978
Nitrogen	output	tons	131
Phosphorus	output	tons	55
Bioresidual application process			
Electricity	input	kWh	16 197
Transport	input	tkm	324 635
Transport [diesel]	input	ton	7
Application [Diesel]	input	ton	3,72
Bioresidual [DM]	input	m2	5 010
Bioresidual [dry]	input	m3	16 978
Nitrogen	input	tons	131
Phosphorus	input	tons	55
CH4 emissions	output	tons	0,03
NH3 emissions	output	tons	52
N2O emissions	output	tons	0
N2 emissions	output	tons	1
Total Nitrogen	output	tons	78
Plant available N	output	tons	66

Plant available P	output	tons	55
Bioresidual applied [DM]	output	tons	4 958
Bioresidual applied	output	tons	16 925
Biogas system process			
Electricity	input	kWh	33 624
Destroyed matter	input	tons	4 058
Biogas	input	Nm3	3 661 362
Destroyed matter	output	tons	4 058
Biogas	output	Nm3	3 661 362
Biogas upgrade process			
Electricity	input	kWh	842 113
Destroyed matter	input	tons	4 058
Biogas	input	Nm3	3 661 362
Water	input	m3	805
CH4 emissions	output	tons	17
CO2 emissions	output	tons	2 325
Water	output	m3	805
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane compression process			
Electricity	input	kWh	506 574
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane transport process			
Transport	input	tkm	16 897
Transport [diesel]	input	tons	0,37
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane tanking process			
Electricity	input	kWh	253 287
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane application process			
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608

Appendix 6 Inventory table Case 4

Case 4: Inventory for 9 196 tons DM			
Process	**Direction**	**Unit**	**Amount**
Collection process			
Kvernevik [bio]	input	m3	3 844
Ytre Sandviken [bio]	input	m3	3 300
Flesland [bio]	input	m3	11 084
Holen [bio]	input	m3	6 784
Garnes [bio]	input	m3	1 476
Knappen [Chem]	input	m3	4 740
Septic	input	m3	3 560
Commercial food waste	input	m3	3 252
Cooking oil	input	m3	160
Grease waste	input	m3	80
Glycol	input	m3	900
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Transport	input	tkm	29 439 408
Transport [diesel]	input	tons	648
Electricity	input	kWh	151 380
Mixed sludge	output	m3	39 180
Water import process			
Electricity	input	kWh	8 050
Water	input	m3	22 461
Water	output	m3	22 461
Pretreatment process			
Heat	input	MJ	11 399 354
Water	input	m3	22 461
Reject water [pretreatment]	input	m3	91 478
Sludge	input	m3	39 180
Watered sludge	output	m3	153 118
Hygienisation process			
Electricity	input	kWh	473 558
Watered sludge	input	m3	153 118
Hygienisated sludge	output	m3	153 118
Anaerobic digestion process			
Electricity	input	kWh	237 082
Hygienisated sludge	input	m3	153 118
Nitrogen	input	tons	220,4
Phosphorus	input	tons	60,6
Nitrogen loss	output	tons	27,9
Phosphorus loss	output	tons	6,1
Nitrogen	output	tons	192,5
Phosphorus	output	tons	54,5
Bioresidual [wet]	output	m3	149 026
Destroyed matter	output	tons	4 058
Bioresidual dewatering process			
Electricity	input	kWh	213 216

Bioresidual [wet]	input	m3	149 026
Polymer	input	tons	26
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP]	output	m3	40 486
Bioresidual [dry]	output	m3	17 062
Reject water [pretreatment] process			
Nitrogen	input	tons	40
Reject water [pretreatment]	input	m3	91 478
Nitrogen	output	tons	40
Reject water [pretreatment]	output	m3	91 478
Reject water [WWTP] process			
Electricity	input	kWh	14 511
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 486
Nitrogen	output	tons	18
Reject water [WWTP]	output	m3	40 512
WWT process			
Electricity	input	kWh	44 360
Nitrogen	input	tons	18
Reject water [WWTP]	input	m3	40 512
Incineration process			
Electricity	input	kWh	1 351 845
Bioresidual [DM]	input	m2	5 037
Bioresidual [dry]	input	m3	17 004
Bottom ash	output	tons	2 195
Fly ash	output	tons	244
Heat	output	MJ	25 810 626
Electricity	output	kWh	955 949
Bottom ash transport process			
Bottom ash	input	tons	2 195
Transport	input	tkm	19 536
Transport [diesel]	input	tons	429,99
Fly ash transport process			
Fly ash	input	tons	244
Transport	input	tkm	65 362
Transport [diesel]	input	tons	1 438,66
Biogas system process			
Electricity	input	kWh	33 624
Destroyed matter	input	tons	153 118
Biogas	input	Nm3	3 661 362
Destroyed matter	output	tons	4 058
Biogas	output	Nm3	3 661 362
Biogas upgrade process			
Electricity	input	kWh	842 113
Destroyed matter	input	tons	4 058
Biogas	input	Nm3	3 661 362
Water	input	m3	805
CH4 emissions	output	tons	17
CO2 emissions	output	tons	2 325

Water	output	m3	805
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane compression process			
Electricity	input	kWh	506 574
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane transport process			
Transport	input	tkm	16 897
Transport [diesel]	input	tons	0,37
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane tanking process			
Electricity	input	kWh	253 287
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608
Biomethane	output	tons	1 716
Biomethane	output	Nm3	2 302 608
Biomethane application process			
Biomethane	input	tons	1 716
Biomethane	input	Nm3	2 302 608

Appendix 7 MFA parameters

	Parameters	**Short name**	**Value**	**Unit**
	Sewage sludge (incl. Septic)			
1	Sewage sludge (aggregated, incl. Septic)	DM_1.6	8133	[ton/year]
2	Kvernevik [bio]		961	[ton/year]
3	Ytre Sandviken [bio]		825	[ton/year]
4	Flesland [bio]		2771	[ton/year]
5	Holen [bio]		1696	[ton/year]
6	Garnes [bio]		369	[ton/year]
7	Knappen [Chem]		1422	[ton/year]
8	Septic		89	[ton/year]
9	DM in biological sludge		0,25	[%]
10	DM in chemical sludge/septic after dewatering		0,3	[%]
11	DM in septic		0,025	[%]
12	Seperation of inrganics in Septic (eg. Sand)		0,1	[%]
13	VS in biological sludge		0,70	[%]
14	VS in chemical sludge		0,77	[%]
15	VS in septic		0,65	[%]
	Heavy metal content in sludge from Knappen			
16	Cadmium (Cd)		0,3	[mg/kg DM]
17	Lead (Pb)		8,8	[mg/kg DM]
18	Mercury (Hg)		0,2	[mg/kg DM]
19	Nickel (Ni)		5,1	[mg/kg DM]
20	Zinc (Zn)		235	[mg/kg DM]
21	Copper (Cu)		94	[mg/kg DM]
22	Cromium (Cr)		7,8	[mg/kg DM]
23	Heavy metal content in biological sludge compared to chemical sludge (% of)		0,9	[%] *assumed
24	**Commercial waste**	DM_2.6	813	[ton/year]
25	DM in Commerical waste		0,25	[%]
26	VS in Commercial waste		0,85	[%]
27	**Cooking oil**	DM_3.6	152	[ton/year]
28	DM in Cooking oil		0,95	[%]
29	VS in Cooking oil		0,9	[%]
30	**Grease waste**	DM_4.6	8	[ton/year]
31	DM in Grease waste		0,1	[%]

32	VS in Grease waste		0,6	[%]
33	**Glycol**	DM_5.6	90	[ton/year]
34	"DM" in Glycol (% of glycol in mix)		0,1	[%]
35	VS in Glycol		1	[%]
	Phosphorus contents			
36	Biological sludge		0,006	[%]
37	Chemical sludge		0,014	[%]
38	Septic		0,014	[%]
39	Commercial waste		0,004	[%]
40	Cooking oil		-	[%]
41	Grease waste		0,004	[%]
42	Glycol		-	[%]
	Nitrogen contents			
43	Biological sludge		0,029	[%]
44	Chemical sludge		0,007	[%]
45	Septic		0,007	[%]
46	Commercial waste		0,022	[%]
47	Cooking oil		-	[%]
48	Grease waste		0,016	[%]
49	Glycol		-	[%]
	Biogas production			
50	Biological sludge		0,9	[Nm3/kg]
51	Chemical sludge		0,9	[Nm3/kg]
52	Septic		0,9	[Nm3/kg]
53	Commercial waste		0,9	[Nm3/kg]
54	Cooking oil		0,9	[Nm3/kg]
55	Grease waste		0,9	[Nm3/kg]
56	Glycol (per ton incoming feedstock)		100	[Nm3/kg]
	Higher Heating Values			
57	Sewage sludge (incl. Septic)		25,7	[MJ/kg DM]
58	Commercial waste		18,5	[MJ/kg DM]
59	Cooking oil		39,3	[MJ/kg DM]
60	Grease waste		37,3	[MJ/kg DM]
61	Glycol		18	[MJ/kg DM]

	Transport feedstock	Case 1+2	Case 3+4	
62	Kvernevik [bio]	25	745	[km]
63	Ytre Sandviken [bio]	19	747	[km]
64	Flesland [bio]	9	752	[km]
65	Holen [bio]	14	758	[km]
66	Garnes [bio]	47	730	[km]
67	Knappen [Chem]	13	756	[km]
68	Septic	21	748	[km]
69	Commercial food waste	16	754	[km]
70	Cooking oil	16	754	[km]
71	Grease waste	21	748	[km]
72	Glycol	9	752	[km]
	Transport Compost			
	Kvernevik [bio]			
73	to Sløvåg		60	[km]
74	to Odda		126	[km]
	Ytre Sandviken [bio]			
75	to Sløvåg		70	[km]
76	to Odda		128	[km]
	Flesland [bio]			
77	to Sløvåg		91	[km]
78	to Odda		134	[km]
	Holen [bio]			
79	to Sløvåg		80	[km]
80	to Odda		138	[km]
	Garnes [bio]			
81	to Sløvåg		75	[km]
82	to Odda		110	[km]

	Knappen [Chem]			
83	to Sløvåg		85	[km]
84	to Odda		136	[km]
	Septic			
85	to Rådalen		21	[km]
86	to Sløvåg		87	[km]
87	to Odda		129	[km]
	Transport other			
88	Biomethane		10	[km]
89	Natural gas		70	[km]
90	Bioresidual		19	[km]
91	Bottom ash (Norway)		42	[km]
92	Bottom ash (Sweden)		9	[km]
93	Fly ash (Norway)		455	[km]
94	Fly ash (Sweden)		268	[km]
	Technology parameters			
	Collection of substrates [aggregatet]			
95	Sludge		2,62	[kWh/m3]
96	Septic		6,64	[kWh/m3]
97	Commercial waste		8,59	[kWh/m3]
98	Grease waste and cooking oil		53,40	[kWh/m3]
99	Glycol		5,64	[kWh/m3]
	Pretreatment [aggregated]			
100	Heating of water		4,40	[MJ/°C/ton]
101	Efficiency of heating of water		0,95	[%]
102	Degreas needed heating by incineration plant		18	[°C]
	Hygienisation [aggregatet]			
103	Electricity [NOR]		3,09	[kWh/m3]
	Anaerobic digestion			
104	Electricity [NOR]		1,55	[kWh/m3]
105	Decomposation rate		0,6	[% of VS]
106	DM content into AD		0,06	[%]
107	Nitrogen loss		0,13	[%]
108	Phosphorus loss		0,1	[%]

	Bioresidual and reject			
109	Electricity [NOR]		1,40	[kWh/m3]
110	DM into dewatering		0,03	[%]
111	DM after dewatering		0,30	[%]
	Polymer			
112	Electricity [NOR]		0,95	[kWh/m3]
113	Polymer		5	[kg/DM]
	Reject water to WWTP [sewage pipes]			
114	Electricity [NOR]		0,36	[kWh/m3]
	Land application			
115	Diesel consumption		0,73	[kg diesel]
116	Electricity [NOR]		3,18	[kWh/ton DM]
117	Plant available N		0,85	[%]
118	Plant available P		1	[%]
	Biogas system; Biogas from AD to Biogas upgrading			
119	Electricity [NOR]		0,01	[kWh/Nm3]
	Biogas upgrading [corrected for per Nm3]			
120	Electricity [NOR]		0,23	[kWh/Nm3]
121	Water [H2O]		0,22	[l/Nm3]
122	Methane loss [CH4]		0,01	[%]
123	Methane content [CH4]		0,98	[%]
124	Methane loss		0,01	[kg]
	Biomethane compression			
125	Electricity [NOR]		0,22	[kWh/Nm3]
	Biomethane tanking			
126	Electricity [NOR]		0,11	[kWh/Nm3]
	Incineration [digestate]			
127	Energy efficiency [2013] Bergen municipal I.P.		0,725	[%]
128	Heat		0,640	[%]*calc.
129	Electricity		0,085	[%]*calc.
130	Electricity [NOR]		265	[kWh/ton DM]
	Ash is all that is not VS			
131	Bottom ash		0,9	[%]
132	Fly ash		0,1	[%]
133	HHV		8920	[MJ/ton DM]

	Compost			
134	Electricity [NOR]		30	[kWh/ton DM]
135	Diesel		8,4	[kg/ton DM]
	WWTP			
136	Electricity		1,095	[kWh/m3]

Appendix 8 LCA parameters

	SimaPro 8.0.3.14	calculation setups	07.06.2015
	Project	MasterThesis	
	Input parameters		
	Sewage_Sludge_and_Septic	0	--
1	Input_Kvernevik	961	DM input of Kvernevik
2	Input_YtreSandviken	825	DM input of Ytre Sandviken
3	Input_Flesland	2771	DM input of Flesland
4	Input_Holen	1696	DM input of Holen
5	Input_Garnes	369	DM input of Garnes
6	Input_Knappen	1422	DM input of Knappen
7	Input_Septic	89	DM input of Septic
8	DM_BioSludge	0,25	DM content of sewage sludge from biological treatment [%]
9	DM_ChemSludge	0,3	DM content of sewage sludge from chemical treatment [%]
10	DM_Septic	0,025	DM content of sewage sludge from septic [%]

11	DM_SepticCompost	0,3	
12	VS_ChemSludge	0,769	VS content of biological and chemical sludge and septic [%]
13	VS_BioSludge	0,7	
14	VS_Septic	0,65	
15	N_BioSludge	0,029	Kjeldahl nitrogen for sludge from biological treatment [%]
16	N_ChemSludgeSeptic	0,007	Kjeldahl nitrogen for sludge from chemical sludge and septic [%]
17	P_BioSludge	0,0055	Phosphorus content of biological sludge [%]
18	P_ChemSludgeSeptic	0,014	Phosphorus content of chemical sludge and septic [%]
19	CH4_SewageSludge	0,65	
			...
			Commercial waste
	Commercial_Waste	0	--
20	Input_CW	813	DM input of commercial waste
21	DM_CW	0,25	DM content of commercial waste [%]
22	VS_CW	0,85	VS content of commercial waste [%]
23	N_CW	0,0218	Kjeldahl nitrogen for commercial waste [%]
24	P_CW	0,0038	Phosphorus content of commercial waste [%]
25	CH4_CW	0,63	
			...
			Cooking oil

	Cooking_Oil	0	--
26	Input_CO	152	DM input of cooking oil
27	DM_CO	0,95	DM content of cooking oil [%]
28	VS_CO	0,9	VS content of cooking oil [%]
29	N_CO	0	Kjeldahl nitrogen for cooking oil [%]
30	P_CO	0	Phosphorus content of cooking oil [%]
31	CH4_CO	0,65	
			...
			Grease waste
	Grease_Waste	0	--
32	Input_GW	8	DM input of grease waste
33	DM_GW	0,1	DM content of grease waste [%]
34	VS_GW	0,6	VS content of grease waste [%]
35	N_GW	0	Kjeldahl nitrogen for grease waste [%]
36	P_GW	0	Phosphorus content of grease waste [%]
37	CH4_GW	0,68	
			...
			Glycol
	Glycol	0	--
38	Input_G	90	DM input of glycol
39	DM_G	0,1	DM content of glycol [%]
40	VS_G	1	VS content of glycol [%]
41	N_G	0	Kjeldahl nitrogen for glycol [%]
42	P_G	0	Phosphorus content of glycol [%]
43	CH4_G	0,653	assumed from average of other values for CH4 content
44	D_G	1	destruction % in the AD, Akervold 2015

			…
			Biogas production
45	AD_E	0,6	Decomposition efficiency of VS in the AD process
46	B_Kvernevik	0,9	0,9 Nm3/kg degraded matter
47	B_YtreSandviken	0,9	0,9 Nm3/kg degraded matter
48	B_Flesland	0,9	0,9 Nm3/kg degraded matter
49	B_Holen	0,9	0,9 Nm3/kg degraded matter
50	B_Garnes	0,9	0,9 Nm3/kg degraded matter
51	B_Knappen	0,9	0,9 Nm3/kg degraded matter
52	B_Septic	0,9	0,9 Nm3/kg degraded matter
53	B_CW	0,9	0,9 Nm3/kg degraded matter
54	B_CO	0,9	0,9 Nm3/kg degraded matter
55	B_GW	0,9	0,9 Nm3/kg degraded matter
56	B_G	100	100 Nm3/ton incoming substrate
57	CH4_Loss	0,01	1% loss in upgrade process
58	CH4_LossSA	1,3446	Methane loss from compost (assumed) and storage and application.
59	BioMethanePurity	0,98	Methane content of 98% in Biomethane
60	DM_AD	0,06	Sande et al. 2008
61	Weight_CO2	1,9768	kg/m3
62	Weight_CH4	0,72	kg/m3
63	Weight_Biomethane	0,745136	adjusted for the methane content

64	DM_Bioresidual	0,3	Sande et al. 2008
			…
			Incineration
65	H2O_HV	4,18	specific heating value of water
66	Flyash	0,1	what’s not VS goes into fly ash after incineration
67	Bottomash	0,9	what’s not VS goes into bottom ash after incineration
68	HHV_CW	18500	MJ/ton DM
69	HHV_CO	39300	MJ/ton DM
70	HHV_GW	37300	MJ/ton DM
71	HHV_Bioresidual	8920	MJ/ton DM
72	N_C	0,02397	ton N per ton DM compost
73	P_C	0,00708	ton P per ton DM compost
74	N_available	0,85	plant availability
75	P_available	1	plant availability
76	N_Content_H2O	0,001	ton/m3 H2O
77	P_AD_Loss	0,1	loss of P via the AD process
78	N_Removal_H2O	0,56	removal rate of N lost to water, assumed kept in dry mass
79	NH3_S	0,04	% of lost N
80	NH3_A	0,96	% of lost N
81	N2O_S	0,91	% of lost N
82	N2O_A	0,09	% of lost N
83	N2_S	0,48	% of lost N
84	N2_A	0,52	% of lost N
	Transport_	0	

	parameters		
			...
	Case_0	0	
	Case_12	0	Sande et al. 2008
85	Kvernevik_km12	25	Sande et al. 2008
86	YtreSandviken_km12	19	Sande et al. 2008
87	Flesland_km12	9	Sande et al. 2008
88	Holen_km12	14	Sande et al. 2008
89	Garnes_km12	47	Sande et al. 2008
90	Knappen_km12	13	Sande et al. 2008
91	CW_km012	16	Sande et al. 2008
92	CO_km012	16	Sande et al. 2008
93	G_km012	9	Sande et al. 2008
			...
95	Case_34	0	
96	Kvernevik_km34	745	from given location to Gothenburg downtown, Google Maps
97	YtreSandviken_km34	747	from given location to Gothenburg downtown, Google Maps
98	Flesland_km34	752	from given location to Gothenburg downtown, Google Maps
99	Holen_km34	758	from given location to Gothenburg downtown, Google Maps

100	Garnes_km34	730	from given location to Gothenburg downtown, Google Maps
101	Knappen_km34	756	from given location to Gothenburg downtown, Google Maps
102	Septic_km34	748	from given location to Gothenburg downtown, Google Maps
103	CW_km34	754	from given location to Gothenburg downtown, Google Maps
104	CO_km34	754	from given location to Gothenburg downtown, Google Maps
105	GW_km34	748	from given location to Gothenburg downtown, Google Maps
106	G_km34	752	from given location to Gothenburg downtown, Google Maps
107	Biomethane_km	10,4	RBP to Mannsverk bus depot, Google Maps
108	FlyAsh_km2	455	RBP to Langøya, Google Maps
109	FlyAsh_km4	268	Gothenburg downtown to Langøya, Google Maps
110	BottomAsh_km2	42,4	RBP to Mjeldstad Miljø AS, Google Maps
111	BottomAsh_km4	8,9	Gothenburg downtown to Tagene Landfill, Google Maps
112	Kvernevik_Slovag	60,2	from given location to Sløvåg, Google Maps
113	Kvernevik_Odda	126	from given location to Odda, Google Maps
114	YtreSandviken_Slovag	70	from given location to Sløvåg, Google Maps
115	YtreSandviken_Odda	128	from given location to Odda, Google Maps

116	Flesland_Slovag	91,2	from given location to Sløvåg, Google Maps
117	Flesland_Odda	134	from given location to Odda, Google Maps
118	Holen_Slovag	80	from given location to Sløvåg, Google Maps
119	Holen_Odda	138	from given location to Odda, Google Maps
120	Garnes_Slovag	75,4	from given location to Sløvåg, Google Maps
121	Garnes_Odda	110	from given location to Odda, Google Maps
122	Knappen_Slovag	85,4	from given location to Sløvåg, Google Maps
123	Knappen_Odda	136	from given location to Odda, Google Maps
124	Septic_Slovag	86,6	from given location to Sløvåg, Google Maps
125	Septic_Odda	129	from given location to Odda, Google Maps
	Calculated parameters		
	Collection_and_Biogas		--
126	Tot_Input	Input_Kvernevik+Input_YtreSandviken+Input_Flesland+Input_Holen+Input_Garnes+Input_Knappen+Input_Septic+Input_CW+Input_CO+Input_GW+Input_G	total DM feedstock
127	Tot_InputWet	((Input_Kvernevik+Input_YtreSandviken+Input_Flesland+Input_Holen+Input_Garnes)/DM_BioSludge)+(Input_Knappen/DM_ChemSludge)+(Input_Septic/DM_Septic)+(Input_CW/DM_CW)+(Input_CO/DM_CO)+(Input_GW/DM_GW)+(Input_G/DM_G)	total wet feedstock

128	Kvernevik	(Input_Kvernevik/Tot_Input)	DM input
129	BG_Kvernevik	Kvernevik*VS_BioSludge*AD_E*1000*B_Kvernevik	Biogas production
130	BP_Kvernevik	(((Kvernevik*VS_BioSludge)-(Kvernevik*VS_BioSludge*AD_E))*1000)*B_Kvernevik	Biogas potential left in bioresidual
131	YtreSandviken	(Input_YtreSandviken/Tot_Input)	feedstock type amount of FU
132	BG_YtreSandviken	YtreSandviken*VS_BioSludge*AD_E*1000*B_YtreSandviken	biogas production
133	BP_YtreSandviken	(((YtreSandviken*VS_BioSludge)-(YtreSandviken*VS_BioSludge*AD_E))*1000)*B_YtreSandviken	Biogas potential left in bioresidual
134	Flesland	(Input_Flesland/Tot_Input)	feedstock type amount of FU
135	BG_Flesland	Flesland*VS_BioSludge*AD_E*1000*B_Flesland	biogas production
136	BP_Flesland	(((Flesland*VS_BioSludge)-(Flesland*VS_BioSludge*AD_E))*1000)*B_Flesland	Biogas potential left in bioresidual
137	Holen	(Input_Holen/Tot_Input)	feedstock type amount of FU
138	BG_Holen	Holen*VS_BioSludge*AD_E*1000*B_Holen	biogas production
139	BP_Holen	(((Holen*VS_BioSludge)-(Holen*VS_BioSludge*AD_E))*1000)*B_Holen	Biogas potential left in bioresidual
140	Garnes	(Input_Garnes/Tot_Input)	feedstock type amount of FU
141	BG_Garnes	Garnes*VS_BioSludge*AD_E*1000*B_Garnes	biogas production
142	BP_Garnes	(((Garnes*VS_BioSludge)-(Garnes*VS_BioSludge*AD_E))*1000)*B_Garnes	Biogas potential left in bioresidual
143	Knappen	(Input_Knappen/Tot_Input)	feedstock type amount of FU

144	BG_Knappen	Knappen*VS_ChemSludge*AD_E*1000*B_Knappen	biogas production
145	BP_Knappen	(((Knappen*VS_ChemSludge)-(Knappen*VS_ChemSludge*AD_E))*1000)*B_Knappen	Biogas potential left in bioresidual
146	Septic	(Input_Septic*0,9)/Tot_Input	feedstock type amount of FU
147	BG_Septic	Septic*VS_Septic*AD_E*1000*B_Septic	biogas production
148	BP_Septic	(((Septic*VS_Septic)-(Septic*VS_Septic*AD_E))*1000)*B_Septic	Biogas potential left in bioresidual
149	SewageSludge	Kvernevik+YtreSandviken+Flesland+Holen+Garnes+Knappen+Septic	feedstock type amount of FU
150	CW	(Input_CW/Tot_Input)	feedstock type amount of FU
151	BG_CW	CW*VS_CW*AD_E*1000*B_CW	biogas production
152	BP_CW	(((CW*VS_CW)-(CW*VS_CW*AD_E))*1000)*B_CW	Biogas potential left in bioresidual
153	CO	(Input_CO/Tot_Input)	feedstock type amount of FU
154	BG_CO	CO*VS_CO*AD_E*1000*B_CO	biogas production
155	BP_CO	(((CO*VS_CO)-(CO*VS_CO*AD_E))*1000)*B_CO	Biogas potential left in bioresidual
156	GW	(Input_GW/Tot_Input)	feedstock type amount of FU
157	BG_GW	GW*VS_GW*AD_E*1000*B_GW	biogas production
158	BP_GW	(((GW*VS_GW)-(GW*VS_GW*AD_E))*1000)*B_GW	Biogas potential left in bioresidual
159	G	(Input_G/Tot_Input)	feedstock type amount of FU
160	BG_G	(G/DM_G)*B_G	biogas production

161	BP_G	0	Biogas potential left in bioresidual
162	BG_tot	BG_Kvernevik+BG_YtreSandviken+BG_Flesland+BG_Holen+BG_Garnes+BG_Knappen+BG_Septic+BG_CW+BG_CO+BG_GW+BG_G	total biogas production
163	BP_tot	BP_Kvernevik+BP_YtreSandviken+BP_Flesland+BP_Holen+BP_Garnes+BP_Knappen+BP_Septic+BP_CW+BP_CO+BP_GW+BP_G	total biogas potential left in bioresidual
164	FU_Wet	Kvernevik/DM_BioSludge+YtreSandviken/DM_BioSludge+Flesland/DM_BioSludge+Holen/DM_BioSludge+Garnes/DM_BioSludge+Knappen/DM_ChemSludge+Septic/DM_Septic+CW/DM_CW+CO/DM_CO+GW/DM_GW+G/DM_G	wet weight of the FU
165	FU	Kvernevik+YtreSandviken+Flesland+Holen+Garnes+Knappen+Septic+CW+CO+GW+G	FU=1 ton DM
166	VS	((Kvernevik+YtreSandviken+Flesland+Holen+Garnes)*VS_Biosludge)+(Knappen*VS_ChemSludge)+(Septic*VS_Septic)+(CW*VS_CW)+(CO*VS_CO)+(GW*VS_GW)+(G*VS_G)	ton VS
167	DestroyedMatter	((VS-(G*VS_G))*AD_E)+(G*VS_G)	ton DecomposedMatter
168	Bioresidual_DM	FU-DestroyedMatter	ton bioresidual
			...
	Pretreatment	0	
169	Water	AD_Mass-FU_Wet	--
			...
	Biogas		
170	CH4_Avg	(CH4_SewageSludge*SewageSludge)+(CH4_CW*CW)+(CH4_CO*CO)+(CH4_GW*GW)+(CH4_G*G)	adjusted methane concentration
171	MethaneProd	(BG_tot*CH4_Avg)	100% methane produced
172	MethaneLossUpgrade	((BG_tot*CH4_Avg)*CH4_Loss)	loss from upgrade of biogas in methane
173	Biomethane	(MethaneProd-MethaneLossUpgrade)*BiomethanePurity	amount of produced biomethane

174	MethaneCompost	(BG_Kvernevik+BG_YtreSandviken+BG_Flesland+BG_Holen+BG_Garnes+BG_Knappen+BG_Septic+BG_Kvernevik+BG_YtreSandviken+BG_Flesland+BG_Holen+BG_Garnes+BG_Knappen+BG_Septic)*CH4_SewageSludge	methane content in FU compost
175	MethaneLossCompost	(CH4_LossSA*1000)/((MethaneCompost/CompostWet)*(Weight_CH4*1000))	loss of methane from compost
176	MethaneBioresidual	BP_tot*CH4_Avg	not used
177	MethaneLossBioresidual	(CH4_LossSA*1000)/((MethaneBioresidual/FU_Wet)*(Weight_CH4*1000))	not used
178	LossCH4Storage	1342,6/1344,6	% loss to storage
179	LossCH4Application	2/1344,6	% loss to application--------------------------------------
			...
	AnaerobicDigestion		
180	N_AD_Loss	(1-(6,2/7,1))	N loss from AD process
181	N_AD	((Kvernevik+YtreSandviken+Flesland+Holen+Garnes)*N_BioSludge)+((Knappen+Septic)*N_ChemSludgeSeptic)+(CW*N_CW)+(CO*N_CO)+(GW*N_GW)+(G*N_G)	total N into AD
182	P_AD	((Kvernevik+YtreSandviken+Flesland+Holen+Garnes)*P_BioSludge)+((Knappen+Septic)*P_ChemSludgeSeptic)+(CW*P_CW)+(CO*P_CO)+(GW*P_GW)+(G*P_G)	total P into AD
183	AD_Mass	FU/DM_AD	total mass flow including water into AD
184	CompostWet	Kvernevik/DM_BioSludge+YtreSandviken/DM_BioSludge+Flesland/DM_BioSludge+Holen/DM_BioSludge+Garnes/DM_BioSludge+Knappen/DM_ChemSludge+Septic/DM_SepticCompost	wet weight of mass going into Compost
185	CompostDM	Kvernevik+YtreSandviken+Flesland+Holen+Garnes+Knappen+Septic	dry weight of mass going into Compost

186	N_Water	N_Content_H2O*(1-N_Removal_H2O)	N per l water
187	N_Compost	N_C*CompostDM	N content going into Compost
188	N_Loss_AD	N_AD*N_AD_Loss	amount of N lost in AD
189	P_Loss_AD	P_AD*P_AD_Loss	amount of P lost in AD
190	BioresidualWet	AD_Mass-DestroyedMatter-N_Loss_AD-P_Loss_AD	out of AD process
191	BioresidualDry	(Bioresidual_DM/DM_Bioresidual)-N_Loss_AD-P_Loss_AD	bioresidual after losses in AD
	Reject_Water_WWTP	0	--
192	RejectWater	BioresidualWet-BioresidualDry	reject water from Bioresidual and reject into WWTP
193	N_RejectWater	N_Water*RejectWater	N content in reject water
	Bio_Residual	0	--
194	Ntot	(N_AD-N_Loss_AD-N_RejectWater)	total N before storage and application
195	Ptot	(P_AD-P_Loss_AD)*P_Available	total P after loss in AD
196	NH3_SA	Ntot*(0,42*((0,96+0,96)/2))	emission of NH3 in storage and application
197	N2O_SA	Ntot*(0,42*((0,0077+0,02)/2))	emission of N2O in storage and application
198	N2_SA	(Ntot*0,42*((0,0323+0,02)/2))	emission of N2 in storage and application
199	NH3_C	N_C*(0,42*((0,96+0,96)/2))	emission of NH3 in storage and application

200	N2O_C	N_C*(0,42*((0,0077+0,02)/2))	emission of N2O in storage and application
201	N2_C	(N_C*0,42*((0,0323+0,02)/2))	emission of N2 in storage and application
			...
			Incineration
202	El_E	((8765*8)/(8765*60+8765*8))*0,725	how much of the Incineration plant efficiency is electricity
203	Heat_E	((8765*60)/(8765*60+8765*8))*0,725	how much of the Incineration plant efficiency is heat
	Incineration_Case0		
204	H2O_Heat_Case0	H2O_HV*((CW/DM_CW+CO/DM_CO+GW/DM_GW)-(CW+CO+GW))*(120-15)	how much energy is lossed in order to get rid of water
205	Heat_Case0	((CW*HHV_CW+CO*HHV_CO+GW*HHV_GW)-H2O_Heat_Case0)*Heat_E	heat produced from burning OIW
206	El_Case0	((CW*HHV_CW+CO*HHV_CO+GW*HHV_GW)-H2O_Heat_Case0)*El_E	electricity produced from burning OIW
207	B_Ash_Case0	((CW+CO+GW)-(CW*VS_CW+CO*VS_CO+GW*VS_GW))*BottomAsh	amount of bottom ash from burning bioresidual
208	F_Ash_Case0	((CW+CO+GW)-(CW*VS_CW+CO*VS_CO+GW*VS_GW))*FlyAsh	amount of fly ash from burning bioresidual
209	Incineration_Case2and4		
210	H2O_Heat_Case2and4	H2O_HV*(BioresidualDry-(BioresidualDry*DM_Bioresidual))*(120-30)	how much energy is lossed in order to get rid of water
211	Heat_Case2and4	(((BioresidualDry*DM_Bioresidual)*HHV_Bioresidual)-H2O_Heat_Case2and4)*Heat_E	heat produced from burning bioresidual
212	El_Case2and4	(((BioresidualDry*DM_Bioresidual)*HHV_Bioresidual)-H2O_Heat_Case2and4)*El_E	electricity produced from burning bioresidual
213	B_Ash_Cas	(Bioresidual_DM-(VS-DestroyedMatter))*BottomAsh	amount of bottom ash from burning bioresidual

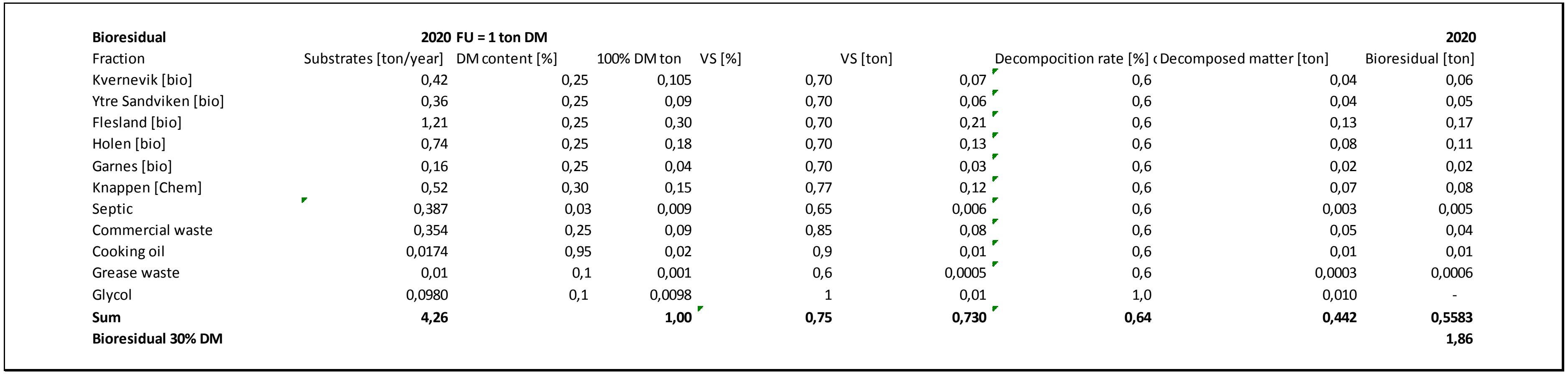
	e2and4		
214	F_Ash_Case2and4	(Bioresidual_DM-(VS-DestroyedMatter))*FlyAsh	amount of fly ash from burning bioresidual
			...
			Transport. tkm for different locations and the numbers after the names defines the cases they belong to. Sløvåg/Odda belongs to Case 0.
	Transport Parameters		
215	Septic_km012	((Kvernevik_km12+YtreSandviken_km12+Flesland_km12+Holen_km12+Garnes_km12+Knappen_km12)/6)	
216	GW_km012	((Kvernevik_km12+YtreSandviken_km12+Flesland_km12+Holen_km12+Garnes_km12+Knappen_km12)/6)	
217	Bioresidual_km	((Kvernevik_km12+YtreSandviken_km12+Flesland_km12+Holen_km12+Garnes_km12+Knappen_km12+Septic_km012+CW_km012+CO_km012+GW_km012+G_km012)/11)	
218	tkm_KvernevikSlovag	Kvernevik/DM_BioSludge/2*Kvernevik_Slovag	
219	tkm_KvernevikOdda	Kvernevik/DM_BioSludge/2*Kvernevik_Odda	
220	tkm_Kvernevik12	Kvernevik/DM_BioSludge*Kvernevik_km12	
221	tkm_Kvernevik34	Kvernevik/DM_BioSludge*Kvernevik_km34	
222	tkm_YtreSandvikenSlovag	YtreSandviken/DM_BioSludge/2*YtreSandviken_Slovag	
223	tkm_YtreSandvikenOdda	YtreSandviken/DM_BioSludge/2*YtreSandviken_Odda	

224	tkm_YtreSandviken12	YtreSandviken/DM_BioSludge*YtreSandviken_km12	
225	tkm_YtreSandviken34	YtreSandviken/DM_BioSludge*YtreSandviken_km34	
226	tkm_FleslandSlovag	Flesland/DM_BioSludge/2*Flesland_Slovag	
227	tkm_FleslandOdda	Flesland/DM_BioSludge/2*Flesland_Odda	
228	tkm_Flesland12	Flesland/DM_BioSludge*Flesland_km12	
229	tkm_Flesland34	Flesland/DM_BioSludge*Flesland_km34	
230	tkm_HolenSlovag	Holen/DM_BioSludge/2*Holen_Slovag	
231	tkm_HolenOdda	Holen/DM_BioSludge/2*Holen_Odda	
232	tkm_Holen12	Holen/DM_BioSludge*Holen_km12	
233	tkm_Holen34	Holen/DM_BioSludge*Holen_km34	
234	tkm_GarnesSlovag	Garnes/DM_BioSludge/2*Garnes_Slovag	
235	tkm_GarnesOdda	Garnes/DM_BioSludge/2*Garnes_Odda	
236	tkm_Garnes12	Garnes/DM_BioSludge*Garnes_km12	
237	tkm_Garnes34	Garnes/DM_BioSludge*Garnes_km34	

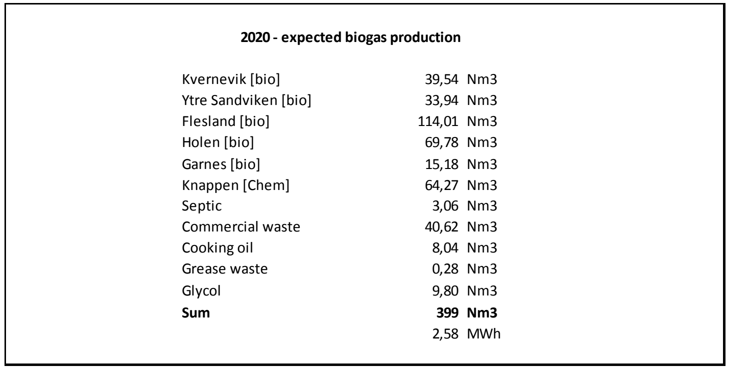
238	tkm_KnappenSlovag	Knappen/DM_ChemSludge/2*Knappen_Slovag	
239	tkm_KnappenOdda	Knappen/DM_ChemSludge/2*Knappen_Odda	
240	tkm_Knappen12	Knappen/DM_ChemSludge*Knappen_km12	
241	tkm_Knappen34	Knappen/DM_ChemSludge*Knappen_km34	
242	tkm_SepticSlovag	Septic/DM_SepticCompost/2*Septic_Slovag	
243	tkm_SepticOdda	Septic/DM_SepticCompost/2*Septic_Odda	
244	tkm_Septic012	Septic/DM_Septic*Septic_km012	
245	tkm_Septic34	Septic/DM_Septic*Septic_km34	
246	tkm_CW012	CW/DM_CW*CW_km012	
247	tkm_CW34	CW/DM_CW*CW_km34	
248	tkm_CO012	CO/DM_CO*CO_km012	
249	tkm_CO34	CO/DM_CO*CO_km34	
250	tkm_GW012	GW/DM_GW*GW_km012	
251	tkm_GW34	GW/DM_GW*GW_km34	
252	tkm_G12	G/DM_G*G_km012	

253	tkm_G34	G/DM_G*G_km34	
254	T_Feedstock_Case12	tkm_Kvernevik12+tkm_YtreSandviken12+tkm_Flesland12+tkm_Holen12+tkm_Garnes12+tkm_Knappen12+tkm_Septic012+tkm_CW012+tkm_CO012+tkm_GW012+tkm_G12	total feedstock Cases 1 and 2
255	T_Feedstock_Case34	tkm_Kvernevik34+tkm_YtreSandviken34+tkm_Flesland34+tkm_Holen34+tkm_Garnes34+tkm_Knappen34+tkm_Septic34+tkm_CW34+tkm_CO34+tkm_GW34+tkm_G34	total feedstock Cases 3 and 4
256	T_Feedstock_Case0	tkm_CW012+tkm_CO012+tkm_GW012	total feedstock Case 0_Incineration
257	T_Feedstock_Slovag	tkm_KvernevikSlovag+tkm_YtreSandvikenSlovag+tkm_FleslandSlovag+tkm_HolenSlovag+tkm_GarnesSlovag+tkm_KnappenSlovag+tkm_SepticSlovag+(tkm_Septic012/2)	total feedstock Sløvåg_Compost
258	T_Feedstock_Odda	tkm_KvernevikOdda+tkm_YtreSandvikenOdda+tkm_FleslandOdda+tkm_HolenOdda+tkm_GarnesOdda+tkm_KnappenOdda+tkm_SepticOdda+(tkm_Septic012/2)	total feedstock Odda_Compost

Appendix 9 Bioresidual and biogas production (Basic parameters in Excel MFA model)



Bioresidual	**2020**	**FU = 1 ton DM**						**2020**
Fraction	Substrates [ton/year]	DM content [%]	100% DM ton	VS [%]	VS [ton]	Decompocition rate [%] (	Decomposed matter [ton]	Bioresidual [ton]
Kvernevik [bio]	0,42	0,25	0,105	0,70	0,07	0,6	0,04	0,06
Ytre Sandviken [bio]	0,36	0,25	0,09	0,70	0,06	0,6	0,04	0,05
Flesland [bio]	1,21	0,25	0,30	0,70	0,21	0,6	0,13	0,17
Holen [bio]	0,74	0,25	0,18	0,70	0,13	0,6	0,08	0,11
Garnes [bio]	0,16	0,25	0,04	0,70	0,03	0,6	0,02	0,02
Knappen [Chem]	0,52	0,30	0,15	0,77	0,12	0,6	0,07	0,08
Septic	0,387	0,03	0,009	0,65	0,006	0,6	0,003	0,005
Commercial waste	0,354	0,25	0,09	0,85	0,08	0,6	0,05	0,04
Cooking oil	0,0174	0,95	0,02	0,9	0,01	0,6	0,01	0,01
Grease waste	0,01	0,1	0,001	0,6	0,0005	0,6	0,0003	0,0006
Glycol	0,0980	0,1	0,0098	1	0,01	1,0	0,010	-
Sum	**4,26**		**1,00**	**0,75**	**0,730**	**0,64**	**0,442**	**0,5583**
Bioresidual 30% DM								**1,86**



2020 - expected biogas production

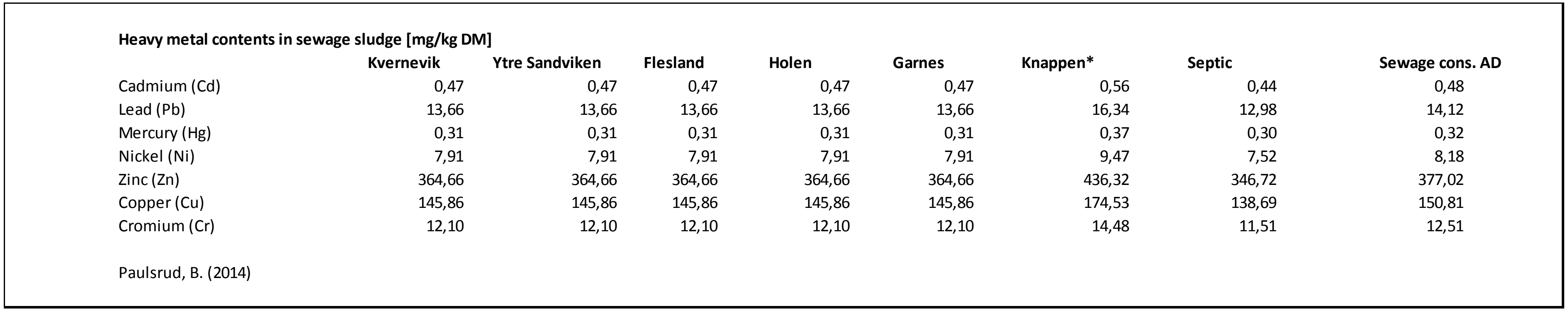
Kvernevik [bio]	39,54	Nm3
Ytre Sandviken [bio]	33,94	Nm3
Flesland [bio]	114,01	Nm3
Holen [bio]	69,78	Nm3
Garnes [bio]	15,18	Nm3
Knappen [Chem]	64,27	Nm3
Septic	3,06	Nm3
Commercial waste	40,62	Nm3
Cooking oil	8,04	Nm3
Grease waste	0,28	Nm3
Glycol	9,80	Nm3
Sum	**399**	**Nm3**
	2,58	MWh

The 100% DM ton column was calculated by dividing the individual DM flow by the total DM flow, thus getting the divisions necessary to get the FU of one ton DM organic waste substrate.

Bioresidual is the column 100% DM ton – Decomposed matter [ton]. The decomposed matter is treated as the biogas weight, where the Decomposed matter [ton] is timed by 1000 and then the biogas potential per decomposed kg of organic matter. However as Glycol has a biogas potential defined at per ton incoming matter, thus the multiplication with 1000 is not done here.

Information in the tables above are a combination of Sande et al. (2008), Paulsrud (2014), Purac AB (2011) and Sande & Seim (2011), this was done in order to fulfil missing information about the different substrate and to get as much detail about it as possible.

Appendix 10 Heavy metals (Basic parameters in Excel MFA model)



Heavy metal contents in sewage sludge [mg/kg DM]

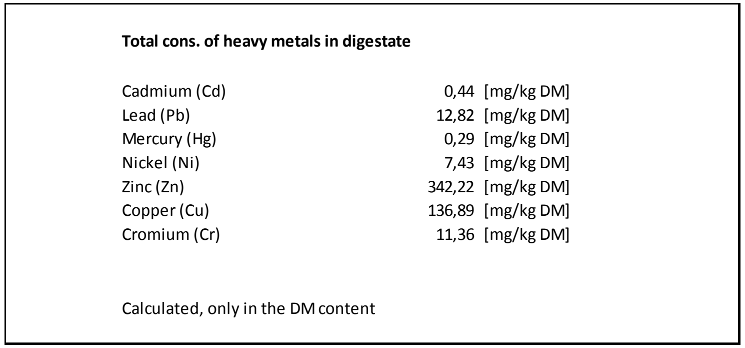
	Kvernevik	**Ytre Sandviken**	**Flesland**	**Holen**	**Garnes**	**Knappen***	**Septic**	**Sewage cons. AD**
Cadmium (Cd)	0,47	0,47	0,47	0,47	0,47	0,56	0,44	0,48
Lead (Pb)	13,66	13,66	13,66	13,66	13,66	16,34	12,98	14,12
Mercury (Hg)	0,31	0,31	0,31	0,31	0,31	0,37	0,30	0,32
Nickel (Ni)	7,91	7,91	7,91	7,91	7,91	9,47	7,52	8,18
Zinc (Zn)	364,66	364,66	364,66	364,66	364,66	436,32	346,72	377,02
Copper (Cu)	145,86	145,86	145,86	145,86	145,86	174,53	138,69	150,81
Cromium (Cr)	12,10	12,10	12,10	12,10	12,10	14,48	11,51	12,51

Paulsrud, B. (2014)

The individual concentrations of different heavy metals are calculated with the original concentration divided by 1 minus the VS percentage timed by the AD efficiency. When matter goes through an AD process the heavy metal persist, thus by this calculation the increase in concentration is accounted for (Paulsrud 2014). Following is an example of the calculation for Cadmium (Cd) for Kvernevik = D34/(1-($D$28*'Technology parameters'!$P$37)).

The heavy metal concentration is calculated by multiplying the individual concentration with the amount of matter belonging to the locations divided by the total amount of substrates. Cadmium (Cd) conc. = (AN9*($F$48/SUMMER($F$48:$F$54))+(AO9*($F$49/SUMMER($F$48:$F$54)))+(AP9*($F$50/SUMMER($F$48:$F$54)))+(AQ9*($F$51/SUMMER($F$48:$F$54)))+(AR9*($F$52/SUMMER($F$48:$F$54)))+(AS9*($F$53/SUMMER($F$48:$F$54)))+(AT9*($F$54/SUMMER($F$48:$F$54)))).

Further the heavy metal concentration in the bioresidual is calculated, because when adding matter with no heavy metal content the concentration will go down, to get the new concentration the concentration found above is divided by the total amount of DM mass and then multiplied by the mass containing heavy metals, as shown for Cadmium. Cadmium (Cd) AD = (AV9/$K$59)*SUMMER($K$48:$K$54).



Total cons. of heavy metals in digestate

Cadmium (Cd)	0,44	[mg/kg DM]
Lead (Pb)	12,82	[mg/kg DM]
Mercury (Hg)	0,29	[mg/kg DM]
Nickel (Ni)	7,43	[mg/kg DM]
Zinc (Zn)	342,22	[mg/kg DM]
Copper (Cu)	136,89	[mg/kg DM]
Cromium (Cr)	11,36	[mg/kg DM]

Calculated, only in the DM content