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Resource efficiency and life cycle environmental impacts of biogas production at Greve Biogass

Ressurseffektivitet og livsløps
miljøpåvirkning av biogassproduksjon ved
Greve Biogass

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Abstract

In Norway, the municipalities are obligated to contribute to the reduction of greenhouse gas emissions as well as to a transition towards green energy. Biogas production based on manure, sewage sludge and different types of waste holds a large potential for decreasing emissions of climate gases. Greve Biogass AS, on behalf of its owner municipalities in Vestfold and Telemark will build a biogas plant, “The Magic Factory”, with the purpose of ensuring local recycling. The biogas plant will utilize large amounts of manure as substitution for clean drinking water as process water.

The objective of this Thesis is to study the specific choices made regarding the operation of “The Magic Factory”, considering potential outputs, resource efficiency and environmental impacts. Three main choices have been studied:

- benefits of establishing “The Magic Factory”
- benefits of the water choices
- benefits of “The Magic Factory” compared to other biogas plants that do not treat such large amount of manure

This has been carried out by use of material flow analysis and life cycle assessment, investigating six different scenarios, each of them representing different substrate mixtures and handlings. The environmental impacts have been concentrated on four impact categories:

- climate change
- human toxicity
- water depletion
- fossil depletion

The results from the material flow analysis show that the outputs and resource efficiency are dependent on substrate mixture and transportation distance. When a co-digestion benefit has not been accounted for, a higher output of biofuel is seen by processing solid manure over liquid manure, and food waste over manure.

This Thesis supports the choices made by Greve Biogass AS for the operation of “The Magic Factory”, considering environmental benefits. The results show that there is an environmental benefit of establishing “The Magic Factory”, considering all four impact categories. Environmentally, it is slightly beneficial to substitute clean water with liquid manure and “The Magic Factory” asserts itself good environmentally when compared to other plants by including manure in the biogas production.

The sensitivity analysis performed shows that out of the uncertain parameters, degradability is the one with the highest impact on the outputs, resource efficiency as well as on the environment. This means that the parameter should be evaluated and adjusted after the results of a case specific digestion test are known. The driving distance related to collection and transportation of the food waste does have an influence that should be taken into account when considering what waste fractions to be processed at the plant.

Key words: Biogas, Anaerobic co-digestion, Manure, Food waste, Material Flow Analysis/MFA, Life Cycle Assessment/LCA

Sammendrag

Kommunene I Norge er forpliktet til å bidra til en reduksjon i klimagassutslipp, samt en overgang til grønn energi. Biogassproduksjon basert på husdyrgjødsel, kloakkslam og ulike typer avfall har et stort potensial for å redusere utslippene av klimagasser. Greve Biogass AS vil på vegne av eierkommunene i Vestfold og Grenland bygge en biogassfabrikk, «Den Magiske Fabrikken», som har som formål å sikre lokal gjenvinning. Biogassanlegget vil benytte store mengder husdyrgjødsel som erstatning for rent drikkevann som prosessvann.

Målet med denne oppgaven er å undersøke de spesifikke valgene som er gjort med hensyn til driften av «Den Magiske Fabrikken» med tanke på potensielle sluttprodukter, ressurseffektivitet og miljøpåvirkninger. Tre hovedvalg er undersøkt:

- fordelene ved etablering av «Den Magiske Fabrikken»
- fordelene med vannvalget
- fordelene ved «Den Magiske Fabrikken» sammenlignet med andre biogassanlegg som ikke behandler en slik mengde med husdyrgjødsel

Dette er gjort ved bruk av materialstrømanalyse og livsløpsanalyse, seks ulike scenarier som hver representerer ulike substratblandinger og behandlings metoder. De miljømessige konsekvensene har vært fokusert rundt fire påvirkningskategorier:

- klimaendringer
- giftighetsgrad for mennesker (human toxicity)
- vannforbruk
- forbruk av fossile ressurser

Resultatene fra materialstrømanalysen viser at mengden sluttprodukter og ressurseffektivitet avhenger av substratblanding og transportavstander. Når en samråtningseffekt ikke er lagt inn, er det observert en høyere produksjon av biodrivstoff ved behandling av fast husdyrgjødsel fremfor flytende husdyrgjødsel, og ved matavfall fremfor husdyrgjødsel.

Denne oppgaven støtter de valg Greve Biogass AS har tatt angående driften av «Den Magiske Fabrikken», med tanke på miljøpåvirkninger. Resultatene viser at det for alle fire påvirkningskategorier er en miljøgevinst ved å etablere «Den Magiske Fabrikken». Det er en liten miljøgevinst som følge av å erstatte rent vann med flytende husdyrgjødsel. «Den Magiske Fabrikken» vil hevde seg godt miljømessig sammenlignet med andre biogassanlegg ved å inkludere husdyrgjødsel i biogassproduksjonen.

Den gjennomførte sensitivitetsanalysen viser at av de usikre parameterne, er nedbrytbarhet den med høyest påvirkning på mengden sluttprodukter, ressurseffektivitet og miljøpåvirkning. Dette parameteret burde dermed vurderes og justeres når resultatene fra utråtningsforsøk foreligger. Kjøreavstand knyttet til innsamling og transport av matavfallet påvirker til en slik grad at det burde tas i betraktning ved vurdering av hvilke avfallsfraksjoner som skal behandles i biogassanlegget.

Emneord: Biogass, Anaerob samråtning, husdyrgjødsel, Matavfall, Materialstrømanalyse, Livsløpsanalyse

Preface

This Thesis is carried out in collaboration with Greve Biogass AS, as the final assignment of the Industrial Ecology Master Program at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

The choice of topic for this Thesis was based up on previous student work that inspired me to learn more about utilization of waste. I consider the opportunity to convert waste from a problem to a resource is one of the instruments for making the world more sustainable. Working on this Thesis has been interesting and challenging. I think it has prepared me for situations I could meet when I am about to build a career, at the same time as I got to know myself better and how I approach this type of work.

There is one deviation from the initial Thesis assignment text. At an early stage, it became clear that a fellow student would develop the LCA model. I have maintained a close collaboration with this student. I contributed in the development by assisting the work within areas of my knowledge by providing inputs to the model structure and by being available for discussions.

I would like to thank some of those who have contributed to and facilitated my work. I would not have been able to conduct and complete this Thesis without your support and contributions:

- Kristina Mørk Jacobsen and Ivar Sørby at VESAR and Greve Biogass AS, for the cooperation, technical guidance and the foundation of data
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Nomenclature

AD	anaerobic digestion
CH_4	methane
CO_2	carbon dioxide
DM	dry matter
H_2S	hydrogen sulfide
HHV	higher heating value
kWh	kilo watt-hour
LCA	Life Cycle Assessment
LM	liquid manure
LOIW	liquid organic industrial waste
MC	methane content
MFA	Material Flow Analysis
MWh	Mega watt-hour
Nm^3	normal cubic meter, gas volume at 273.15 K (0° C) and 1.01325 bar
O_2	oxygen (in its most stable form, dioxygen)
OMW	organic municipal waste
SM	solid manure
SOW	solid organic waste
VS	volatile solids
WW	wet weight

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1 Introduction

This Thesis is a student assignment carried out in collaboration with Greve Biogass AS. The Thesis will investigate the potential outputs, the energy yield and the environmental benefits associated with specific choices made regarding the operation of their biogas plant, “The Magic Factory”. This will be done by use of life cycle assessment and material flow analysis where different input scenarios will be examined and compared to alternative handlings of the same input fractions. The background and objective for the Thesis will be presented in this chapter, along with the issues for research that formed the basis of the Thesis.

1.1 Background

The Government of Norway 4 September 2009 resolved the introduction of an obligation for the municipalities to contribute to the reduction of greenhouse gas emissions as well as a transition towards green energy (Klima- og miljødepartementet 2009b). In the White Paper 21 about Norway’s climate policy there is stated that the Government would promote biogas production in Norway. The emissions from agriculture and waste are estimated to be 5.2 million tons CO_2- equivalents in 2020 provided the current policy instruments continues (*Meld. St. 21 2011–2012*). As seen from Figure 1, agriculture was responsible for 8 % and waste for 2 % of the total emissions in 2010.

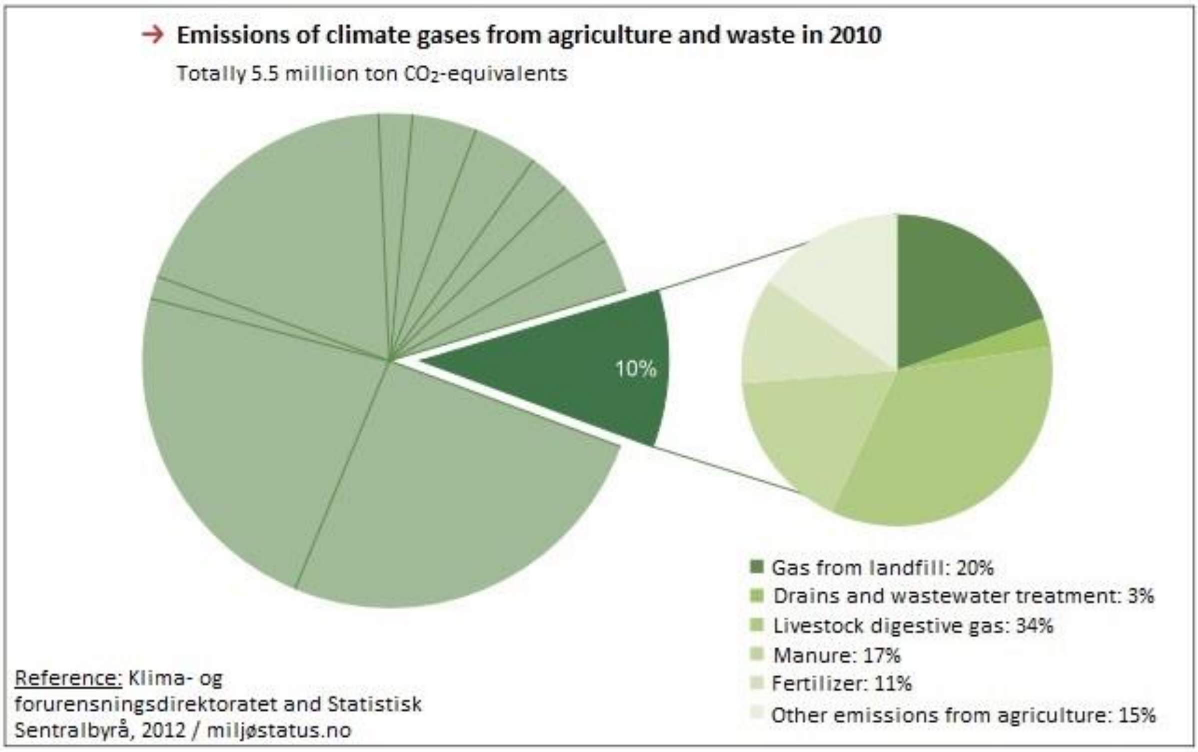

Figure 1: Emissions of climate gases from agriculture and waste in 2010 (Meld. St. 21 2011–2012)

Biogas production based on manure, sewage sludge and different types of waste has a large potential for decreasing the emissions of climate gases. A large part of such a reduction would come as a result of biogas substituting fossil energy; hence a reduction of emissions from sectors such as transporting or heating of buildings. To achieve the goal of higher biogas production in Norway, Klimakur 2020 anticipated that 30 % of the manure and 200 000 tons waste should be used for biogas production in 2020. Klimakur 2020 also underlines a plant that utilizes both manure and organic waste in co-digestion as the most cost-effective biogas initiative linked to reduction of climate gas emissions (*Meld. St. 21 2011–2012*).

Landfilling of waste is regulated by the Norwegian Waste Regulation of 2009 which in Article 9-4 prescribes that it is prohibited to send biodegradable waste to landfill (Klima- og miljødepartementet 2009a). This forced several waste companies to look for alternative ways of processing their waste and thereby reorganize their operations.

Based on these assumptions, Greve Biogass AS (see chapter 3.2 Case: Greve Biogass AS) has decided to build a biogas plant that will help the municipalities reach their climate-reduction objectives.

1.2 Objective of the Thesis

The objective of this Thesis is to carry out a material flow analysis and a life cycle assessment studying the specific choices made regarding the operation of "The Magic Factory". The technologies to be used in this factory are already decided upon, so there is no point in making comparative analyses on different technology options. Instead it is of interest to examine results from environmental systems analysis regarding what is expected to be likely resource efficiency and potential life cycle environmental impacts of the plant, and in particular to determine what are the critical variables affecting the results and how, such as the effect of variations in substrate mixture and transportation distances.

The material flow analysis will be carried out to investigate the outputs of "The Magic Factory" and by this establish an energy yield. The studied system will be limited to:

- transport of the substrates to "The Magic Factory"
- processing of the substrates at "The Magic Factory"
- the distribution of the outputs

In other words, the system limitations are set to include transport on both sides of the biogas production. The functional unit for the material flow analysis is: 1 ton dry matter of organic waste substrate for anaerobic digestion.

For the life cycle analysis, the system limitations were extended as compared to the material flow analysis:

- to include the use of the outputs as replacement for fuel and agricultural artificial fertilizer

- to handle a larger amount of organic waste substrate. This allows for including the treatment of the desired substrate regardless where it is processed or handled (manure spread directly as fertilizer or waste sent to another plant for instance); thus making the scenarios comparable.

The functional unit for the life cycle assessment is: treatment of 1 ton dry matter of organic waste substrate.

1.3 Issues for research

General research questions of relevance to this work are:

- What are previous studies telling us about climate benefits of biogas production from organic municipal waste in Norway?
- Are there any potential benefits of co-digesting organic waste with manure?

Case specific research questions are:

- What are the environmental benefits of establishing "The Magic Factory" compared to current handling of the waste in the region to be served by this new factory?
- To what extent will the use of liquid manure instead of clean water as process water give environmental benefits?
- How will "The Magic Factory" assert itself environmentally compared to other biogas plants that do not treat such large amount of manure?

2 Literature

This chapter will present literature on biogas and biogas production. It will discuss the biogas potential in Norway from the perspective of

- different types of substrates
- the upgrading process of biogas to biofuel

The chapter further will present

- different types of biogas substrates
- Bioresidual and use of Bioresidual
- technologies for biogas production
- studies that have examined the benefits of co-digestion
- life cycle assessment studies on biogas production from organic waste substrates, Norwegian case studies

2.1 Biogas

Biogas consists mainly of methane (50 - 70 %) and carbon dioxide (30 - 45 %), but also several impurities (H_2S, NH_3, H_2O, N_2, dust and siloxanes) (Deublein & Steinhauser 2008). Deublein and Steinhauser (2008) explains the formation of methane as a biological process that occurs naturally when organic material decomposes in a humid environment in absence of air but in the presence of natural microorganisms which are metabolically active, i.e. methane bacteria. Several factors influence the production of biogas and the ratio between methane and carbon dioxide. According to Khalid et al. (2011) they are:

- temperature
- pH
- moisture
- substrate/carbon source
- nitrogen
- carbon/nitrogen ratio

2.1.1 Biogas potential in Norway

In theory, the energy potential from biogas resources of waste/by-products in Norway are calculated to about 6 TWh/year (Raadal et al. 2008). Manure holds the largest potential, 42 %, followed by industry, 23 %, and organic municipal waste, 11 %. The theoretical energy potentials hold by the different biogas resources are presented in Table 1.

Table 1: Theoretical energy potential from different biogas resources in Norway in GWh/year (Raadal et al. 2008)

Organic industrial waste from			**Organic municipal waste**	**Straw**	**Manure**	**Sewage sludge**	**Landfills**	**Total**
Large-scale households	Trade	Industry						
149	50	1 401	644	575	2 480	266	292	5 857

The split of these between the counties Vestfold and Telemark is presented in Table 2, except for industry and straw for which the energy potential is not possible to split between counties. (Vestfold and Grenland are presented separately in the table as Grenland is a part of Telemark and numbers specifically for Grenland do not exist. The numbers for Telemark therefore are too high compared to the potential for Grenland and it would be misleading to present the potential of Vestfold and Telemark into one value representing the Vestfold and Grenland region.)

Table 2: Theoretical energy potential from different biogas substrates in GWh/year for Norway, Vestfold and Telemark (Raadal et al. 2008)

		Norway	**Vestfold**	**Telemark**
Manure		2 480	100	40
Sewage sludge		266	*25	*9
Organic municipal waste		644	35	26
Organic industrial waste	Large-scale households	149	5	4
	Trade	50	1.8	2.2
	Industries	1 400	-	-

* calculated based on Nm^3 CH_4 presented by Raadal et al. (2008) and key figure for energy potential in methane from Norges Bondelag (2011).

2.1.2 Upgrading of biogas to fuel quality

The transport sector in Norway is a large contributor to fossil CO_2- emissions; a change towards biofuel would help decrease this emission (Hovland et al. 2009). But to be able to use biogas as fuel, it must be upgraded to close to 100 % methane. All contaminants and carbon dioxide has to be removed from the biogas to reach a sufficient gas quality for vehicles (Persson et al. 2006). The upgraded biogas in gaseous form are called biomethane, which could further be liquefied and is then called LBG (liquid biogas).

Several technologies are available for cleaning contaminants from biogas and by this upgrading the gas to fuel quality (Persson et al. 2006). It is technically possible to run a vehicle on biogas, but the reason for upgrading the biogas is to increase the heating value and by this increase the driving distance for a specific gas storage volume. The upgrading also secures a consistent quality of the gas regardless of what biogas plant that produced it, and a quality similar to natural gas which allows a distribution through the natural gas grid. When the carbon dioxide is removed, so are small amounts of methane. This methane loss has to be kept as small as possible to limit the loss of fuel (economic losses) and for environmental reasons since methane as a greenhouse gas is 21 times stronger than CO_2. The technologies used for biogas upgrading are explained in chapter 2.4 Technologies.

The gross potential of production of biofuel in Norway are calculated to be almost 130 million Nm^3/year; this equals 1.25 TWh (Marthinsen 2012).

2.2 Biogas substrates

All types of biomass can be used as substrate in biogas production as long as they contain carbohydrates, proteins, fats, cellulose and hemi-cellulose as main components (Deublein & Steinhauser 2008).

Substrates treated in biogas plants (in Sweden) consist primarily of organic waste from households, restaurants and large-scale households, food industry and biomass from industry (Carlsson & Uldal 2009). When assessing the suitability of the substrates for biogas production, several factors are important; according to Carlsson and Uldal (2009) some of which are:

- Dry matter content – indicates the remaining components of a material after the water is evaporated at 105^{o}C. Materials with a high dry matter content (>10-15 %) often need to be diluted to work in the receiving device, pumps and the mixer. However, this does not apply to all types of substrates. For example, fatty substrates have very high dry matter content and are still pump able. Examples of this are cream with a dry matter content of 60 % and syrup 85 %, still both of them possible to pump. Materials with low dry matter content (<10 %) could be used to dilute the thicker substrates, and by this improve the mechanical property.

- Volatile solids content – indicates that the materials contain flammable substance at 550^o C, representing a useful tool for calculating the organic content in a substrate. A high content of volatile solids will generally indicate high transport efficiency, thus a high gas yield per transport unit. This is because only the organic part of the dry matter decomposes and contributes in the biogas production. A low content of volatile solids in the anaerobic digester gives an ineffective utilization of the volume of the digester. A high volatile solids content often, but not always, results in a high biogas yield. An example is plastic, since plastic is part of the volatile solids, but will not decompose in the digester.

- It is important to determine the content of dry matter and volatile solid for each of the substrates whenever different substrates are mixed in the digestion. Furthermore, it is important to assess how these substrates will affect the dry matter- and volatile solids content in the mix. It is necessary continuously to analyze the content of dry matter and volatile solids in the final mixture to determine if it should be diluted or if it is too thin before it goes further into the process of biogas production.

- Biogas yield – describes the volume of biogas per kg volatile solids. The mix of substrates, the access to nutrients, the presence of inhibitory substances, the time in the anaerobic digester, the system load and the stirring effectiveness affect the biogas yield for a substrate. The biogas yield for different substrates are determined by the dry matter content, the organic content in the dry matter, the organic matters composition of fats, carbohydrates and protein and the degradability of the organic matter (Litorell & Persson 2007). The biogas yield can often be increased by a co-digestion of different substrates, a so-called positive co-digestion.

- Nutritional composition – affects the microorganisms in the digestion. Microorganisms need carbon, nitrogen and phosphorus together with micronutrients, vitamins and trace elements to grow. The final waste mix must therefore contain all these elements in a sufficient and available quantity, to satisfy the needs of certain microorganisms. Shortcomings in the nutritional conditions of different substrates can be adjusted by co-digestion of different waste types, such as nitrogen rich substrates (like chicken manure) with more nitrogen poor substrates (like sugar beet). It is also desirable to have a high content of available nutrients in the Bioresidual.

- Risk of problems – Mechanical as well as microbiological problems may occur. Foaming, fermentation and sedimentation are examples of mechanical problems that could occur during the digestion. Light materials (like straw and feathers) will float and form a cover, while heavier particles sink and accumulate at the bottom of the digester instead of being flushed out. Accumulation will decrease the available volume, and thus the residence time in the digester. Materials can accumulate on the stirrer and then reduce the stirring effect. Foaming may occur if the incoming mixture contains a high percentage of fat. Microbiological problems are often associated with an overload, technical problems or a not optimal nutritional composition. High levels of heavy metals or other toxic substance (from such as detergents, pesticides or antibiotics) can also inhibit the microbial process. Some substances, like heavy metals and chlorinated compounds, will influence the microorganisms in the digester negatively even at very low concentrations. It is therefore important to know the material content of the substrate. It is also a risk that easily degradable materials like fat and protein could cause inhibitory problems. A high content of fat in the mixture could give decreasing pH, while the decomposing of proteins forms ammonium and ammonia, which at high concentrations can be toxic to methanogens. It is important to estimate the composition of fat, carbohydrate and protein in the final mixture to know how this will affect the digestion process.

2.2.1 Manure

Manure is described by Raadal et al. (2008) as an important biogas resource, the effect of which varies with type and pretreatment. Different types of manure have different dry matter contents, the higher the dry matter contents, the higher the biogas yield. Manure with low dry matter content should go through a dewatering process before processed to the biogas production, so that the volume processed is reduced. The content of different manure types will also vary with storage, pretreatment etc. Some of the types could cause problems. A high mineral content could cause sedimentation and bottom accumulation. With too high contents of fiber and litter, manure may cause a formation of a floating crust. The values presented in Table 1 and 2 are calculated based on manure from horses, cattle, sheep, goats, pigs and chickens; the time when the animals are grazing and the use of litter are taken into account.

Manure from pigs and poultry produces more biogas than manure from ruminants, thus manure from ruminants to some extent already is partly anaerobically digested in the animal (Steffen et al. 1998). Steffen et al. (1998) also state that manure contains relatively low percentages of fats, slightly higher protein content and carbohydrates as the major components. Manure from cattle and pigs has a dry matter content of about 8 %, of which about 80 % are volatile solids. The pig manure differs from the cattle manure in lower fiber content and a high content of minerals, which enables rapid sedimentation. In addition, pig manure is rich in nitrogen, which increases the risk of ammonium in the anaerobic digestion.

According to Hagelberg et al. (1988) as accounted by Carlsson and Uldal (2009) manure from horses is relatively dry and contains large amounts of litter, resulting in a low biogas yield per unit volume. The dry matter content in the manure-litter mix is about 30-50 % and 80-90 % of this is volatile solids. Further on, manure from chickens is described with a fine structure that easily falls apart. Chicken manure could give complications associated with sedimentation and a floating crust because of the high contents of eggshell, minerals and feather. Because of the high level of phosphorus in chicken feed, the phosphorus content in chicken manure is significantly higher than in other nutrients. Chicken manure also contains high amounts of nitrogen of which a large part is in the form of ammonium; this leads to a risk of ammonium inhibition if the substrate digests alone. Generally, chicken manure has a high dry matter content of about 20-25 %, 75 % of which is volatile solids.

2.2.2 Sewage sludge

Sewage sludge is a waste product consisting of organic material and nutrients, removed from the wastewater at the wastewater treatment plant (Miljøstatus 2013). Currently, sewage sludge is the biogas substrate that is most widely used for biogas production in Norway (Raadal et al. 2008). The reason for this is that biogas production from sewage sludge has long worked as a treatment method of sewage sludge. The energy production from this type of biogas plant, consequently only has been considered as a byproduct of the sewage sludge treatment solution. This has lead to a low utilization of the produced biogas from this type of biogas plants, because little attention has been given to the actual energy production.

Bio sludge is characterized by a relatively low biodegradability, since the waste already has decomposed in previous purification steps (Carlsson & Uldal 2009). Thus, the volatile solid content for this type of waste normally is limited to 50 % only.

2.2.3 Organic municipal waste

Organic municipal waste is composed of different kinds of food waste, typical leftovers, fruit/vegetable peel and various food products that have passed the date of expiry (Raadal et al. 2008). In theory, the energy potential from this sector is dependent on the number of individuals and population density, since the potential is estimated on the basis of the average amount of waste from each individual. The average yearly amount of waste per inhabitant in Norway is calculated to 429 kg/year (2007), 24.3 % of this is organic waste. Sorted food waste has a dry matter content of 30-35 %, of which approximately 85 % is volatile solids (Carlsson & Uldal 2009).

2.2.4 Organic industrial waste

Raadal et al. (2008) states that food waste from large-scale households/restaurants and trade has a composition similar to that of households. The amount of waste from these sectors also varies with the number of inhabitants and the population density. From all kinds of food production and processing, there will be a varying quantity of scrap and production errors, waste, by-products etc., all of which represent biogas resources.

The total amount of organic waste from industries, large-scale households/restaurants and trade in Norway is in the range of 880 000 - 1 980 000 tons (Marthinsen 2012). Marthinsen (2012) describes this amount as very uncertain and different sources give different amounts, most of them based on theoretical approaches. A large amount of organic industrial waste is produced in Norway and it is a large variety depending on the different sources; slaughterhouses, dairies, bakeries, breweries and fisheries/aquacultures among others. According to statistics, the amount of organic waste has increased in every sector since 1995, the exception being organic industrial waste, which has remained more or less unchanged.

2.2.4.1 Slaughterhouses

According to Hagelberg et al. (1988) as accounted by Carlsson and Uldal (2009), in terms of volume slaughterhouses produce four large types of waste: water treatment sludge, offal, manure and gastric and intestinal waste (which is a fertilizer like product). Waste from slaughterhouses is a valuable substrate because of its high contents of energy and thereby provides a high biogas yield. The soft parts (carcass leftovers) are also very rich in nitrogen because of its high protein content. Waste from slaughterhouses might contain bones, rope, tubes from deworming, cords, metal and other impurities, this makes it important to atomize the substrate and remove inorganic objects before the slaughterhouse waste is supplied to the biogas plant.

Waste from slaughterhouses is less suitable for biogas production if it is the only substrate, due to several characteristics, which under certain circumstances may affect the biogas process negatively (Carlsson & Uldal 2009). The high content of fat may lead to accumulation of fatty acids followed by a reduction of pH. According to Koster and Kramer (1987) as accounted by Carlsson and Uldal (2009), the high protein content leads to a high concentration of ammonia in the biogas process, which inhibits the methanogens (microorganisms that produce methane (National Research Council 1993)). Slaughterhouse waste, however, could serve as a valuable nitrogen addition to a substrate with an insufficient nutrient composition (Carlsson & Uldal 2009). Decompose mixtures with slaughterhouse waste added, will often have a very high biogas yield.

2.2.4.2 Dairies

According to Hagelberg et al. (1988) as accounted by Carlsson and Uldal (2009), the production of dairy products generate residues like separator sludge (dry matter content = 7 %), limit milk (dry matter content = 0.5 - 2 %) and whey (dry matter content = 6 %). Limit milk and whey are today used as animal feed (Carlsson & Uldal 2009). From internal purifier, grease sludge will arise, with a high fat content which results in a high gas exchange. However, it does not contribute to any nitrogen inputs to the process. Generally, dairy waste will provide a high gas yield, but due to low alkalinity the substrate may prove problematic to decompose, and should therefore be mixed with some other waste, such as waste from slaughterhouses.

2.2.4.3 Bakeries

Leftovers from bakeries consists of flour spills, dough, discarded bread, production errors and returned bread (Carlsson & Uldal 2009). Usually the waste is a relatively pure product, but has a variable texture, particle size, dry matter content, chemical composition and nutritional value depending on the basic raw materials used for the manufacturing (Ståhlberg & Hill 2007). The waste has generally a high organic content that decomposes relatively rapidly and provides a high gas yield (Carlsson & Uldal 2009). The bakery waste is also easily transported due to its high content of dry matter-/volatile solid.

2.2.4.4 Vegetables and fruit processing

Handling of vegetables and fruits produce large amounts of waste through scaling and cleaning before the main industrial process (Carlsson & Uldal 2009). Vegetable- and fruit waste represents a significant potential resource for the production of biogas and reversal of nutrients to the agricultural land. This occurs in large, clean fractions that easily could be collected and that normally are free from contamination. High volatile solids (95 % of the dry matter) and a very high biodegradability characterize the waste. In some cases the degradation process would be favored by a mix with nitrogen high substrate, particularly for root vegetables without leaves (e.g. potatoes). This is because most of the nutrition for these vegetables is found in the leaves. This results in a high carbon/nitrogen ratio (Parawira et al., 2008) which according to Wannholt (1998) as accounted by Carlsson and Uldal (2009) will slow down the degradation process.

The carbon source in the vegetable- and fruit waste consists mainly of carbohydrates (Carlsson & Uldal 2009). Regarding health, the waste product is of high quality and has a low content of toxic substrates. However, a pesticide analysis should be carried out on the waste if the fruit peel makes up a large share of the total substrate mixture. Naturally inhibitory substances could be present, as oils from citrus peel (Viswanath et al. 1992). Continuous experiments in lab scale with 20 % blend of citrus peel in sorted food waste showed a collapse in the process after approximately 30 days of operation. This was probably caused by limonene, the main component of citrus oil, which turned out to have an inhibitory effect on the digestion process even at low concentrations.

2.2.4.5 Egg industry

Eggshell has a high content of dry matter, contains a nitrogen that could be released relatively quickly as well as calcium, magnesium and phosphorus that release very slowly (Carlsson & Uldal 2009). Anaerobic digestion of eggshells is problematic, since the shells are mostly unaffected by the process and may result in practical problems such as mechanical halting at the production facility. The egg industry also produces waste in the form of downgraded eggs and scrapped egg content. This has a high protein content and a dry matter content of about 15 %, of which 95 % is made of volatile solids and provides a high gas yield.

2.2.4.6 Fisheries

Fisheries and the fish processing industry produce a large amount of waste and by-products, like fish guts, sewage sludge and contaminated rinse water (Carlsson & Uldal 2009). The sludge from the treatment plant is an important feedstock for biogas production. The fish waste and discarded fish will usually be used in animal feed and fishmeal production. Fish waste contains high levels of nitrogen; this could inhibit the decay due to toxic levels of ammonium in the process. Practical problems concerning fish waste are according to Ståhlberg and Hill (2007) as accounted by Carlsson and Uldal (2009), related to a considerable variety in dry matter content and odor; thus, the waste must be covered at temporary storage.

2.2.5 Biogas yields

Some key values for the described biogas substrates are presented in Table 3. The values show a large variation in dry matter contents of different substrates. Wet manure holds a low dry matter content due to the high content of urine and as it contains almost no litter. The organic municipal waste holds an average dry matter content when considering the substrates normally disposed in this type of waste, like dairy products, pastries and eggs among other. The volatile solids contents are more stable, but as this is dependent on the dry matter there will also be a large variation per ton wet weight of the different substrates.

The methane content is mainly in the range 61 – 65 %; however fish waste and straw stand out with slightly higher methane content. We also see that fish waste stands out as the substrate with the highest methane yield, straws has nevertheless and rather low methane yield and it is not possible to see a correlation. It could thus be seen a slightly correlation between dry matter content and biogas yield since it is only the degradable organic fractions that will produce biogas in the digestion.

The values in the table are taken from a report commonly cited in the literature. This report bases its data from several other sources; the validity of the data should therefore be universally valid.

Table 3: Key values for different biogas substrates (Carlsson & Uldal 2009)

Substrate	DM	VS of DM	Methane content	m^3 CH$_4$ / ton VS	m^3 biogas / ton WW
Manure – Cattle (wet)	9 %	80 %	65 %	213	22
Manure – Cattle (solid)	30 %	80 %		250	
Straw	78 %	91 %	70 %	207	288
Manure – Pig (wet)	8 %	80 %	65 %	268	26
Organic municipal waste	33 %	85 %	63 %	461	204
Slaughterhouse – blood	10 %	95 %	63 %	547	83
Slaughterhouse – entrails	16 %	83 %	63 %	434	92
Diary – return products	20 %	95 %	67 %	520	147
Bakery – bread	61 %	87 %	61 %	350	304
Bakery – dough	67 %	90 %	61 %	290	285
Vegetables and fruits	15 %	95 %		666	
Egg	27 %	92 %			241
Fish waste	42 %	98 %	71 %	930	537

2.3 Bioresidual

Bioresidual is a product from biogas production that can be utilized as soil improver and fertilizer (Marthinsen 2012). If the treatment is an anaerobic wet process, the product will be a Bioresidual that can be used directly as a liquid fertilizer in agriculture. This fertilizer has a nutrient level that is close to the level needed by plants and can therefore, in many cases, replace chemical fertilizer. According to Carlsson and Uldal (2009), basically all the nutrients contained in the material brought into the digester will still be present in the Bioresidual. They explain further that, it therefore is important to determine the contents of each substrate to ensure that the Bioresidual will have a high enough nutrient level to be used as fertilizer, in addition to determining if the substrate contains any material that should not be spread on farmland. Thus, the incoming substrates are critical for the quality of the Bioresidual and potentially harmful substances should be avoided.

To limit the amount of heavy metals in soil used for food production, criteria for spreading of the Bioresidual dependent on heavy metal contents are established in Norwegian legislation by the regulations of organic fertilizers (Royal Decree on organic fertilizers Articles 10.1 and 27) (Landbruks- og matdepartementet et al. 2003). The Bioresidual will based on the heavy metal content be classified in one of the categories 0 – 3. Category 0 residual can be spread on all cultivatable land as long as the generated amount does not exceed the plants need for nutrients. Bioresidual in category 1 and 2 can be spread on all cultivatable land as long as it does not exceed the amount restrictions. Category 3 Bioresidual can be spread on land that is not used for food production as long as the amount does not exceed the restrictions.

The liquid fertilizer is mainly for use at crop areas and meadow (Marthinsen 2012). It will have high nitrogen content; this will limit the amount that can be spread per area. There is still sufficient amount of farmland in Norway to dispose of all the Bioresidual from biogas production as fertilizer, even though all food waste was used for biogas production. However, it would be large regional differences. In the western part of Norway it could be a challenge to find enough dispersal area or other utilization of the Bioresidual as there is a relatively high density of livestock, and thus a high amount of manure; while there is a lack of manure to fertilize all agricultural land in the eastern part. The challenge would thus be linked to the profitability of the Bioresidual sale, rapidly decreasing with transportation distance. It is therefore necessary to ensure a local utilization of the Bioresidual.

2.4 Technologies

The different processing steps of the biogas production can be carried out by use of different technologies. These technologies will be presented below, drawing attention to the parts most relevant for this Thesis.

2.4.1 Pretreatment

Some substrates need pretreatment before it is utilized for anaerobic digestion (Carlsson & Uldal 2009). This could be to make the pumping, steering and digestion work as optimal as possible and to remove particles that should not be part of the process. The aim of the pretreatment is to break down the materials so they can be digested within a reasonable time. The pretreatment are done in several operations to ensure a good substrate. The treatments could be comminution, dilution and separation (magnetic, sieving, screw press). The materials that should be sorted out are according to Steffen et al. (1998): plastic, sand, metal, glass, wood etc.

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Some substrates require sanitation to comply with the regulations of organic fertilizers in Norwegian legislation (Regulation of organic fertilizers Article 10.3) (Landbruks- og matdepartementet et al. 2003). This is to avoid that the products and their use involve a risk of transmission of infectious diseases to humans, animals or plants. The original requirement of sanitation according to Angelidaki and Ellegaard (2003) is heating to 70 °C for minimum one hour. They also explain that a number of alternative combinations of temperature and holding times are established that are as efficient as the original requirement when it comes to decay of the most important animal diseases, see Table 4.

Table 4: Combinations of temperature and holding time that satisfies the sanitation requirement (Angelidaki & Ellegaard 2003)

	Sanitation combination requirements			
Temperature (°C)	52	53.5	55	70
Holding time (hours)	10	8	6	1

2.4.2 Anaerobic digestion

Different anaerobic microorganisms operate at different temperatures (Raadal et al. 2008):

- Phsychophilic, < 20 °C. The degradation occurs with a low rate.
- Mesophilic, 32 – 42 °C. The optimal degradation takes place at about 35 degrees and with a degradation time of 20 days.
- Thermophilic, 48 – 55 °C. The degradation goes on for 8 days at optimal temperature.

Phsychophilic degradation takes place at a low temperature and is the type of degradation that happens at landfills. Mesophilic- or thermophilic degradation normally is used in biogas plants. Raadal et al. (2008) explains the biogas production as a three-stage anaerobic digestion.

- Cellulose, proteins and fat in the first stage are hydrolyzed to monomers (water-soluble).
- In the next stage the acetogenesis, the monomers, are degraded further to simple organic acids, alcohols, hydrogen and carbon dioxide.
- The last stage produces methane; this is done by microorganisms that utilize the products from the acetogenesis.

The anaerobic digestion can take place in one or two reactors. Using one reactor, all three stages will take place therein. When two reactors are used, the first stage will take place in the first reactor and stage two and three in the second reactor.

Morken et al. (2005) explain that various systems for biogas production are established according to what type of substrate that is going to be handled. The main difference for the systems is connected to the reactor and its construction. No reactor exists which can process every type of substrate optimally. According to Morken et al. (2005), there are three types of reactors:

- Batch wise digestion: The substrate is added to a reactor that contains minimum 10 % almost total digested material. Air is blown into the digester for two days to create an aerobic composting; this will hydrolyze the substrate and the temperature will increase. The substrate will further be digested anaerobically for some few weeks. About 90 % of the digested material is removed, and the process is repeated. It is normal to have several reactors that will be started at different times to compensate for the unstable biogas production. Batch wise digestion is preferable for digestion of manure with high contents of straw or wood chips, because the residence time can be varied with the type of substrate.
- Accumulation continuous flow (ACF): The reactor is a batch wise reactor that at the same time functions as a storage for manure. The manure is added to the reactor as it is generated and the reactor is emptied when there is a need for biological fertilizer. The reactor will be full in the winter; the excess will be lead to a post-digestion tank that most often is covered with a gas tight lid. A variant is “covered lagoons” – these are manure storages that are covered with gas tight membrane.
- Continuous supply: Continuous supply is the most commonly used method. The reactor has a constant volume and the added substrate replaces a corresponding volume of the reactor. Supply can be added a couple of times each day or continuously by computer operated programs.

Most biogas plants operate with continuous stirring of the substrate in the digester. This is so to quickly mix new substrate with the microorganisms, to keep the temperature constant, prevent precipitation and foaming, at the same time as gas bound in the liquid are released (Morken et al. 2005). The downside of stirring is that some untreated substrate will follow the Bioresidual out of the reactor.

2.4.3 Cleaning and upgrading of biogas

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2.4.4 Cleaning and upgrading of biogas

Several technologies are according to Persson et al. (2006) available for removal of contaminants from the biogas, and by this upgrading the gas to fuel quality also known as biomethane. Deublein and Steinhauser (2008) explain that the cleaning and upgrading are done in several steps:

- Step one is a coarse separation of hydrogen sulfide; this is carried out in the bioreactor or in a separate scrubber.
- In step two the traces of hydrogen sulfide will be removed.
- In the third step, carbon dioxide and other biogas components are separated.
- The fourth step is dehumidification (water removal). (The removal of carbon dioxide could be a dry gas process in which the drying will be carried out before step three.)

The first and fourth steps are conducted in almost every biogas plant, and can be characterized as the cleaning of the biogas (Deublein & Steinhauser 2008). A biogas upgrading will be the result of steps two and three and are necessary only if the gas is desired with biofuel quality. These steps can be conducted by use of different technologies, which according to Deublein and Steinhauser (2008) as accounted by Raadal et al. (2008), may be split into four:

- Water scrubbing – is based on absorption processes, which utilize that methane and carbon dioxide possess different characteristics with respect to dissolution in fluids. The most commonly used liquid is water, or water containing bicarbonate. The water scrubber will usually recycle the water. The carbon dioxide is bound in chemisorption processes; this is unlike other water scrubbers, and will be released again by temperature changes.
- Pressure Swing Absorption – Absorption in combination with changes in pressure utilizes that some materials absorb or emit carbon dioxide as a result of pressure changes. One such widely used material is zeolite, which allows methane to pass by, but absorbs carbon dioxide.
- Membrane technology – A membrane consists of some kind of synthetic material. Membrane technology utilizes the fact that different gases will have different speed through such materials. The principal of biogas cleaning with membrane technology is that carbon dioxide, water and hydrogen sulfide have a relatively higher permeation rate through the membrane than the methane. Thus, the gas can be purified. Nitrogen is however more complicated to clean out by applying this method as methane and nitrogen have almost identical properties considering the permeation of membranes.
- Cryogenic methods – utilizes the fact that different gases condensate at different temperatures. This is a highly successful technique, which requires large amounts of energy and thus has high operating costs.

Raadal et al. (2008) explain that the removal of carbon dioxide will result in some methane loss. The loss varies with technology applied, but is stated to be under 3 %.

2.5 Previous studies

Biogas production has been studied by a number of scientists, applying different approaches. Selected studies from this literature are referred to below, and are presented in two sections referring to which of the two main issues they address:

- Life cycle impacts of biogas production from organic waste substrates in Norway
- Co-digestion of food waste and manure

2.5.1 LCA on biogas production from organic waste substrates, Norwegian case studies

Hung and Solli (2012) studied five scenarios for treatment of food waste from household in the municipality of Trondheim. Two of the scenarios are about incineration, located in Trondheim (current handling) or Sundsvall (Sweden). The three remaining scenarios concern biogas production at different locations, Trondheim, Verdal and Sundsvall. The food waste is assumed to be digested under mesophilic conditions over a digestion period of 20 days. The methane yield is assumed to be 546 Nm^3/ton volatile solids. The chosen volatile solids content is set to 28.1 %, rather high. This is because the anticipated use of thermal hydrolysis pretreatment, which is known to increase the biogas yield in the digestion stage. A 57 % methane content of the produced biogas is expected. For the complete value chain, a methane loss in the upgrading process is estimated, along with a 1 % loss of the total raw biogas volume due to fugitive emissions.

According to the study, the climate benefit of biogas production from municipal food waste in Trondheim compared to the current handling with incineration, is negligible. By including the end products and the direct emissions there from, there is a climate benefit. This is due to the combustion of biogas in buses rather than fossil fuel as being the case when the food waste is incinerated. However, by decreasing the fossil fuel consumption made by the buses in Trondheim, the result was a remarkable reduction of smog formation (photochemical oxidant production), particulate matter formation and fossil depletion impact categories.

The study concludes that the environmental benefit from biogas production most of all depends on the transportation distance of waste and upgraded biogas. It is therefore, based on the study, preferable to produce biogas at a plant in Trondheim. However, the study does not take into account the emissions caused by the building of a new plant.

Østfoldforskning by Møller and Modahl (2013) carried out an analysis of the climate benefit from biogas production with upgrading to fuel quality conducted by Vesar AS. The study primarily analyzes the climate benefit by replacing clean drinking water with diluted livestock manure as process water. Manure is therefore not treated as a substrate in the process, but as a component for processing of organic food waste. The effect of co-digestion in the study is set to 1.05.

According to the study, climate benefit is best achieved by, throughout the life cycle phases, substituting fuel made by biogas and artificial fertilizers with Bioresidual. The highest emissions are related to the transportation to the plant, pretreatment and upgrading of the biogas to fuel quality, Figure 2. The study also concludes that the storing of the Bioresidual is of importance. When storing the Bioresidual in a close unit, the emissions are significantly reduced compared to storage in an open unit. The climate benefits from the processing of the different components were studied. The treatment of food waste results in the biggest climate benefits. Mixing with livestock manure provides a substantial increase in total climate benefits.

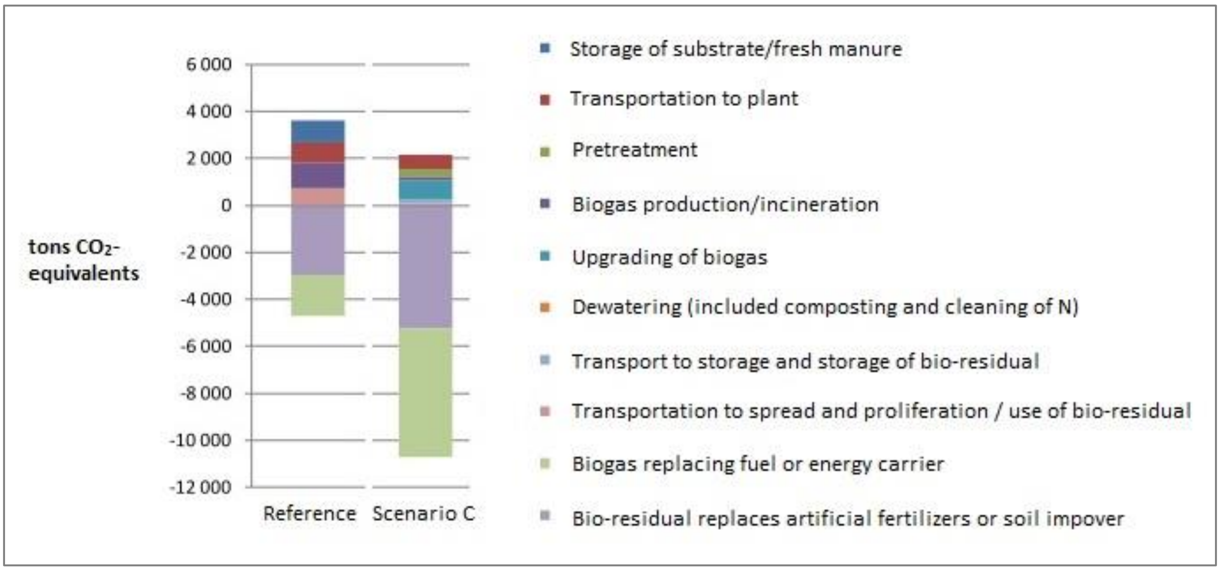


Figure 2: Annual climate impact from the handling of food waste and livestock manure broken down on life cycle phases (Møller & Modahl 2013, modified by author).

In Figure 2, the reference scenario represents the handling of 18 000 tons food waste (33 % DM) of which 60 % is sent for incineration and 40 % is composted. At the same time livestock manure (30 000 tons from cattle and 30 000 tons from pigs) is stored and spread fresh, which replaces artificial fertilizer. Scenario C represents the expected startup scenario for the plant: 18 000 tons food waste is digested for biogas production with upgrading to fuel quality, whereas the Bioresidual is used as fertilizer in agriculture and stored in a sealed tank. 60 000 tons of livestock manure is included in the biogas production.

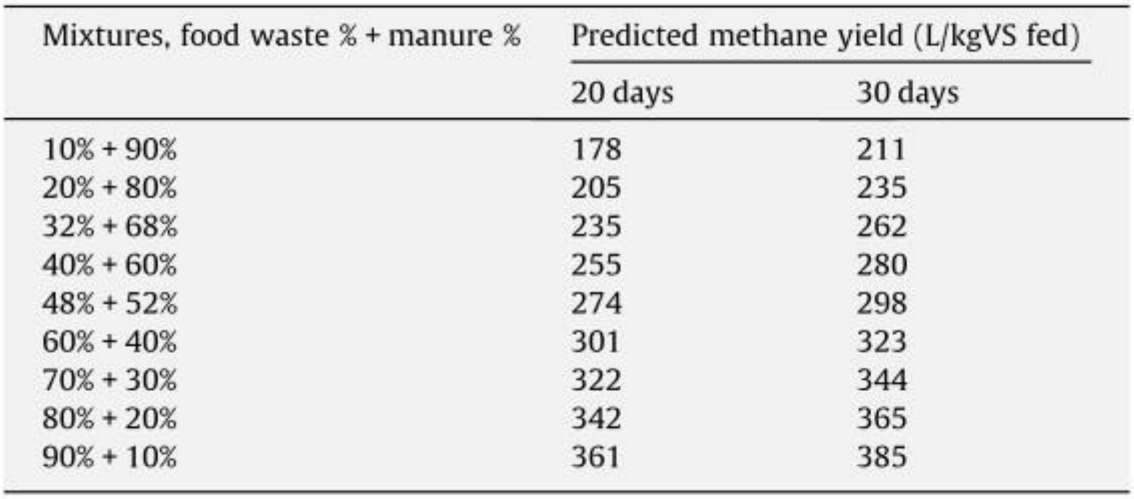
2.5.2 Co-digestion of food waste and manure

Cow manure produces biogas, a source of renewable energy and a Bioresidual that can be used as organic fertilizer, anaerobic digestion is therefore an attractive treatment for such organic waste (Neves et al. 2009). Biogas plants are however hard to run with an economic profit if the process is based only on manure, therefore co-digestion is widely applied to improve the production of methane in agricultural biogas plants. Carlsson and Uldal (2009) points out that co-digestion also would help to obtain an efficient and stable biogas process, since the possibility of obtaining an optimal nutrient composition and structure of the substrate increases. Several studies state that co-digestion of cow manure with food waste results in a higher methane gas yield (Macias-Corral et al. 2008; El-Mashad & Zhang 2010). Different type of waste can be co-digested with food waste, but according to Li et al. (2010) dairy manure is preferable, due to its availability and its suitable physicochemical characteristics.

In the study performed by Li et al. (2010), it was found that the gas production rate increased 0.8-5.5 times when food waste was co-digested with dairy manure under mesophilic conditions in a two-phase digester, compared to the digestion of dairy manure alone. Food waste and dairy manure in the study were mixed at different ratios and with different hydraulic retention time for acidification and methanogenesis. The processes took place in two-phase digesters. The different mixtures of food waste and dairy manure tested were based on volatile solid basis and the ratios were 0:1, 1:1, 3:1 and 6:1. The highest gas production rate of 3.97L/L·day was obtained with a 6:1 mix ratio of food waste and dairy manure (and with a hydraulic retention time of 1 day for acidification). The study also analyzed the methane contents of the biogas from the different mixtures, which turned out at just above 62 %. Statistical analysis showed that there was no significant difference.

A correlation between degradation of organic matter and biogas production was, however, observed. The gas production rate correlates with the change of volatile solids removal.

The effect of co-digestion of dairy manure and food waste under mesophilic conditions was studied by El-Mashad and Zhang (2010). In the study two different mixtures of unscreened manure and food waste, 68/32 % and 52/48 % were digested and studied. The methane yield from the digestions was compared to the methane yield from digestion of unscreened manure alone. The study showed that after 20 days of digestion, the methane yield from the 68/32 % mixture was 251 L/kgVS. The 52/48 % mixture had a methane yield of 293 L/kgVS, while unscreened manure had a methane yield of 218 L/kgVS. The study showed that by increasing the portion of food waste, the methane yield increases. There were remarkable differences in the methane yields from the mixtures compared to unscreened manure alone, independent of a digestion of 20 or 30 days. A model for predicting the methane yield from different mixtures was developed, see Figure 3. Based on this they recommend a mixture of 60 % food waste and 40 % manure for a 20 days digestion time. This model, however, does not include the effect of intermediate compounds, like volatile fatty acids, on the methane production and digestion performance.



Mixtures, food waste % + manure %	Predicted methane yield (L/kgVS fed)	
	20 days	30 days
10% + 90%	178	211
20% + 80%	205	235
32% + 68%	235	262
40% + 60%	255	280
48% + 52%	274	298
60% + 40%	301	323
70% + 30%	322	344
80% + 20%	342	365
90% + 10%	361	385

Figure 3: Predicted methane yields for different mixtures of food waste and dairy manure by the use of the co-digestion model (El-Mashad & Zhang 2010)

Macias-Corral et al. (2008) found that co-digestion of organic fractions of municipal solid waste (62% paper, 23 % food waste and 15 % yard clippings) with cow manure resulted in a production of 194 m^3 methane/ton VS, compared to 77.4 m^3 methane/ton VS for cow manure and 30.5 m^3 methane/ton VS for organic fraction of municipal solid waste. The study showed that co-digestion of cow manure and organic fractions of municipal solid waste resulted in a higher methane gas yield than single waste digestion of the fractions. The mixture used in this experiment consisted of 63.7 % paper, 18.2 % food waste, 9.1 % grass clippings and 9 % cow manure. The ratio of manure and organic fractions of municipal solid waste was put together to obtain a carbon/nitrogen ratio of 20/1. The volatile solids content for the two fractions, organic fractions of municipal solid waste and cow manure, was 89 % and 81-82 %, respectively.

This study digested a mixture of organic fractions of the municipal solid waste and not only food waste, this is likely the reason for the low methane yield for the single digestion of this fraction.

Neves et al. (2009) studied the effect of mesophilic co-digestion of cow manure and food waste, with an intermittent input of fat. Different pulses of an oily waste effluent from a canned fish processing industry were added to reactors with the completely mixed substrate of cow manure and food waste. The composition of cow manure and food waste was of an equal amount expressed as total solids, the feeding of fat was initiated after 148 days of a stable operation of the reactors. One reactor was used for control and was not fed with fat, while three reactors got different pulses of oily waste added on the same day. The study observed that an input of oily waste resulted in increased rate of methane production when cow manure is co-digested with food waste. However, the mixture of lipids present in the oily waste added has to be taken into account; to avoid long-term accumulation of lipids and by that inhibit the biogas production. The study suggested that the threshold of input does not exceed 12 $gCOD_{oil}/l_{reactor}$, this equals a continuous feeding of 100/10 ($V_{manure}/V_{food\ waste}$) with regular oil pulses of 5 % (V_{oil}/V_{manure}).

Alvarez and Lidén (2008) preformed a mesophilic study were they looked at co-digestion of solid cattle and swine slaughterhouse waste, solid cattle and swine manure and fruit and vegetable waste. The results were compared to the digestion of the different substrates alone. Ten different compositions of waste were digested for biogas production and the study showed that a mix of substrates had a higher methane yield than pure substrates. It was however one exception, the mix of equal amounts, on volatile solids ratio, of solid cattle-swine slaughterhouse waste and fruit and vegetable waste. For all other cases, the methane yield was from 1.2 - 130 times higher for co-digestion than for the digestion of the substrates alone. The highest methane content, after 60 days operation and a hydraulic retention time of 30 days, was observed in the mix of 50 % slaughterhouse waste and 50 % manure. The highest methane yield was obtained with a mixture of 17 % slaughterhouse waste, 17 % manure and 67 % fruit and vegetable waste. They concluded that a co-digestion with a mixture of all three substrates gives a better methane yield compared to digestion of one or two substrates. In addition, they assert that a methane yield of about 0.3 m^3/ton VS added, can be expected with a semi-continuous co-digestion process of the three substrates.

By looking at the different studies combine; there is no pattern, and a big variation in methane yield and methane content independent on the mixture used for co-digestion. However, if you look at the different studies separately, they all indicates that a co-digestion of food waste with manure is preferable considering the methane yield. For all studies, the highest methane yield obtained was in the mixture with the highest additive of food waste to the manure. The methane content are nevertheless not consistent with substrate mixture. The different biogas yields, as results of co-digestion of food waste and manure from the studies, are summarized in Appendix 2.

2.5.3 Gaps in the literature

The literature holds little information on the benefits of a substitution of clean drinking water. The previously discussed study by Østfoldforskning investigate it to a certain extent, the results is however hard to interpret. It is difficult to determine whether the effect is due to the choices of water or to the alternative treatment of manure, the latter causing a reduction in emissions due to spreading and storage of manure. It is thus desirable if this Thesis could clarify the effect of substitution of clean water with manure, and by that contribute to fill the gap in the literature.

3 Methodology

In this chapter is described the methodologies chosen and presented the case studied.

3.1 Choice of methodology

The choice of methodology depends on the research questions; one has to choose a design that goes along well with the questions (Jacobsen 2011). Choosing the right methodology is important to ensure a study as reliable as possible.

3.1.1 Literature review

The purpose and function of a literature review is to provide an overview of the literature which is relevant to the overall research objectives (Craswell 2005).

The information collected throughout the literature study is presented in chapter 2 Literature. The corresponding sources are presented continuously all through the chapter. The theoretical parts of the study are mainly based on Swedish and Norwegian reports. The Swedish reports are selected because Sweden has a more developed waste management, considering energy utilization of waste, than Norway. The Norwegian reports are selected because of the Norwegian context and because they deal with Norwegian conditions and resource basis. The part that covers previous studies is based on articles that deals with topics relevant to the choices made by Greve Biogass AS, choices that make their biogas plant special compared to other biogas plants in Norway.

3.1.2 Case study

In a case study, you investigate in depth a few phenomenon, often over time (Jacobsen 2011). It is further important to have a detailed and extensive data collection. Case studies stands out from other studies in that only one case/event/industry is subject to a highly detailed research (Ramian 2007).

Greve Biogass AS is chosen as the case for this Thesis, and will be further presented in chapter 3.2 Case: Greve Biogass AS.

3.1.3 Material Flow Analysis (MFA)

MFA is a good tool for investigating the outputs of “The Magic Factory”, stated as one of the objectives of this Thesis in the introduction. MFA is a well suited tool as it is mass balanced; that makes it possible to determine the expected outputs from various alternatives, based on the intended input. The mass balance also makes it possible to determine the desired additives for the system and to have an idea of what parts of the system which are the most inefficient. The MFA is also a well suited tool as it can be used to establish the outputs based on several units. A functional unit makes it possible to compare outputs from scenarios with different inputs. Nevertheless, it is at the same time possible to use the model to determine annual outputs and by that assume a yearly profit. The results of the MFA are of importance as it will help Greve

Biogass AS to plan their production and estimate the outputs so they can draw up contracts with partners and customers of delivery of the products.

In MFA you systematically evaluate the flows and stock of materials inside a system, defined in space and time (Brunner & Rechberger 2004). A MFA model connects the sources, the pathways and the uptake of the material. The law of conservation makes the results of a MFA possible to control by a material balance that compares all inputs, stocks and outputs of a process. This is characteristic of a MFA, and makes the method popular as a decision support tool in resource management, waste management and environmental management. A MFA model will show, based on total material balance, what processes and flows that have the highest improvement potential and if the set objectives have been achieved.

In the study of flows and stocks of any material based system, MFA stands forth as an appropriate tool (Brunner & Rechberger 2004). It provides insight into the behavior of the system and simplifies the control of an anthropogenic system when combined with energy flow analysis, economic analysis and consumer oriented analysis. Brunner and Rechberger (2004) state that the objectives of MFA are to:

- use well-defined uniform terms to delineate a system of material flows
- ensure a basis for good decision making, while as far as possible reduce the complexity of the system
- in quantitative terms asses the relevant flows, and in that way apply the principle of balance to reveal sensitivities and uncertainties
- in a transparent, reproducible and understandable way present the systems results about flows and stocks
- manage resources, the environment and waste by using the results as a basis, and by this:
    - ensure a timely prediction of environmental impacts by an early recognition of potentially harmful or favorable accumulations and depletion of stocks
    - determine the importance of actions and the order of those actions (measures for environmental protection, resource conservation and waste management)
    - promote environmental protection, resource conservation and waste management by designs of goods, processes and systems (eg. green design, design for recycling etc.)

MFA is a good tool when accessing waste management. According to Brunner and Rechberger (2004), waste management is taking place at the interface between the anthroposphere and the environment, and the definition and objective of waste management is continuously changing.

The elemental composition of waste could be exactly determined in a cost efficient way by the use of MFA (Brunner & Rechberger 2004). This information is essential in the process of determining the best treatment of the waste, whether concerning decisions about recycling, treatment technologies or designing the waste treatment facilities. A MFA can also contribute in the designing of products to make them easier to recycle or treat when they are outdated and become waste. This way of processing is described as design for recycling, design for disposal or design for the environment. Waste management is already included in the economy, but some MFA experienced experts suggest that we should replace waste management with materials and resource management. They argue that it is more efficient to control the material flows through the total economy, rather than separating waste management from the management of production supply and consumption.

During the two past centuries an increased consumption of goods has been observed, yet, there are no clear signs of change (Brunner & Rechberger 2004). Due to this large growth, the amount and composition of waste have changed and will continue to do so in the future. Some materials, like construction materials, have a long residence time. For such materials, a large stock is built up, before, at the end of the life cycle, the waste becomes noticeable. Waste management will take on most of the materials in the stock in the end. The increased complexity of goods results in a growing amount of new materials in waste; several of these are composed of mixtures that are impossible to separate by physical methods. A stock of goods made for a long life is made to withstand degradation and erosion caused by microorganisms, ultraviolet light, temperature, weathering, etc. This results in a higher amount of hazardous substances (heavy metals and slowly degradable organic materials used as stabilizers and additives) in long-lived stocks than in short-lived products that are recycled right away (wrappings, newsprints, glass, etc.). Thus, in the future we will have to separate a large amount of hazardous substances from waste to ensure a safe recycling of the materials of the long-lived stock.

3.1.4 Life Cycle Assessment (LCA)

LCA is a good tool for solving the case-specific issues for research stated in the introduction to this Thesis. The LCA makes it possible to compare different alternative treatments of a waste fraction and to study the processing of different input mixtures. The results will be based on a functional unit, which makes it possible to compare several scenarios concerning different amounts by use of different technologies. This also make it possible to investigate the effect of parameter changes, thus the effect of assumptions can be studied. The model can thus be used for investing the different substrate mixtures and alternative transport distances, which makes it especially well suited for this study. The LCA would determine if different alternative treatments causes problem shifting rather than problem solving, and by that show if an alternative treatment is to prefer. An LCA is also a good tool as it is possible to investigate the impact factors especially interesting for the specific case.

Through a holistic approach LCA is used for improving the understanding of the environmental consequences caused by our activities defined by a functional unit (Strømman 2010). The holistic way of thinking is synonymous with inclusion of all life cycle phases of a system;

production, use and waste management (Strømman 2010; Baumann & Tillman 2004). Strømman (2010), states that all types of products and product systems can be assessed through LCA, and further explains that the objective of LCA is to perform consistent comparisons of technological systems with respect to their environmental impacts. It will, based on this be possible to estimate the most environmental-friendly choice. The principles and framework of the LCA are determined through the international standard ISO 14040:2006. This standard addresses the general description of LCA and the methodological framework (ISO 14040 2006).

One strength of the LCA study is that it implements the whole product system (Baumann & Tillman 2004). This makes it possible to avoid sub-optimization, which could have been a challenge if only a few processes where focused on. In addition, the result of a LCA is related to the function of a product; this enables the possibility of comparison between alternatives. Including the complete product system also ensures that a problem will not be solved by problem shifting (Strømman 2010). This is when a problem is solved by shifting it to a place outside the system or by shifting the impact category being charged. (For example, production of electricity: production by use of coal will have higher CO_2 emissions than production using waterpower, but waterpower would have a higher impact on biodiversity and land use.) LCA is therefore an especially well suited tool to ensure a holistic perspective on environmental impacts so as to avoid problem shifting in times with a special focus on one impact category, like today’s paramount focus on climate change.

Technical systems and potential challenges are studied through an LCA and it can therefore be defined as an engineering tool (Baumann & Tillman 2004). However, the fact that an LCA also models the impacts on the natural environment and the relations people have to such impacts makes it a multi-disciplinary tool. Environmental impacts cannot be modeled at a very detailed level as the LCA it not site-specific, but studies the whole life cycle. A LCA does not include risk or economical and social aspects.

When assessing an LCA, several choices have to be made. A goal and scope has to be determined along with the functional unit and system boundaries (Baumann & Tillman 2004). Through the goal and scope, the product to be studied and the purpose of the study are determined. The goal definition should include the particular use of the study, the reason for carrying it out and to whom the results are to be presented. The purpose of the LCA study has to be formulated clearly. The functional unit is a specification of the model, as LCA relates the environmental impact of a product to the function of a product system. For this to be possible the function has to be expressed in quantitative terms, a functional unit (e.g. liters, kg/day or one unit of a product). The system boundaries decides which processes to include in the study and by this controls the flow model constructed in the inventory analysis. The system boundaries could be hard to determine based on the fact that a LCA focuses on single products, while the life cycles of different products often are connected. This problem is especially challenging if more than one product is produced in a process.

Several environmental impacts can be studied through a LCA, it is therefore necessary to select the ones relevant to the study and the goal of the study (Baumann & Tillman 2004). There is a standard list of impacts considered in most LCAs, including resource use, global warming, acidification and eutrophication. However, in some studies it might be desirable to cover only certain impacts. The chosen impacts will determine the parameters for which data that will be collected during the inventory analysis. The inventory analysis is a model development according to the system to be analyzed and the requirements of the goal and scope definition. The model is a flow model describing the flows through the technical system inside the system boundaries. The system should be in mass and energy balance. The model will usually be displayed as a flowchart including the activities in the system and the flows between these activities. The activities often includes production, processes, transport, use and waste management.

3.2 Case: Greve Biogass AS

Grenland and Vestfold Biogas AS (Greve Biogass) was established 21 October 2013 with the objective of ensuring local recycling of food waste and sludge from the owner municipalities (grevebiogass.no 2014). The owners are:

- Vesar AS (Vestfold Avfall og Ressurs AS)
- the Vestfold county municipalities Horten, Holmestrand, Hof and Andebu
- Tønsberg renseanlegg IKS
- the Grenland (a region in Telemark county) municipalities Porsgrunn, Skien, Kragerø, Siljan and Bamble

The biogas project in Vestfold started as a unique collaboration between 12 municipalities (Lind 2013). The intention of the project was to achieve climate targets and to better utilize the waste in the region. It was decided after a pre study was completed, that the project would be continued. Vesar was commissioned to undertake the necessary processes and has until the establishment of Greve Biogass AS been in charge of the work on behalf of the municipalities. In June 2011, an agreement was signed between Vesar and the municipalities of Grenland for the delivery of food waste and sludge to the biogas plant; this led to a continuation of the project as “Biogas in Vestfold and Grenland”.

Greve Biogass AS on behalf of Tønsberg municipality will project and build a biogas plant, “The Magic Factory”, at Rygg/Taranrød in the northwest area of Tønsberg municipality in Vestfold county (Greve Biogass AS 2014b). Tønsberg municipality will own and finance the project while Greve Biogass AS will rent the plant back on a long-term contract. Public tender will offer the operation of the plant to the company that fulfills all needs and demands and which can offer the lowest operation cost. “The Magic Factory” is scheduled for completion in 2015.

“The Magic Factory”, with the production of biogas as a substitute for fossil fuels combined with complete infrastructure for storage and use of Bioresidual, will be the first facility of its kind in Norway (Lind 2013). The plant also is special because large amounts of manure will replace drinking water as process water (Greve Biogass AS 2014b). The plant will process organic waste from private households, food processing industry, retail and agriculture. Sewage sludge will not be processed at the “The Magic Factory” due to the risk of infectious contents and heavy metals in sewage sludge. According to the White Paper 21, heavy metals makes the Bioresidual unsuitable as fertilizer in agriculture (*Meld. St. 21 2011–2012*). Through regulations of organic fertilizers in Norwegian legislation (Regulation of organic fertilizers Article 25) there are restrictions on what areas Bioresidual containing sewage sludge can be spread, because of the risk of infectious contents in the sewage sludge (Landbruks- og matdepartementet et al. 2003).

“The Magic Factory” will ensure both a cost effective and an environmental efficient processing of food waste from the residents in the owner municipalities (Lind 2013). This treatment of the local food waste will ensure that municipalities, counties and the businesses in the region reach their climate targets. “The Magic Factory” is expected to be the facility in the Nordic countries with the highest net reduction in greenhouse gas emissions per ton food waste. Because of these high environmental and climate benefits, the plant has received financial support from Enova. In addition, the plant is proposed as a national pilot project for industrial plants that will use large amounts of manure as a substitute for process water.

3.2.1 Design and Technologies

Three different companies supplies the different components for the three steps in the biogas production at “The Magic Factory”.

- Section A: Pretreatment – Cellwood Machinery AB
- Section B: Sanitation and biogas production – Goodtech Enwironment Ab
- Section C: Biogas upgrading – Malmberg

The sources for the information presented in this subchapter is Sørby and Jacobsen (2014) and Sørby (2015a). Work drawings decribing the different sections are presented in Appendix 3.

3.2.1.1 Pretreatment

A grinder with subsequent pulper technology and cleaning of reject is chosen as pretreatment at “The Magic Factory”. The food waste and dry manure must be minced into small fractions before it enters the HC-pulper (high consistency pulper). The dry matter content of the waste is in the range 30 – 34 %, the preferred dry matter for the substrate going through the pulper is 18

– 20 %. As a result, a large amount of process water is added; the frictional forces in the liquid tear the particles apart. Before the substrate enters the GRS (Grubbens reject separator) more water is added. In the GRS all unwanted fractions, like plastic and metal along with other things that do not pass through a sieve plate with a holes opening at 6 mm, are sorted out. These unwanted particles ends up in the reject and could be as much as 10 – 15 % of the weight of the food waste. The reject is a waste product and will be incinerated. Further one the substrate will pass through a hydro cyclone that will separate heavy particles such as sand, glass, eggshell etc. from the substrate. After all unwanted components are sorted out the substrate will pass through a screw press. The process water will be reused in the screw press and the dry matter content of the substrate, which goes for biogas production, will be stabilized at 15 %.

The liquid manure that enters “The Magic Factory" has a dry matter content of 3 – 9 %. Some of the liquid will be used as process water. The rest of the water along with the solid particles, will be treated in a hydro cyclone and then further in a screw press. The purpose of this is the same as for the food waste: to sort out unwanted particles and stabilize the dry matter content at 15 %. The liquid organic industrial waste will be received in separate tanks with a total capacity of 200 m^3. Some of the liquid will be used as process water. The rest, with the solid fractions will go straight to biogas production where it will be mixed with the other substrates available.

No methane loss is expected from the pretreatment as the process is carried out at a low temperature that should not give methane production. The pretreatment will be operational during day time, when the operator is present at “The Magic Factory”.

3.2.1.2 Sanitation and biogas production/anaerobic digestion

The substrate will be pumped from the pretreatment into a buffer tank that holds 1 000 m^3. The load from the pretreatment into the buffer tank will be higher than the amount of outgoing substrate. This makes it possible to drift the biogas production twenty-four hours a day, even though the pretreatment is drifted only at daytime. The substrate will hold 10 – 20 °C in the buffer tank. If the temperature in the buffer tank decreases below 10 °C, heating will start by means of circulation of the substrate through a heat exchanger. “The Magic Factory” can handle a flow of 7 – 18 m^3/h biogas substrate out from the buffer tank.

From the buffer tank, the substrate passes through two heat exchangers. This increases the temperature of the substrate to 72 °C before it enters one of the three sanitation tanks for pasteurization. Also up to four liters of ferric chloride will be added to each ton of substrate mix before it enters the sanitation; this is to optimize the biogas production/the conditions for the bacteria. The three sanitation tanks will work in three different phases: filling, unloading and sanitation. To ensure an optimized and smooth operation, the tanks will shift between the different phases at the same time. When a tank is filled, the sanitation starts and the substrate should have a temperature above 70 °C for minimum one hour. If the temperature drops to less than 70 °C, the sanitation will not be sufficient and the process has to start over again. When the tank is unloaded, the substrate is pumped through a heat exchanger that will cool it down to 38 °C. Excess heat will be used to heat the first heat exchanger through which the substrate passes before the sanitation tanks. The substrate further on is sent to anaerobic digestion.

For the anaerobic digestion, two tanks will be used, which will be operated with a one-stage mesophilic process at temperatures in the range 37 – 38 °C. There will be continuously stirring in the anaerobic digesters and the temperature will be regulated by a heat exchanger on a shared circulation circuit. This circuit can be used for both heating and cooling dependent on the requirement. The thermal energy in the Bioresidual leaving the digestion tank will be retained by a two-stage heat exchanger. The heat exchanger will be used to cool down the Bioresidual to 18 °C to reduce emissions from the Bioresidual. The Bioresidual will be stored in one of two storage units at "The Magic Factory" until transported to the farmers and their local storage units.

3.2.1.3 Biogas upgrading

From the anaerobic digestion tanks the biogas will be led to the third step in "The Magic Factory", biogas purification and upgrading by use of water scrubbing. The biogas leaves through the dome of the digesters where the pressure of the gas is measured separately for the two units. In case of a wrong pressure in the digesters, the safety system to be used is water/glycol filled pressure valves.

The biogas with a methane content of 50 – 65 % is led to a gas container for processing. The gas will be flared if the pressure gets too high. The biogas then is compressed and led through a heat exchanger and a condensate separator before it is further compressed and led through the main heat exchangers. The water segregated in the condensate separator will be sent back to the digestion tanks. The heat from the refinement process will be used for heating the building facility at "The Magic Factory". The compressed and chilled biogas will be pumped into an absorption column to be "scrubbed". The process water, which in the presence of high performance packing material located in the column, absorbs the CO_2 and H_2S. The biogas is now upgraded to high-grade biomethane gas.

The gas is pumped from the absorption column through the second condensate separator and into absorption. In the absorption, the remaining water from the biomethane gas is removed by use of two dryers. The gas leaving the dryers will be analyzed; CH_4, CO_2, O_2, water, temperature, pressure and flow is measured and controlled. To recover as much methane as possible from the process, the removed water is depressurized and degassed. CO_2 and H_2S is released and the water is pumped back to the gas refinement process for reuse.

Malmberg notifies that loss of methane could occur at two sites through the process. The portion of the methane in the raw gas that cannot be upgraded is set to 1 %, while the loss of methane in the outgoing process air is set to < 0.1 %.

3.2.2 Energy demand

The different parts of the biogas production have different energy demands that varies through the year dependent on the outside temperature. It is desirable to recover as much as possible of the energy.

Cellwood Machinery AB has estimated an energy use in the pretreatment of < 22 kWh/ton last through the pretreatment. The biogas substrate passes through several heat exchangers on its way through "The Magic Factory". Some of the heat exchangers are connected; this ensures heat recovery and lowers the total energy demand of the plant. Goodtech Environment AB estimates different energy demand depending on the outside temperature. "The Magic Factory" therefore will need supply of heat in the winter, while it will have excess heat in the summer. The demand of heat also depends on the load of substrate; the average need for heat supply based on this will be 348 MWh/year at the expected maximum capacity, 18 m^3/h. The supply of electrical energy will be constant through the year, approximately 12 kWh/m^3. The numbers are based on biogas production 24 hours a day, 365 days a year. An energy balance for section B is presented in Appendix 4. Malmberg provides an installed effect of 505 kW for the upgrading facility; it is expected the use of 70 % of this at a maximum load of 1 200 Nm^3 biogas/h.

The total energy demand thus will vary with the load of the plant, the outside temperature and by the composition of the load (as the biogas amount varies with that).

3.2.3 Inputs and outputs

"The Magic Factory" can handle 23 000 tons of dry matter per year and will process four different inputs:

- solid organic waste from households and food industry
- liquid manure from cattle and pigs
- solid manure from cattle
- liquid organic industrial waste

The scheduled load of the different substrates at a fully operating plant is shown in Table 5.

Table 5: Estimated amounts of inputs to "The Magic Factory" in tons per year and dry matter content of the inputs (Sørby 2015a; Sørby & Jacobsen 2014)

	Solid organic waste from households and industry	**Manure**	
		liquid	solid
Tons/year	50 000	60 000	2 000
Dry matter content	32 - 34 %	3 - 9 %	30 %

The food waste from the owner municipalities, along with the manure, will account for approximately 11 000 tons dry matter (Sørby 2015c).

The households of the Vestfold county are currently sorting their waste in the homes. The organic waste is deposed in special biodegradable-bags that are collected once a week by VESAR (vesar.no 2014). The total amount of organic waste collected in Vestfold in 2013 was 12 049 tons, with an average of 53.9 kg/person (Lind 2013). In Grenland, inhabitants of four out of the five municipalities sort organic waste. 2008 was the first year that saw waste collection of organic waste in special bags, and at this point the amount of waste was between 42-56 kg/person and year (Hovland et al. 2009). As pointed out by Hovland et al. (2009), one would expect better sorting after some time so currently this figure is probably higher. The inhabitants of the municipality of Porsgrunn will start sorting once Greve Biogass AS becomes operational. The expected output of the Grenland region is 6 000 tons organic waste per year (Hovland 2014). The organic waste from households in Grenland is the first waste that will be delivered and processed at “The Magic Factory” (Sørby & Jacobsen 2014) and thus will initiate the whole biogas production.

The winter of 2012-2013 Greve Biogass signed contracts with nine farmers on reception of approximately 50 000 tons of liquid manure each year, 50 % from cattle and 50 % from pork (Greve Biogass AS 2014a). The manure will be non-dewatered. The plant can handle up to 60 000 tons of liquid manure; this will replace approximately 45 000 tons of clean water that would otherwise have to be purchased. This manure will have a dry matter content equivalent to an effect of 7-8 GWh energy and will prove a good basic raw material for the production. This way, the ambition of Greve Biogass AS by 2020 to process 30 % of all manure produced in the Vestfold county for biogas production, will be achieved.

Solid manure from cattle will constitute a resource for “The Magic Factory”. A single contract of 2 000 tons/year will serve as a test to assess the effect of this substrate together with organic waste from households and industry/trade (Sørby & Jacobsen 2014). Solid manure holds a higher energy concentration than liquid manure; this will justify transport without an option of returning Bioresidual on the same vehicle. With solid manure, there will be challenges, among others how straws will affect the pretreatment machinery. The assumption is that 2 000 tons spread out evenly through the year represents a small proportion and therefore will not pose any problem. Solid manure will supply the plant with a lot of carbon that makes the plant more suited to receive nitrogen rich fractions.

The plan is to exploit the rest of the capacity of 12 000 tons dry matter in the market (Sørby 2015c). “The Magic Factory” will have facilities that makes it possible to accommodate both solid and liquid industrial waste. The main share of this is expected to be solid industrial waste. As much as 10 560 tons dry matter will have to come from the market as solid waste, to reach the expected load of 50 000 tons solid food waste per year.

“The Magic Factory” will produce three different types of outputs, which the company wants to utilize:

- liquid bioresidual
- biofuel
- carbon dioxide

The scheduled outputs possible to utilize from a fully operating plant are shown in Table 6.

Table 6: Estimated amounts of outputs from "The Magic Factory" (Greve Biogass AS 2014a; Sørby & Jacobsen 2014)

	Bioresidual	**Biofuel**	**Carbon dioxide**
Amount	150 000 tons	7.5 million Nm^3	4 500 tons

Greve Biogass AS will at maximum capacity supply approximately 150 000 tons Bioresidual annually provided an hourly input of 18 m^3 with a dry matter content of 15 % is maintained continuously (Sørby & Jacobsen 2014). The farmers who deliver manure have an agreement on return of Bioresidual (Greve Biogass AS 2014a). All nutrients will remain in the Bioresidual, thus will replace artificial fertilizers. The farmers will pay a symbolic price for the Bioresidual. The biogas plant will transport and deliver the Bioresidual for free to the farmers.

It is hard to determine the produced amount of biofuel since it depends on the actual biogas yield achieved from the mixture of substrates (Sørby & Jacobsen 2014). The estimates are however, at maximum production, 75 GWh or 7.5 million Nm^3 upgraded biogas. This can substitute approximately 7.5 million liters of diesel. The biofuel will be distributed via pipes to filling stations for garbage trucks (in 2015) and buses and mail vans (in 2016) in the county of Vestfold (Greve Biogass AS 2014a). The biofuel will substitute fossil fuel and therefore will make an impact as a positive climate contribution in the transport sector.

Greve Biogass AS wants to build a large greenhouse for food production in cooperation with "The Magic Factory" (Greve Biogass AS 2014a). The greenhouse could utilize 4 500 tons of carbon dioxide developed from the upgrading of the biogas to biofuel quality on maximum production, for food production. In the event that the greenhouse becomes operational, "The Magic Factory" will contribute substantially to a better climate and will be unique in Europe.

3.3 Scenarios

Six scenarios are developed and interpreted. In groups of two, the scenarios are compared to investigate the potential outputs, the resource efficiency and the environmental benefits of choices made for the operation of "The Magic Factory". The amounts of waste from different sources handled in the different scenarios, together with the dry matter contents are presented in Table 7. The values used for the MFA describe the amounts processed at "The Magic Factory". The values for the LCA express the expanded system.

Table 7: For the range of the dry matter content of the different substrates, the number in brackets is used for converting. For the amounts of the different substrates dealt with in each scenario for the two different tools of analysis, the numbers are in tons/year and the numbers in parentheses represents the equivalent amount of dry matter in tons (Sørby 2015a; Sørby & Jacobsen 2014).

	Solid organic waste from households and industry	**Manure**		**Total**
		Liquid	Solid	
Dry matter content	32 - 34 % (33 %)	3 - 9 % (6 %)	30 %	
		MFA		
Reference	0	0	0	0
Scenario 1	18 000 (5 940)	50 000 (3 000)	2 000 (600)	70 000 (9 540)
Scenario 2	50 000 (16 500)	60 000 (3 600)	2 000 (600)	112 000 (20 700)
Scenario 3	50 000 (16 500)	0	14 000 (4 200)	64 000 (20 700)
Scenario 4	56 970 (18 800)	60 000 (3 600)	2 000 (600)	118 970 (23 000)
Scenario 5	69 697 (23 000)	0	0	69 697 (23 000)
		LCA		
Reference	18 000 (5 940)	60 000 (3 600)	2 000 (600)	80 000 (10 140)
Scenario 1	18 000 (5 940)	60 000 (3 600)	2 000 (600)	80 000 (10 140)
Scenario 2	50 000 (16 500)	60 000 (3 600)	2 000 (600)	112 000 (20 700)
Scenario 3	50 000 (16 500)	0	14 000 (4 200)	64 000 (20 700)
Scenario 4	69 697 (23 000)	60 000 (3 600)	2 000 (600)	131 697 (27 200)
Scenario 5	69 697 (23 000)	60 000 (3 600)	2 000 (600)	131 697 (27 200)

The liquid manure is approximately a mix of 50 % manure from cattle and 50 % manure from pigs, the solid manure is from cattle only. The Bioresidual in all cases will be stored in a unit sealed for runoff and with a roof. The Bioresidual in all scenarios is considered to replace artificial fertilizer; this also applies to the manure spread on farmland in the reference scenario and in scenario 5.

3.3.1 Environmental benefits of establishing “The Magic Factory”

The reference scenario represents the handling of organic municipal waste (Lind 2013) and manure in 2013. Scenario 1 represents the planed processing of these substrates after establishing “The Magic Factory” in September 2015.

Scenario 1 represents the startup load for the “The Magic Factory” once it has become operational (Sørby 2015a). These scenarios are chosen to investigate the environmental benefits from the establishing “The Magic Factory” compared to those of the current handling. To investigate environmental benefits of processing food waste locally at The Magic Factory, scenario 1 is compared to the reference scenario.

Reference: 18 000 tons (5 940 tons DM) food waste are transported about 500 kilometers to Linköping in Sweden for biogas production with upgrading to fuel quality. The bioresidual is used as fertilizer in agriculture. 2 000 tons (600 tons DM) solid manure and 60 000 tons (3 600 tons DM) liquid manure are spread on farmland.

Scenario 1: 18 000 tons (5 940 tons DM) of food waste, 2 000 tons (600 tons DM) solid manure and 50 000 tons (3 000 tons DM) liquid manure are digested for biogas production with upgrading to fuel quality. The Bioresidual is used as agricultural fertilizer. 10 000 tons (600 tons DM) of liquid manure are spread on farmland.

An illustration of these scenarios can be seen in Figure 4 and 5.

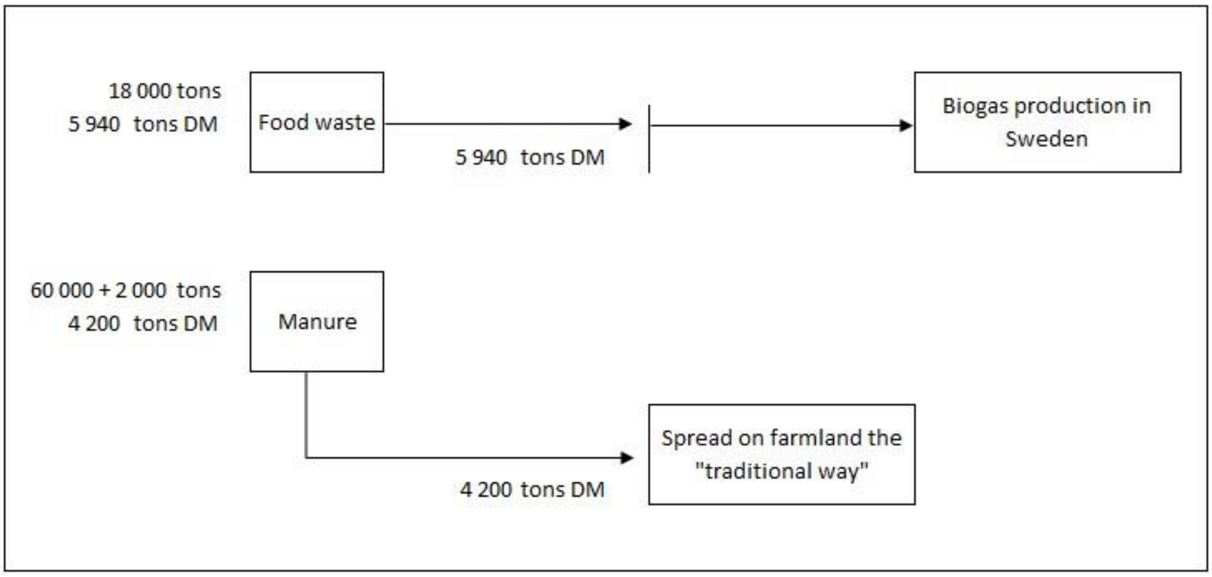


Figure 4: The distribution of food waste and manure in the Reference scenario, in ton wet weight and ton dry matter

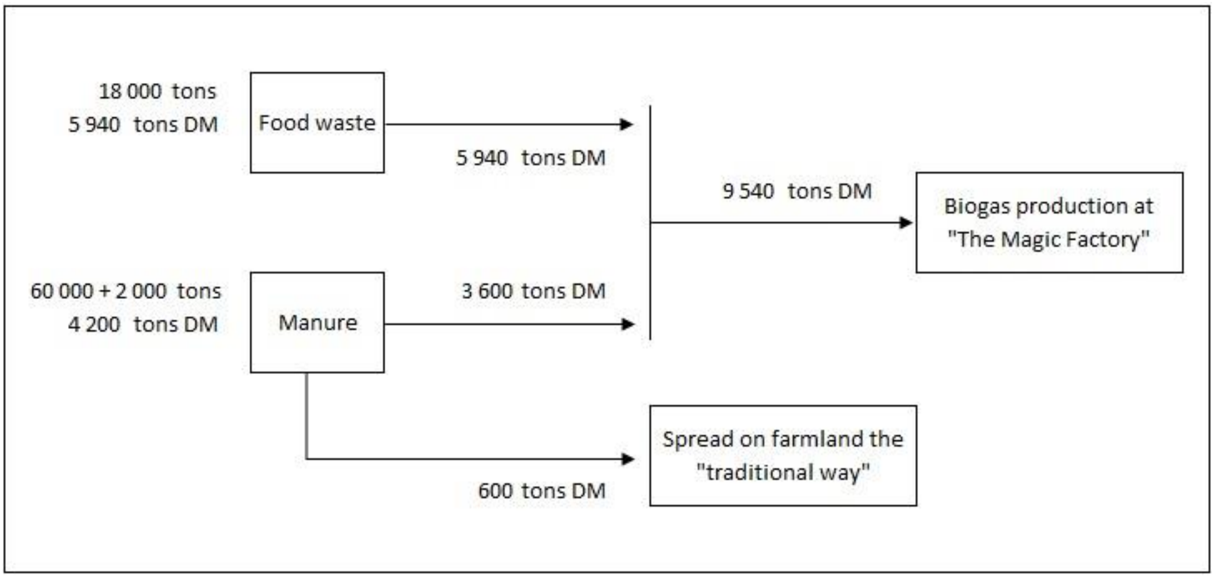


Figure 5: The distribution of food waste and manure in Scenario 1, in ton wet weight and ton dry matter

3.3.2 Environmental benefits of water choices, with expected load in 2017

For "The Magic Factory" it has been chosen to use large amounts of wet manure to substitute clean drinking water as process water. Scenario 2 and 3 are for the purpose of investigating the different environmental impacts related to this choice. Thus, transportation of water in the form of wet manure is compared to the use of clean drinking water. Scenario 2 represents the method chosen at "The Magic Factory", which means usage of wet manure as process water. Scenario 3 on the other hand addresses the process in which manure based on dry manure, while drinking water is added to the substrate mixture at "The Magic factory".

The amount of substrate used for Scenario 2 and 3 are the planned load of substrate for 2017. This is so to assess the environmental benefit from a fully running plant with an expected load close to the maximum. The amount of solid organic waste is based on the data from the project planning (Sørby 2015a) and the amount of manure is based on the maximum load (Sørby & Jacobsen 2014).

Scenario 2: 50 000 tons (16 500 tons DM) of solid food waste from industry and municipalities are together with 2 000 tons (600 tons DM) solid manure and 60 000 tons (3 600 tons DM) liquid manure digested for biogas production with upgrading to fuel quality. The Bioresidual is used as agricultural fertilizer.

Scenario 3: 50 000 tons (16 500 tons DM) of solid food waste from industry and municipalities are together with 14 000 tons (4 200 tons DM) solid manure, digested for biogas production with upgrading to fuel quality. The Bioresidual is used as agricultural fertilizer.

These scenarios can be seen in Figure 6.

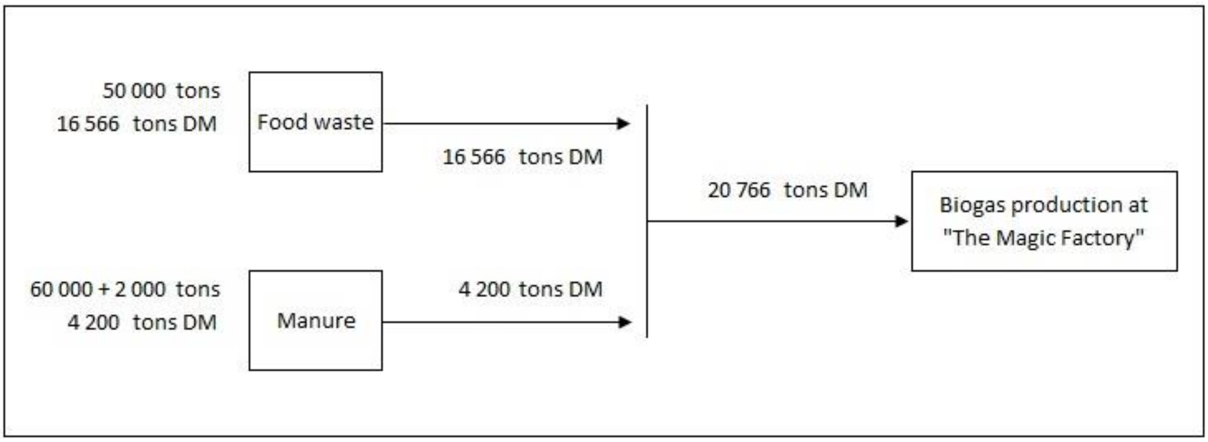


Figure 6: The distribution of food waste and manure in Scenario 2 and 3, in ton wet weight and ton dry matter

3.3.3 Environmental benefits of "The Magic Factory" compared to other biogas plants

"The Magic Factory" will process a large amount of manure compared to other plants. Scenario 4 and 5 are chosen to investigate the effect of manure as a substrate in the biogas production. The issue is to investigate the difference in environmental benefits from "The Magic Factory" compared to a plant running only on food waste, which is a more common way of producing biogas.

Scenario 4 presents biogas production at "The Magic Factory" with the maximum possible load of the different substrates, a total of 23 000 tons dry matter (Sørby & Jacobsen 2014; Sørby 2015a). Scenario 5 on the other hand represents the same amount of dry matter into the plant as scenario 4, but with a load consisting of only food waste. The total amount of dry matter handled in each scenario is however higher than the capacity of "The Magic Factory". This is to make these two scenarios comparable, see Figure 7 and 8.

The amount of food waste exceeding the capacity of "The Magic Factory" in Scenario 4 is assumed transported to another biogas plant. For this plant it is assumed an average transport distance equal to the average transport distance for food waste to be processed at "The Magic Factory". The LCA therefore will be conducted as if the whole amount of food waste was processed at "The Magic Factory", an impossibly large amount. The results of the LCA are however possible to use to study "The Magic Factory", as they are based on the functional unit (treatment of 1 ton dry matter of organic waste substrate). Based on this, the LCA will mainly show the impacts related to the handling of manure for biogas production versus spreading manure the traditional way.

Scenario 4: 56 970 tons (18 800 tons DM) food waste along with 2 000 tons (600 tons DM) solid manure and 60 000 tons (3 600 tons DM) liquid manure are digested for biogas production with upgrading to fuel quality. The Bioresidual is used as agricultural fertilizer. 12 727 tons (4 200 tons DM) food waste are sent to biogas production at another plant.

Scenario 5: 69 697 tons (23 000 tons DM) food waste are digested for biogas production with upgrading to fuel quality. The Bioresidual is used as agricultural fertilizer. 2 000 tons (600 tons DM) solid manure and 60 000 tons (3 600 tons DM) liquid manure are spread on farmland.

This distribution of the food waste and manure to different treatments for the two scenarios can be seen in Figure 7 and 8.

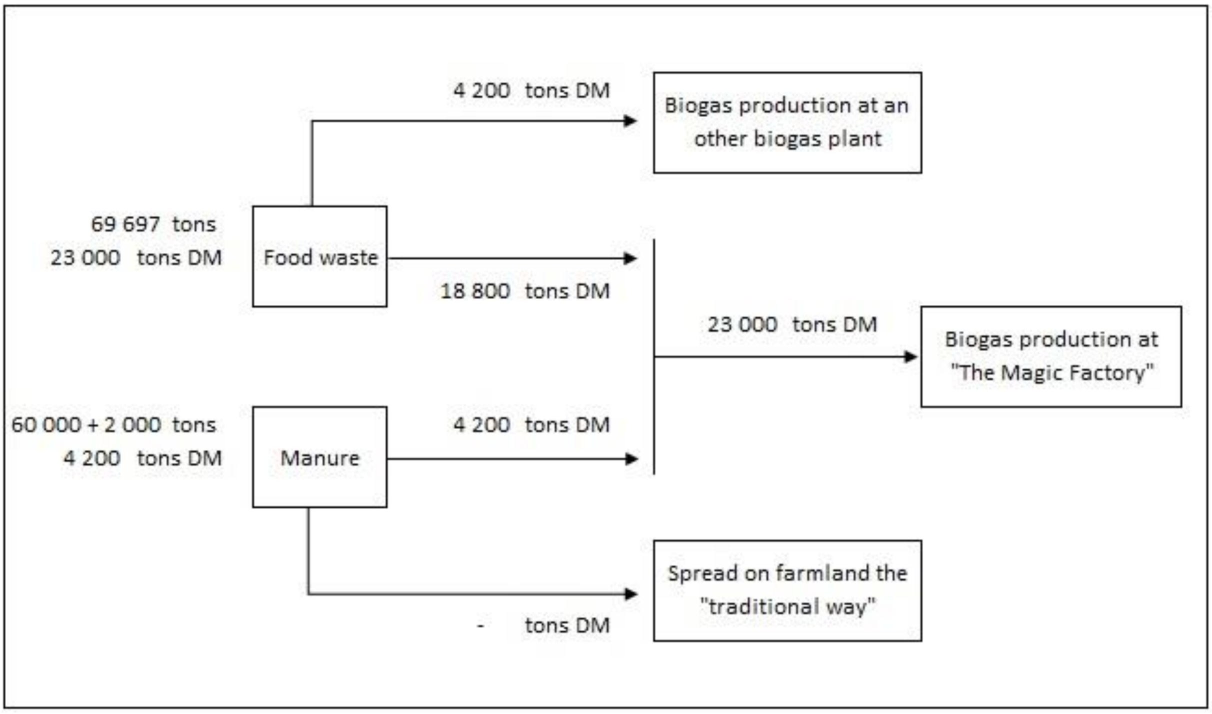


Figure 7: The distribution of food waste and manure in Scenario 4, in ton wet weight and ton dry matter

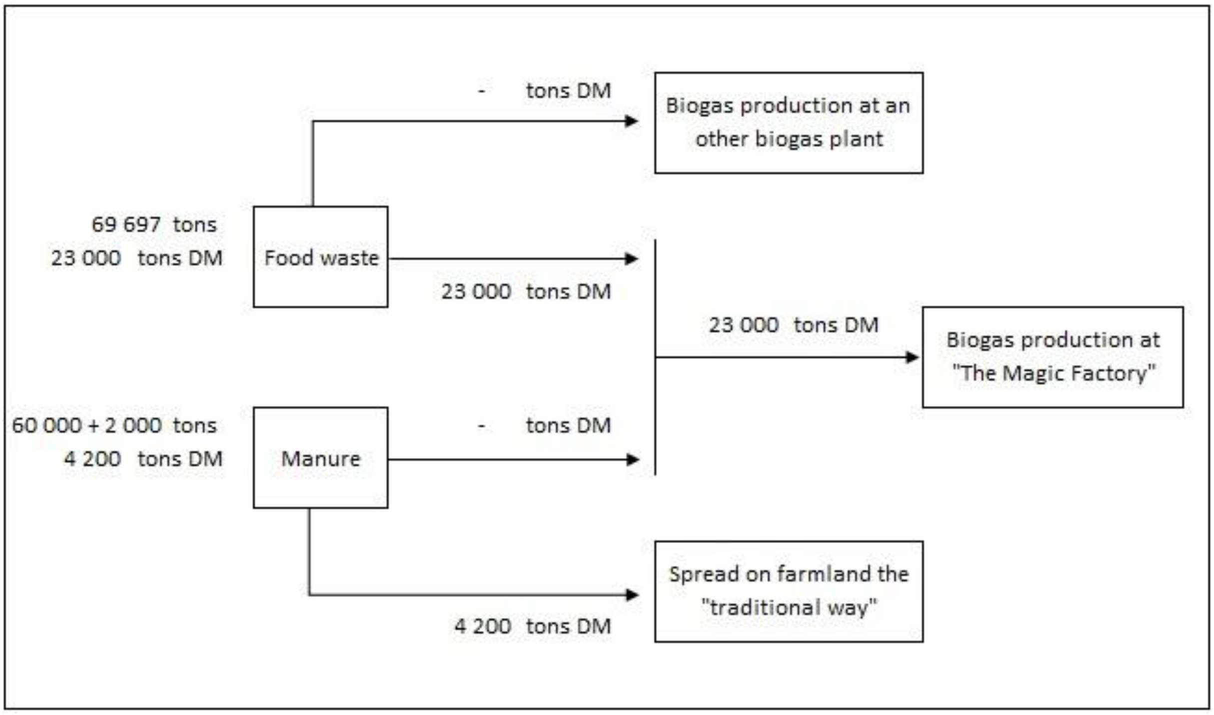


Figure 8: The distribution of food waste and manure in Scenario 5, in ton wet weight and ton dry matter

3.4 Model development

Two models are used to carry out this Thesis, a MFA model and a LCA model. The MFA model is made especially for this Thesis and the specific case; it should however be possible to use for other cases by adjustment of the input values and parameters. The LCA model used in the Thesis is developed by Saxegård (2015), a fellow student at the Industrial Ecology program at NTNU. This version of the LCA has been developed by use of SimaPro 8.0. The background data is collected from ecoinvent 3.01. The ecoinvent database contains Life Cycle Inventory data for various sectors and interlinked datasets describing life cycle inventory at process level. The libraries in SimaPro contain all the processes in the ecoinvent database. The value chain used for the LCA model is presented in Appendix 5. The functional unit for the LCA model is the treatment of 1 ton dry matter of organic waste substrate.

The MFA model is a flow model developed as part of the inventory analysis and built up with the purpose of achieving mass balance. The development of the model is based on data submitted by Greve Biogass AS describing the technologies, steps of process and energy use at "The Magic Factory" (described in chapter 3.2 Case: Greve Biogass AS). The flow chart describing the model is found in Figure 9. The functional unit for the MFA model is 1 ton dry matter of organic waste substrate for anaerobic digestion.

The biogas production at "The Magic Factory" in the MFA model is aggregated into 20 processes. The mass flows among the different processes are calculated per functional unit, 1 ton organic waste substrate for anaerobic digestion. Both the wet weight and the dry weight for each flow is established. The temperatures in the mass flows are established for section B along with the energy used in all three sections. The processes, flows, temperatures and energy use in the sections, are all listed in Appendix 6.

All MFA results are calculated based on mass balance. The main objective of the MFA is to estimate the amount of the three outputs from "The Magic Factory", which Greve Biogass AS wants to utilize: biofuel, Bioresidual and carbon dioxide. Establishing an energy yield for "The Magic Factory" also is an objective. The amount of the outputs is calculated by use of the model. The energy yield is the ratio between the energy possible to produce by "The Magic Factory" and the energy consumed in the process of manufacturing the end product. The calculation is made by use of equation (1), while the variables are established by use of the MFA model:

$$\eta_E = \frac{E_{Bio\_Methane}}{E_{Feedstock} + E_{\Pr ocess} + E_{Transport}} \tag{1}$$

$E_{Bio\_Methane}$ = Energy in produced bio methane [kWh]
$E_{Feedstock}$ = Energy in processed feedstock [kWh]
$E_{Process}$ = Energy consumed at the plant [kWh]
$E_{Tramsport}$ = Energy consumed by transportation of feedstock and bioresidual [kWh]

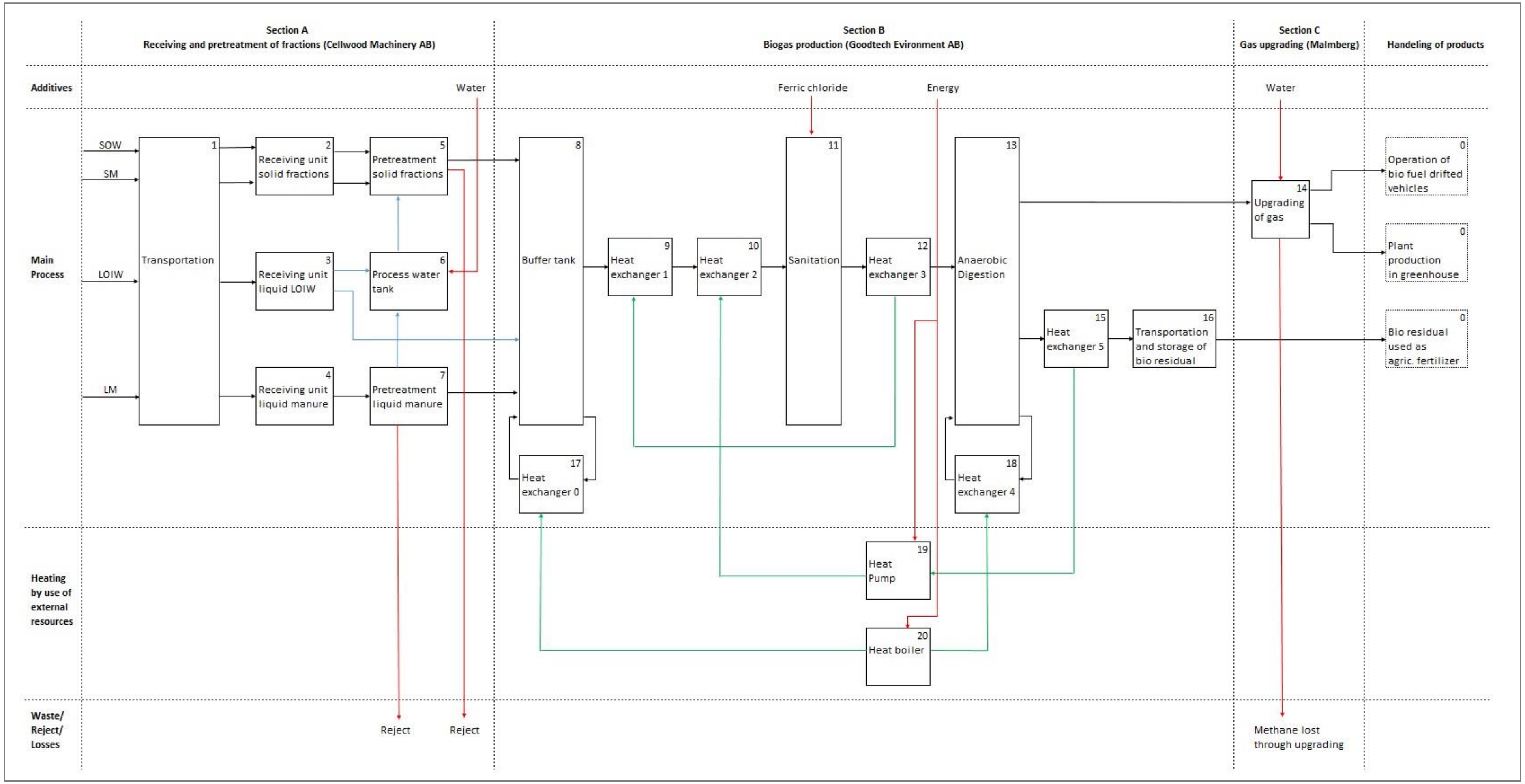


Figure 9: Flowchart describing the MFA model. Black arrows represent the mass flow through "The Magic Factory", red arrows additives and waste/reject/losses, blue arrows the flows of process water and green arrows energy. (For the Flowchart split into the sections, for higher picture resolution, see Appendix 7)

3.4.1 Assumptions and input values

All values used in the models will be presented in this chapter. The parameters will be explained along with the source of information used and the assumptions made. The variables will be presented for each scenario and the basis for the establishment of the variables will be explained.

3.4.1.1 Parameters

The parameters are mainly based on data specific for "The Magic Factory". For the parameters where case specific data are not available, the parameters are established by use of literature directly or as a basis for assumptions. The different parameters used for the MFA and the LCA are presented in Table 8, and further explained under the table.

Table 8: Parameters used for the MFA (DM – dry matter, SOW – solid organic waste, SM – solid manure, LM – liquid manure, LOIW – liquid organic industrial waste, MC – methane content, HHV – higher heating value, VS – volatile solids)

Parameter name	Value	Unit	Reference
DM content SOW	33 %	DM/ton	Sørby 2015b
DM content SM	30 %	DM/ton	Sørby 2015b
DM content LM	6 %	DM/ton	Sørby 2015b
DM content LOIW	7 %	DM/ton	Assumed: based on Carlsson & Uldal 2009
Reject SOW	12.5 %	of weight	Sørby 2015b
Reject SM	8 %	of weight	Assumed
Reject LM	3 %	of weight	Assumed
DM reject	100 %	of weight	Assumed
DM content of Biogas substrate into section B	15 %	DM/ton	Sørby & Jacobsen 2014
Hours of operation section B	8 760	h/y	Sørby 2015b
Ferric chloride (FC)	4.00E-03	ton FC/ton substrate mix	Sørby 2015b
DM content FC	0 %	DM/ton	Assumed
Methane lost through upgrading	1.1 %		Sørby 2015b
Water for upgrading of biogas	6.41E-05	m^3/Nm^3 biogas	Sørby 2015c
Energy demand pretreatment	22.00	kWh/ton	Sørby 2015b
Electricity demand biogas production	11.60	kWh/m^3	Sørby 2015b
Heat demand biogas production	2.72	kWh/m^3	Sørby 2015b
Energy demand biogas upgrading	0.29	kWh/Nm^3 biogas	Holen 2015
Energy in upgraded biogas (97 % CH_4)	10.1	kWh/ m^3	Norges Bondelag 2011
HHV SOW	18 500	MJ/ton DM	Wirsenius 2000
HHV cattle	15 358	MJ/ton DM	Annamalia et al. 1987
HHV pig	16 500	MJ/ton DM	Assumed
Pressure	1.01E+05	Pa	
Volume	1	Nm^3	
Gas constant	8.3145	J/mol K	
Temperature	273.15	K	

Molar mass Methane	16.04	g/mol	
Molar mass Carbon dioxide	44	g/mol	
Mass of 1 Nm^3 Methane	716	g/Nm^3	
Mass of 1 Nm^3 Carbon dioxide	1 963	g/Nm^3	
VS % of DM SOW	90 %		Sørby 2015a
VS % of DM LM cattle	80 %		Sørby 2015a
VS % of DM LM pigs	80 %		Sørby 2015a
VS % of DM SM	80 %		Sørby 2015a
VS % of DM LOIW	94 %		Assumed: based on Carlsson & Uldal 2009
m^3 CH_4 / ton VS of SOW	550	m^3 CH_4/ton VS	Sørby 2015a
m^3 CH_4 / ton VS of LM cattle	150	m^3 CH_4/ton VS	Sørby 2015a
m^3 CH_4 / ton VS of LM pigs	250	m^3 CH_4/ton VS	Sørby 2015a
m^3 CH_4 / ton VS of SM	250	m^3 CH_4/ton VS	Sørby 2015a
m^3 CH_4 / ton VS of LOIW	500	m^3 CH_4/ton VS	Assumed: based on Carlsson & Uldal 2009
MC in biogas from SOW	63 %		Carlsson & Uldal 2009
MC in biogas from LM cattle	65 %		Carlsson & Uldal 2009
MC in biogas from LM pigs	65 %		Carlsson & Uldal 2009
MC in biogas from SM	67 %		Assumed: based on Carlsson & Uldal 2009
MC in biogas from LOIW	60 %		Assumed: based on Carlsson & Uldal 2009
Degradability SOW	63 %	of VS that degrades	Hamelin et al. 2014
Degradability manure	62 %	of VS that degrades	Hamelin et al. 2014
Diesel consumption waste collection	0.336	kg/tonkm	Ecoinvent 2015
Diesel consumption waste transport (EURO 5)	0.022	kg/tonkm	Ecoinvent 2015
Energy in diesel	43.1	MJ/kg	Hofstad 2014

The dry matter contents of the different substrates are based on data and system descriptions from Greve Biogass AS, provided by Ivar Sørby (2015a). The dry matter content of solid manure from cattle is not easy to estimate and a test on the relevant manure showed a lower dry matter. It will therefore be carried out a sensitivity analysis on this parameter. Greve Biogass AS did not provide the dry matter content for liquid organic industrial waste; this amount therefore is estimated based on data from Carlsson og Uldal (2009). They list the dry matter contents for several liquid industrial waste types with a high variety, sludge from grease separator is listed with 4 % dry matter, while glycerol is listed with 100 % and blood from slaughterhouse 10 %. As demonstrated, the dry matter content of liquid industrial waste can vary a lot. The estimated amount therefore is moderated and can be adjusted provided the content of the substrate is known. Estimates in the scenarios are, however, not made with any input of liquid industrial waste and this number therefore is not uncertain in this study.

According to Greve Biogass AS, the reject from organic waste is difficult to estimate and could be in the range from 10 – 15 % of the weight of the food waste (Sørby 2015a). The reject should desirably be less than 10 %. The middle value, 12.5 % of the amount of food waste is chosen for this study. Reject from manure is not given and therefore has been assumed. The solid manure will contain straws and it is uncertain how much of this will be sorted out with the reject. It is also possible that the manure will contain sand or similar fractions that will be sorted out in the hydro cyclone. The amount of reject from both solid (8 %) and liquid manure (3 %) is hard to determine and probably is estimated a bit high so as to moderate the outputs. Based on the substantial uncertainty of this parameter, a sensitivity analysis will be carried out. The dry matter of the reject is assumed to be 100 % because the reject will go through a dewatering process. This number is however unsecure as there might be some substrates that contain water, such as straws, which will be sorted out with the reject.

The dry matter content of the substrate after the pretreatment, but before it enters the biogas production will be stabilized at 15 %; this is provided by Greve Biogass AS and is optimal for the further treatment (Sørby & Jacobsen 2014). The hours of operation are set to 24 hours/day, 365 days/year for the biogas production, section B. Liquid Ferric chloride will be added to the substrate and is stated to be up to four liters per ton substrate mixture; the dry matter content of Ferric chloride is assumed to 0 %.

Malmberg notifies that methane loss could occur at two sites throughout the process (Sørby 2015a). The portion of the methane in the raw gas, which cannot be upgraded, is set to 1 %, while the loss of methane in the outgoing process air is set to < 0.1 %. The methane loss in the model therefore is set to 1.1 %. The water needed for the upgrading is provided by Greve Biogass AS and expected to be 2 m^3/day at maximum capacity 1 200 Nm^3 biogas/h, this equals 0.064 liter water/Nm^3 biogas (Sørby 2015d).

The energy demand for the pretreatment is supplied by Cellwood Machinery Ab and set to < 22 kWh/ton waste through the pretreatment (Sørby 2015a). An energy description of the biogas production from Goodtech Environment Ab assumes an electricity demand of 3 600 kWh/d at a substrate load of 13 m^3/h and 5 040 kWh/d at a load of 18 m^3/h, 24 hours of operation 365 days a year. This equals an electricity demand of 11.54 kWh and 11.67 kWh per m^3 substrate respectively from the pretreatment to the biogas production. The parameter used is the average of these two values, 11.60 kWh/m^3 substrate from the pretreatment to the biogas production. The demand for external heat is estimated at a year average of 1 009 kWh/d at a substrate load of 13 m^3/h and 955 kWh/d at a load of 18 m^3/h, by 24 hours of operation 365 days a year. This equals a heat demand of 3.23 kWh and 2.21 kWh per m^3 substrate respectively from the pretreatment to the biogas production. The average of these two values, 2.72 kWh per m^3 substrate from the pretreatment to the biogas production will be used in the model. This number seems however a bit low since the specific heat capacity for biogas substrate is assumed, by Coultry et al. (2013), to be the same as for water 4.18 MJ/ton °C (≈ 1.16 kWh/ton °C). We know from the model development that a temperature increase of 7.6 °C by use of external energy is required. A sensitivity analysis on the parameter therefore will be carried out. The energy demand for the biogas upgrading is based on data from Malmberg (Holen 2015). They provide an installed effect of 505 kW for the upgrading facility, with an expected use of 70 % at maximum load of 1 200 Nm^3 biogas/h; this equals an energy demand of 0.29 kWh/Nm^3 biogas.

The energy in upgraded biogas (97 % methane) is 10.1 kWh/m^3 (Norges Bondelag 2011). The higher heating value of the different substrates is hard to determine. The portion of the dry matter that is organic material influences the value. The higher heating value also will be influenced by the amount and type of litter mixed with the manure. The higher heating value is however 18 500 MJ/ton dry matter for solid organic waste (Wirsenius 2000). The higher heating value for cattle manure 15 358 MJ/ton dry matter is an average based on several values presented by Annamalia et al. (1987). The higher heating value for pig manure has not been established, but is assumed to be 16 500 MJ/ton dry matter (about 7.5 % higher than manure from cattle). This assumption is based on the higher heating value for cattle manure and the fact that the digestion system of cattle increases their digestion and by that increased energy utilization compared to the one for pigs. A sensitivity analysis of the higher heating value for pig manure will be carried out. The higher heating value for liquid organic industrial waste has not been established and will have to be further studied when the composition is known.

The mass of methane and carbon dioxide, $1Nm^3$, is calculated by use of the ideal gas low equation (2):

$$PV = nRT \tag{2}$$

The letters denotes pressure, volume, amount in moles, ideal gas constant and temperature, respectively. The amount of a substance equals the mass (m) divided by the molar mass (M), equation (3); this gives:

$$n = \frac{m}{M} \tag{3}$$

$$PV = \frac{m}{M} RT \tag{4}$$

$$m = \frac{PVM}{RT} \tag{5}$$

By calculating the mass of methane and carbon dioxide (by use of equation 5), it is possible to calculate the weight of $1m^3$ biogas based on the methane content of the biogas.

The volatile solid content of the dry matter and the methane yield per ton volatile solid for the different substrates, are based on values from Greve Biogass AS (Sørby 2015b). This does however not hold any information on liquid organic industrial waste, numbers for which therefore are based on data from Carlsson and Uldal (2009) on a middle value for several waste types; it would therefore be beneficial to adjust these values when the content of this fraction has been established. Liquid industrial waste is not a part of the scenarios studied and will therefore represent any uncertainty in the calculations.

The methane contents in the biogas from the different waste fractions have been collected from Carlsson and Uldal (2009). There is an uncertainty regarding the methane content for the solid organic waste. The value used by Carlsson and Uldal (2009) is based on the methane content of organic municipal waste, while the solid mixture at "The Magic Factory" may contain several different solid waste fractions, like inter alia waste from large-scale households/restaurants, dairies, slaughterhouses or bakeries. It is however, a fair assumption that the methane content for organic municipal waste is representative as it contains a mixture of all fractions in question. Carlsson and Uldal (2009) do not state a specific value for solid manure from cattle, so the value (67 %) is based on a mixture of straws (methane content 70 %) and liquid cattle manure (methane content 65 %). For liquid industrial waste, the same problems exist as for the parameters listed above.

The degradability ratios for organic municipal waste and manure are found in Hamelin et al. (2014). These values are however expected by Greve Biogass to be higher (up to 80 %) and it will therefore be carried out a sensitivity analysis on these parameters.

The energy use for collecting and transporting the waste fractions to "The Magic Factory" is based on diesel consumption retrieved from Ecoinvent (2015) and further based on EURO 5 standard, the energy content of diesel is obtained collected from Hofstad (2014).

3.4.1.2 Variables

The variables are stated as values used for the LCA and the MFA, varying with the different scenarios discussed. The values are displayed in Table 9 and further presented with a description of the procedure used to establish them.

Table 9: The different variables applied for the LCA and the MFA; specified for the different scenarios. Transport is given in tonkm

Variable	**Reference scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
MC (% of biogas)	65 %	63.9 %	63.5 %	63.8 %	63.4 %	63.0 %
Transport SOW		1 806 000	5 016 667	5 016 667	5 715 990	6 992 932
Transport LOIW	-	-	-	-	-	-
Transport SM		40 000	40 000	232 000	40 000	-
Transport LM		800 000	960 000	-	960 000	-
Transport bioresidual		957 615	1 987 553	1 942 529	2 196 558	2 089607

The methane content in the biogas may vary considerably; the system description of the biogas upgrading assumes a raw biogas with a methane content of 50 - 65 % (Sørby 2015a). The value used for the models is weighed averages calculated based on methane contents (MC) for the different substrates (Carlsson & Uldal 2009), the amount of dry matter from the different substrates and the total dry matter:

$$MC = \sum_{i=1}^{n} \frac{DM_i \bullet MC_i}{DM_{TOT}} \bullet 100\% \qquad (6)$$

DM_i = dry matter of substrate i [kg DM/year]
MC_i = methane content of biogas from substrate i [%]
DM_{TOT} = total dry matter of all substrates [kg DM/year]

This number will vary with the input of the different substrates and consequently change with different scenarios. The methane content used for the Reference scenario is stated by Tekniska verken (2014), the plant used in this scenario. Said number also corresponds to the value reached by use of equation (6), the given substrate mixture at Tekniska verken (48 % SOW, 20 % offal, 28 % waste products from the food industry and 4 % other vegetable materials (Slycke 2015b)) and values for methane content from Carlsson and Uldal (2009).

Transport distance for solid organic waste depends on several factors. The solid organic waste consists of organic municipal waste from the Vestfold and Grenland region as well as solid organic industrial waste. The transport distance for this substrate therefore is stated as an aggregated value based on the distances listed in Table 10.

Table 10: Transport distances for organic municipal waste in the Vestfold and Grenland region

Transport	Distance (km)	Tons	Reference (distance, weight)
Collecting Vesar area	75	7 500	Jacobsen 2015, Lind 2013
Collecting to Grinda	50	4 500	Assumed, Lind 2013
Grinda to “The Magic Factory”	33	4 500	Kartdata 2015a, Lind 2013
Collecting to Bjorstaddalen	75	6 000	Assumed, Hovland 2014
Bjorstaddalen to “The Magic Factory”	70	6 000	Kartdata 2015b, Hovland 2014

The average driving distance for the renovation trucks collecting organic municipal waste in the Vesar area (the Vestfold county excluding the municipalities Larvik and Sandefjord) is 75 km (Jacobsen 2015). The organic municipal waste collected in Larvik and Sandefjord is assumed to have a collection distance of 50 km from the households to the transshipping area at Grinda (outside of Larvik). This value is based on the collection distance for the Vesar area and the fact that the Larvik and Sandefjord area is more densely populated, the value therefore is stated as lower than for the Vesar area. The distance from Grinda to “The Magic Factory” is about 33 km (Kartdata 2015a). The organic municipal waste collected in Grenland is assumed to have an average collection distance of 75 km from the households to the transshipping area at Bjorstaddalen. This value is stated as the same as for the Vesar area as both routes cover cities as well as areas of a more rural character. The distance from Bjorstaddalen to “The Magic Factory” is about 70 km (Kartdata 2015b).

The expected inputs of organic municipal solid waste from the Vestfold and Grenland region are listed as about 18 000 tons wet weight (see chapter 03 Inputs and outputs). The additional amount of solid organic waste handled in Scenario 2 to 5 is therefore assumed to be solid organic industrial waste from the region or municipal waste from outside the region. It is in a previous student discussion concluded that there is a feasible amount of solid industrial waste in the regions; about 20 000 tons/year (this result is based on a large amount of references, the main findings are attached in Appendix 8.) It is therefore assumed that this waste amount is collected in the region. An average transport distance for all solid organic waste is calculated based on the values given in Table 10 by use of equation (7).

$$TD_{SOW} = \sum_{i=1}^{n} \frac{WW_i \bullet (CD_i + TD_i)}{WW_{TOT}} \tag{7}$$

TD_{SOW} = Average transport distance for solid organic waste [km]
WW_i = Wet weight of organic municipal waste fraction i [ton/year]
CD_i = Average collecting distance of organic municipal waste fraction i [km]
TD_i = Average transport distance of organic municipal waste fraction i [km]
WW_{TOT} = Total wet weight of organic municipal waste [ton/year]

The remaining fractions of solid organic waste are assumed to be collected outside the region; the transport distance for said fractions therefore probably is higher. Despite this, the value estimated as the average transport distance is used for all solid organic waste. This is to limit the complexity of the calculations and because the transport distance will have to be the same for the scenarios that are to be compared. The idea is to make it possible to compare the technical choices to be investigated (wet manure vs. adding of water, and plant drifted on only food waste vs. plant with substrate mixture containing manure). The transport distance is believed to have a high impact on the energy and environmental results and a sensitivity analysis on both transport distance and collection distance will be carried out.

Liquid organic industrial waste will not be considered an input to “The Magic Factory” in the scenarios studied. The driving distance therefore is set as zero.

Solid manure is subject to a single contract, the distance from the particular farm to “The Magic Factory” is about 20 km (Sørby 2015d). In scenario 3, where the whole fraction of manure is solid, the transport distance will be 20 km for 2 000 tons and the distance for liquid manure will be used for the remaining fraction. The point of scenarios 2 and 3 is to investigate the differences in transport of water via the manure, as compared to adding clean drinking water to the mixture at “The Magic Factory”. This means that the distances are the same.

The liquid manure will be collected at several farms and the average transport distance from the farms to “The Magic Factory” is 16 km (Sørby 2015d). The return of Bioresidual to the farms amounts to an average transport distance of 18 km (Sørby 2015d).

For having the distances in ton-kilometer, they have to be multiplied with the relevant waste amounts. In addition, the amounts of each waste fraction will vary for the different scenarios as described in chapter 3.3 Scenarios.

3.4.1.3 Parameter adjustments for the Life Cycle Assessment

A list of all parameters embedded in the LCA model is attached with explanations in Appendix 9. Some of the parameters are however adjusted according to the case and the scenarios. The parameters as adjusted and the values used for all scenarios are presented in Table 11. The parameters adjusted to the different scenarios are presented in Table 12 and described below the table.

Table 11: Parameters used in the LCA analysis as adjusted in the model to fit to the specific case, “The Magic Factory”. All values in bold are assumed to be the same for the biogas plant in Sweden as for "The Magic Factory". The values known for the plant in Sweden are based on Slycke (2015a).

Parameter name	Value	Description
OWc_AD	**0.85**	DM content of Biogas substrate into section B, described under chapter 3.4.1.1 Parameters
Fat	0	Input of fat is set to zero for all scenarios
OIW	0	Input of organic industrial waste is set to zero for all scenarios, the solid part of the fraction are included in OMW
SwSl	0	Input of sewage sludge is set to zero for all scenarios
Inorganic_OMW	**0.125**	Reject if solid organic waste, described under chapter 3.4.1.1 Parameters
Digestate_Use_Wet	1	Bioresidual is used wet
Digestate_Use_Dry	0	Bioresidual is used wet
Biomethane_Use_Bus	1	The biofuel from "The Magic Factory" will be used in garbage trucks, buses and mail vehicles (see chapter 3.2.3 Inputs and outputs), the distribution is unknown. It is therefore, to simplify the calculations, assumed that all the biofuel is used in busses. Same for the Reference scenario where the biofuel is used in busses, trucks and cars
Bm_Compression200	1	Assumed compression to 200 bar as the fuel is assumed to be used in busses, the plant in Sweden does however compress to 220
HM_0	1	The composition of the biogas substrate makes it natural to assume a low heavy metal concentration in the bioresidual.
HM_1	0	
Lr_Ch4_UpT_WS	**0.011**	Methane lost through upgrading, described under chapter 3.4.1.1 Parameters

DMC_Pig	0.06	Dry matter content solid organic waste, described under chapter 3.4.1.1 Parameters
DMC_OMW	0.33	Dry matter content manure from pig, described under chapter 3.4.1.1 Parameters
VS_Cattle	0.8	Volatile solids percentage of DM in manure from cattle, described under chapter 3.4.1.1 Parameters
VS_Pig	0.8	Volatile solids percentage of DM in manure from pigs, described under chapter 3.4.1.1 Parameters
VS_OMW	0.9	Volatile solids percentage of DM in solid organic waste, described under chapter 3.4.1.1 Parameters
MY_Pig	250	m^3 CH_4 / ton VS of LM pigs, described under chapter 3.4.1.1 Parameters
MY_OMW	550	m^3 CH_4 / ton VS of SOW, described under chapter 3.4.1.1 Parameters
DS_Cattle	0.504	Remaining solids of DM cattle manure; Remaining solids = 1 - (VS * Degradability coefficient of VS), VS and Degradability coefficient of VS described under chapter 3.4.1.1 Parameters
DS_Pig	0.504	Remaining solids of DM pig manure; Remaining solids = 1 - (VS * Degradability coefficient of VS), VS and Degradability coefficient of VS described under chapter 3.4.1.1 Parameters
DS_OMW	0.433	Remaining solids of DM solid organic waste; Remaining solids = 1 - (VS * Degradability coefficient of VS), VS and Degradability coefficient of VS described under chapter 3.4.1.1 Parameters
HHV_Pig	16 500	MJ / ton DM pig manure (HHV), described in chapter 3.4.1.1 Parameters
FSH	**15**	Middle value of temperature in feedstock into plant, described in chapter 3.2.1.2 Sanitation and biogas production/anaerobic digestion
AFSH	**64.4**	Temperature in biogas substrate after heat recovery, obtained from the model development (temp. in feedstock + heat recovered in “The Magic Factory”)
PH	**72**	Temperature in biogas substrate into sanitation, described in chapter 3.2.1.2 Sanitation and biogas production/anaerobic digestion
E_Sorting	22	Energy need in section A (Pretreatment) aggregated into one value, described under chapter 3.4.1.1 Parameters
E_Pasteurization	0	Energy need in section B (Sanitation and biogas production) is aggregated into one value inserted in parameter E_AD
E_AD	14.32	Energy need in section B (Sanitation and biogas production) sum of heat and electricity demand, described under chapter 3.4.1.1 Parameters
E_Dewatering	0	Energy need in section B (Sanitation and biogas production) is aggregated into one value inserted in parameter E_AD

E_UpT_WS	0.29	Energy need in section C (Biogas upgrading) aggregated into one value, described under chapter 3.4.1.1 Parameters
km_OMW	**69**	Average collection distance for solid organic industrial waste, calculated by use of equation (7) described under chapter 3.4.1.2 Variables (the calculation are however done without use of the TD_i as it is for only the collection)
km_Dg	**18**	Average transport distance for bioresidual, described under chapter 3.4.1.2 Variables

Table 12: Parameters used in the LCA analysis and which are adjusted specifically to the scenarios

Parameter name	**Reference scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Manure	0.41	0.41	0.20	0.20	0.15	0.15
OMW	0.59	0.59	0.80	0.80	0.85	0.85
SC	0	1	1	1	1	1
MDF	1	0.14	0	0	0	1
UpT_WS	0.66	1	1	1	1	1
UpT_ChS	0.33	0	0	0	0	0
DMC_Cattle	0.075	0.075	0.075	0.3	0.075	0.075
Share_Cattle	0.57	0.57	0.57	1.00	0.57	0.57
Share_Pig	0.43	0.43	0.43	0.00	0.43	0.43
CH4_Share_Cattle	0.655	0.655	0.655	0.67	0.655	0.655
MY_Cattle	175	175	175	250	175	175
km_Manure	-	16.15	16.13	17.00	16.13	0.00
km_OMWc	531	31	31	31	31	31

Parameter; Manure and OMW: The share of the different substrates is based on the presented scenarios. The values are presented as the numeric percentage and represent the share of the substrate in the total dry matter of organic waste.

Parameter, SC: Storage of bioresidual. If the Bioresidual is stored under coverage, the process should be turned on by applying 1 as the parameter value. (0 indicates that the process is turned off and that the bioresidual is stored without coverage.) The Bioresidual from the plant in Sweden is not stored under coverage (Slycke 2015a); this is however a requirement for the Bioresidual from "The Magic Factory".

Parameter, MDF: Numeric percentage of the manure spread directly as fertilizer the traditional way, the values are based on the scenario description.

Parameter, UpT_WS and UpT_ChS: The biogas plant in Sweden upgrades the biogas by use of a chemical scrubber and two water scrubbers (Slycke 2015a). It is assumed an evenly distribution of the biogas between the three units. "The Magic Factory" upgrades the biogas by use of water scrubbing.

Parameter: DMC_Cattle: The dry matter content in manure from cattle is the weighted average of dry matter in SM and LM from cattle. (Total dry matter from cattle divided on total wet weight from cattle).

Parameter: Share_Cattle and Share_Pig: Describes the share of manure from cattle and pigs in the manure mixture. This value takes into account the 50/50 share in LM and that SM only consists of cattle manure. (Total dry matter of manure from one animal divided on the total dry matter of manure).

MY_Cattle: The methane yield in the manure from cattle is the weighted average of methane yield in SM and LM from cattle.

km_Manure: The transport distance for manure is a weighted average based on the transport distance of LM and SM. (The value for Scenario 3 is described under chapter 3.4.1.2 Variables.)

km_OMWc: The transport distance of waste is calculated by use of equation (7) in chapter 3.4.1.2 Variables. The transport distance from "The Magic Factory" to the plant in Sweden is added to this distance for the Reference scenario.

3.4.2 Sensitivity analysis

Seven sensitivity analyses are carried out by use of the MFA model. Eight parameters and two variables are adjusted. They were chosen based on the uncertainties described above. The sensitivity analyses were carried out to study the effect of these parameters and variables on the outputs from "The Magic Factory". The adjustments are explained below:

- DMSM; dry matter of solid manure: a decrease from 30 to 17 %, a reduction of 43 %. This reduction is worst case and based on values obtained by analyses of the solid manure that will be utilized by "The Magic Factory".
- RSM and RLM; reject from solid and liquid manure: a decreased from 8 and 3 % to 0 %, a reduction of 100 %. Greve Biogass AS does not apply reject from manure; the reduction is made to meet this fact.
- HB; heat demand from biogas production: an increase from 2.72 kWh/m^3 to 8.82 kWh/ton, an increase of 224 %. This increase is based on heat demand obtained in the MFA model and specific heat capacity:
    - 70 °C (temperature in substrate out from sanitation) - 18 °C (temperature in Bioresidual) = 52 °C (heat available for recovery)
    - 5 % loss = 49.4 °C (heat accessible for recovery)
    - average temperature in substrate into "The Magic Factory" 15 °C
    - temperature in substrate after heat recovery = 15 °C + 49.4 °C = 64.4 °C
    - temperature in substrate into sanitation 72 °C
    - need for heating by external source = 72 °C – 64.4 °C = 7.6 °C
    - specific heat capacity for water = 4.18 MJ/ton*C (Coultry et al. 2013)

    - energy demand for heating one ton 7.6 °C = (7.6 °C * 4.18 MJ/ton*C) / 3.6 MJ/kWh = 8.82 kWh/ton
- TSOWt; average transport distance for solid organic waste: an increase from 31 to 62 km doubles average transport distance for each ton of solid organic waste. The large amount of solid organic waste in Scenario 2 to 5 justifies the assumption that part of the waste originates from outside the Vestfold and Grenland region, the average transport distance for the waste therefore will increase.
- TSOWc; average collection distance for solid organic waste: an increase from 69 to 76 km, a 10 % increase in average collection distance for each ton of solid organic waste. The distances for collection of solid organic waste are estimated based on the average distance in the Vesar area. This number is uncertain and probably is significant due to the high energy consumption in waste collection.
- HHVP; higher heating value of manure from pig: an increase from 16 500 to 17 662 MJ/ton DM, 7 % increase and an increase of 15 % compared to the higher heating value of manure from cattle.
- DSOW and DM; degradability of solid organic waste and manure: an increase from 63 to 80 % for solid organic waste, and an increase from 62 to 80 % for manure, an increase of 27 % and 29 % respectively. The literature indicates lower values than expected by Greve Biogass AS. This increase is made to adjust to expectations of Greve Biogass AS.

The LCA sensitivity analyses have been carried out using Scenario 2 as a Baseline. The reason for this is that it is the most realistic scenario considering a fully up-and-running plant in 2017. The same parameter changes have been studied as for the MFA model, except reject from manure. This is because the LCA model does not include reject from manure in the first place. However, the list of parameters is not the same for both models. Therefore, for some of the sensitivity analyses, one change has affected several parameters. The parameters adjusted for the LCA sensitivity analyses are listed in Table 13.

Table 13: The parameter changes, according to the Baseline (Scenario 2), carried out for the sensitivity analysis of the LCA results

Parameter name	Baseline (Scenario 2)	Adjusted value	Sensitivity
DMC_Cattle	0.075	0.067	DMSM; Dry matter solid manure
Share_Cattle	0.571	0.54	DMSM; Dry matter solid manure
Share_Pig	0.428	0.46	DMSM; Dry matter solid manure
DS_Cattle	0.504	0.36	DSOW_DM; Degradability
DS_Pig	0.504	0.36	DSOW_DM; Degradability
DS_OMW	0.433	0.28	DSOW_DM; Degradability
HHV_Pig	16 500	17 662	HHVp; Higher heating value, pig
E_AD	14.32	20.42	HB; Heat demand biog. prod.
km_OMW	69	76	TSOWc; Collection distance
km_OMWc	31	62	TSOWt; Transport distance

4 Results

In this chapter will be presented the results of the MFA and LCA models for the various scenarios, with the emphasis put on:

- outputs and requirements
- environmental impacts
- sensitivity analysis

4.1 Outputs and requirements

The outputs and the requirements from "The Magic Factory" are determined by use of the MFA model. The results are presented per functional unit, 1 ton dry matter of organic waste substrate for anaerobic digestion and per year. The results are based on the inputs described in the scenarios and presented in Table 14.

Table 14: Outputs and demand for water from "The Magic Factory" by functional unit and year based on input of substrate stated in the scenarios

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Unit
Amount per ton DM for AD	Biofuel (CH_4)	228	264	271	269	308	m^3
	CO_2	130	154	155	157	183	m^3
	Bioresidual DM	0.58	0.51	0.50	0.50	0.42	ton
	Bioresidual WW	6.27	6.20	6.19	6.19	6.11	ton
	Water added	-1.30	0.75	3.31	1.01	3.38	ton
Total amount per year	Biofuel (CH_4)	1 971 974	4 886 794	4 964 047	5 508 176	6 206 948	m^3
	CO_2	1 125 127	2 840 510	2 842 432	3 208 448	3 685 895	m^3
	Bioresidual DM	5 024	9 369	9 130	10 210	8 398	ton
	Bioresidual WW	54 325	114 591	113 326	126 890	122 977	ton
	Water added	-11 437	13 381	60 073	20 115	67 345	ton
Energy yield		39 %	43 %	45 %	44 %	48 %	

The outputs per functional unit can be compared for all the scenarios. The highest output of methane per ton dry matter organic waste substrate is for Scenario 5, while the lowest is for Scenario 1. The same applies to the amount of CO_2 indicating that this is a result of the total of biogas produced, rather than the methane content in the biogas. This is quite similar for all the scenarios but highest for Scenario 1, 63.2 % and lowest for Scenario 5, 62.3 %.

The highest output of Bioresidual is for Scenario 1, both when considering wet weight and dry matter content. This scenario is also the one with the highest dry matter content in the Bioresidual, 9.3 %, while Scenario 5 has the lowest, 6.9 %.

The amount of water added varies a lot for the different scenarios. There is a need for water in two parts of the plant, in the pretreatment and in the biogas cleaning and upgrading. The need for water in the pretreatment is to establish the desired dry matter content of the substrate mixture when it enter the biogas production section. The need for water in the biogas upgrading is to separate impurities. Scenario 1 has a net overload of water, indicating that the water content of the incoming substrates is higher than the total need for water in the said two parts. All other scenarios require addition of water. The demand varies from 0.75 ton water per ton dry matter organic waste substrate for anaerobic digestion in Scenario 2 to 3.38 ton water in Scenario 5.

The energy yield for the different scenarios varies from 39 % for Scenario 1 to 48 % for Scenario 5, a noticeable difference. The energy yield for the reminding scenarios is however quite similar, located around 44 %.

It is not possible to compare the annual results since the input is different in the scenarios. It is possible to compare Scenario 2 with 3 and Scenario 4 with 5 as they have the same input of dry matter. The difference between the values is the same as the difference between the values describing the outputs per functional unit. However, the annual results clearly indicate that the outputs are strongly correlated to the inputs. Higher inputs result in higher outputs, and substrate mixture influences both the outputs and the demand for water.

4.2 Environmental impacts

The environmental impacts caused by the functional unit (treatment of 1 ton dry matter of organic waste substrate) for the different scenarios are studied by use of the LCA. The study has been concentrated on four different impact categories:

- climate change
- human toxicity
- water depletion
- fossil depletion

These were chosen since they are the most commonly studied impact categories. They will further be presented along with:

- the impact caused by the functional unit for each scenario
- the share of the impacts between the different processes

4.2.1 Climate change

Climate change impacts caused by the functional unit for the different scenarios are presented in Figure 10. The Reference scenario has a high net climate change impact, while all the other scenarios have a net negative climate change impact. The highest climate change impact reduction is seen for Scenario 2, 3 and 4 and the lowest for Scenario 5.

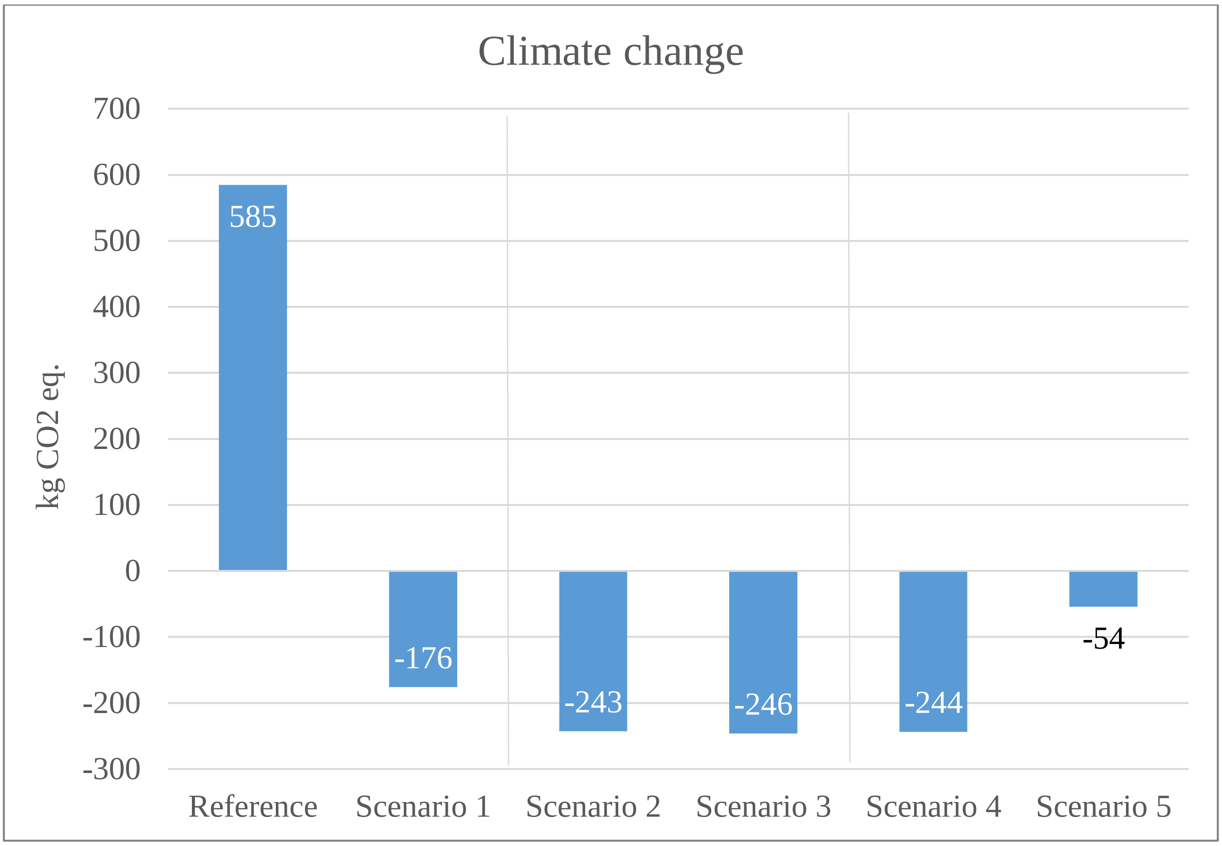


Figure 10: Climate change impact caused by the functional unit (treatment of 1 ton dry matter of organic waste substrate), for the different scenarios

The shares of the climate change impact among the different processes for each of the scenarios are presented in Figure 11. The Reference scenario along with Scenario 1 and 5 stand out with an impact caused by Manure storage and application. This is a result of manure spread on farmland the "traditional way". Further, the highest climate change impact reduction is caused by Fuel substitution; this is related to biofuel substituting fossil fuel in busses. The second process that contributes to a large portion of the climate change impact reduction is Bioresidual, substituting artificial fertilizer. The major contributor to climate change impact is Transport of organic waste for all scenarios except for the Reference scenario, where this is the second highest. The process with the highest climate change impact for the Reference scenario is however the same as the second highest for the other scenarios, Post treatment of Bioresidual. The difference in this for the Reference scenario compared to the other scenarios is caused by the storage of Bioresidual without cover.

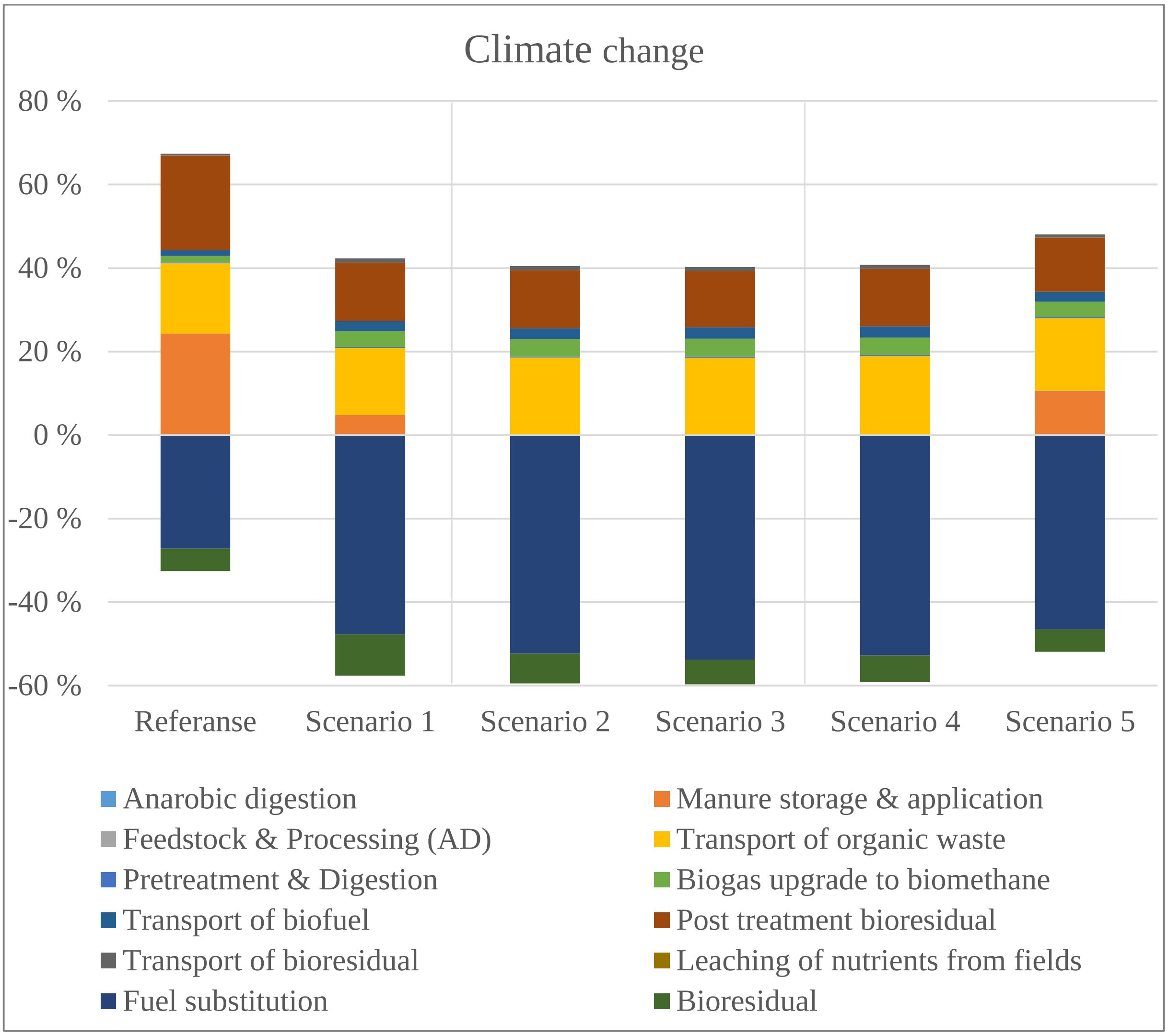


Figure 11: Share of climate change impact caused by the different processes, for each scenario

4.2.2 Human toxicity

Human toxicity impacts caused by the functional unit for the different scenarios are presented in Figure 12. All scenarios have a net human toxicity impact. The highest impact caused by the functional unit is for the Reference scenario, followed by Scenario 1 and 5. The lowest impact per functional unit is caused in Scenario 4.

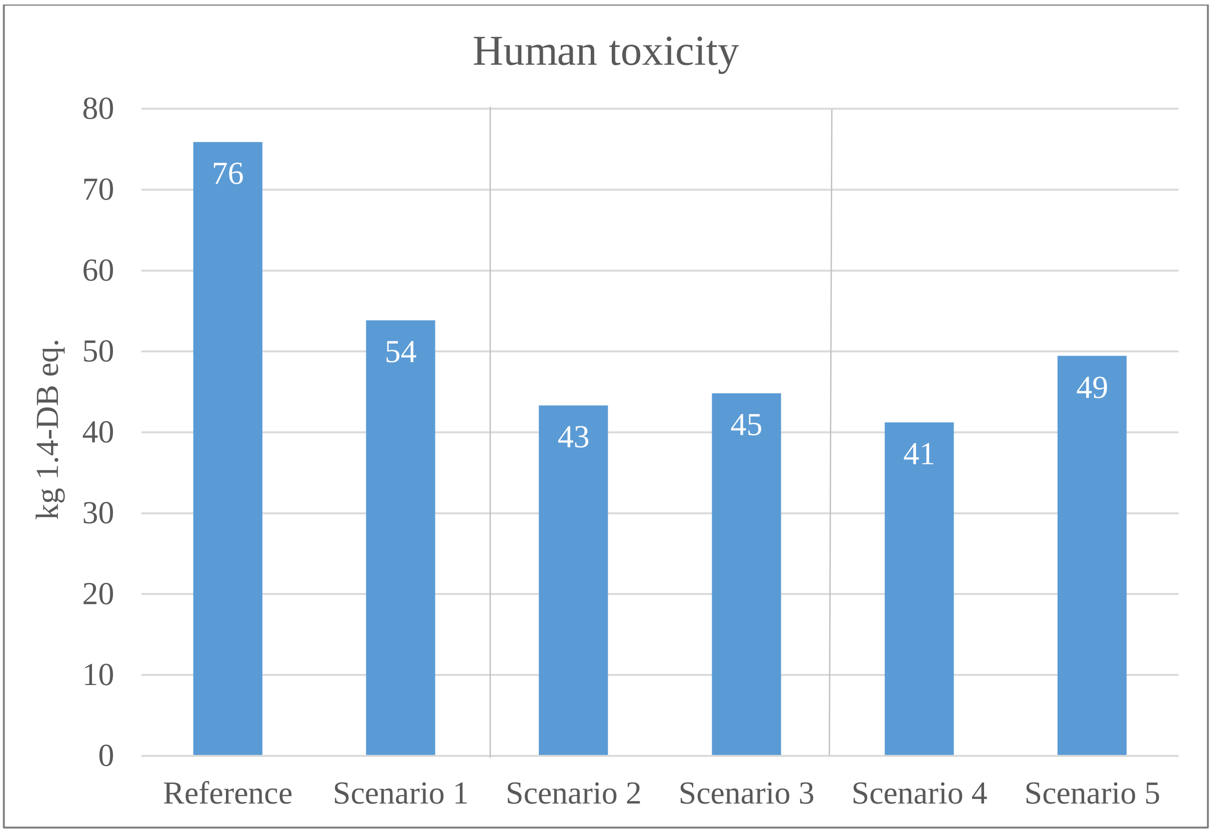


Figure 12: Human toxicity impact caused by the functional unit (treatment of 1 ton dry matter of organic waste substrate), for the different scenarios

The share of human toxicity impact between the different processes, for each of the scenarios, is presented in Figure 13. The highest impact for all scenarios is caused by Post treatment of Bioresidual, the second highest is for all scenarios Transport of organic waste. This is however higher for the Reference scenario than for the other scenarios, due to the extra transport distance from "The Magic Factory" to the plant in Sweden. The major reduction in human toxicity impact is a result of the Bioresidual replacing artificial fertilizer, followed by Fuel substitution, biomethane substitution fossil fuel.

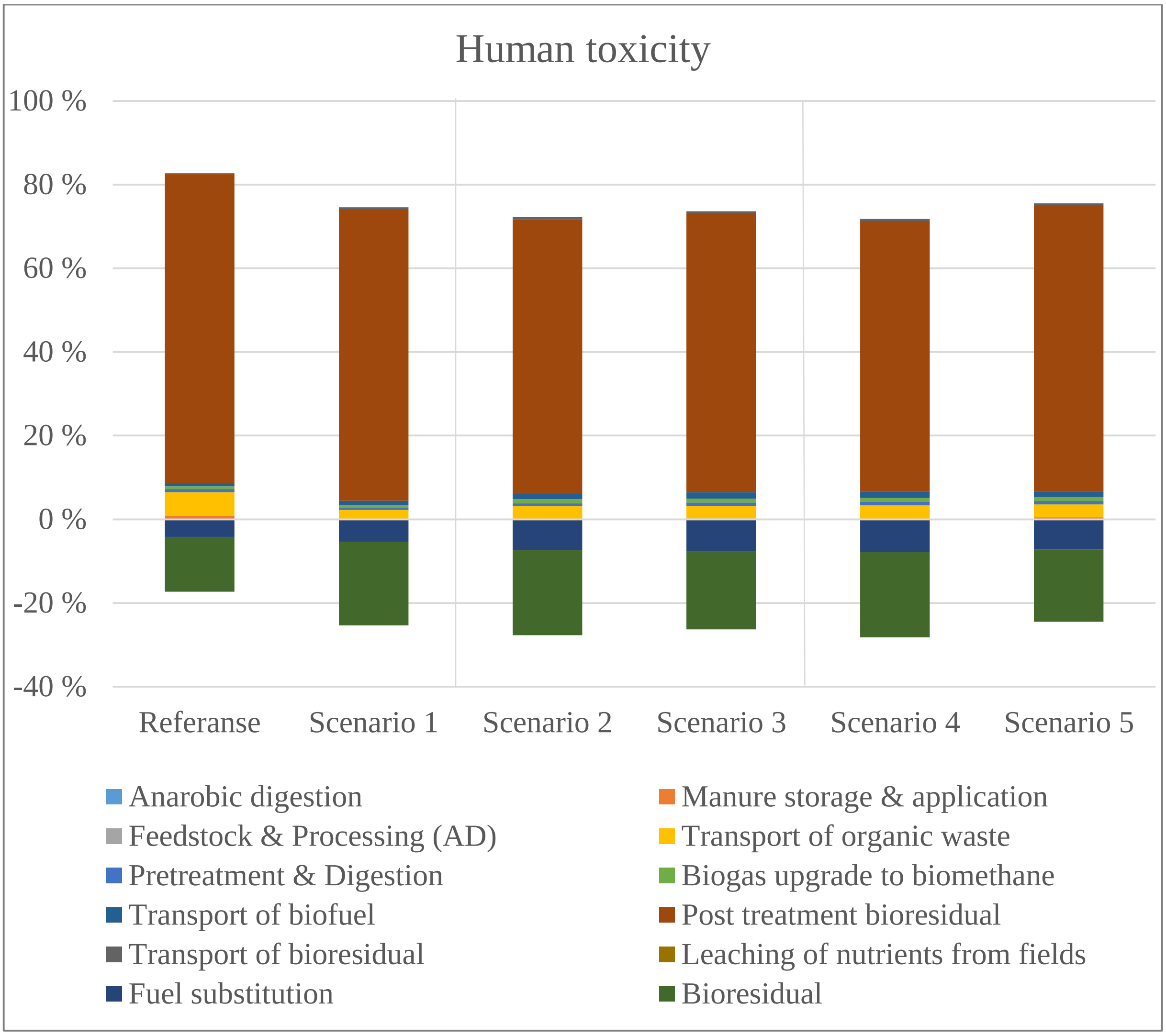


Figure 13: Share of human toxicity impact caused by the different processes, for each scenario

4.2.3 Water depletion

Water depletion caused by the functional unit for the different scenarios is presented in Figure 14. All scenarios have water depletion in the range 441 – 487 m^3 per ton dry matter of organic waste substrate, except for Scenario 1 which has a slightly lower impact.

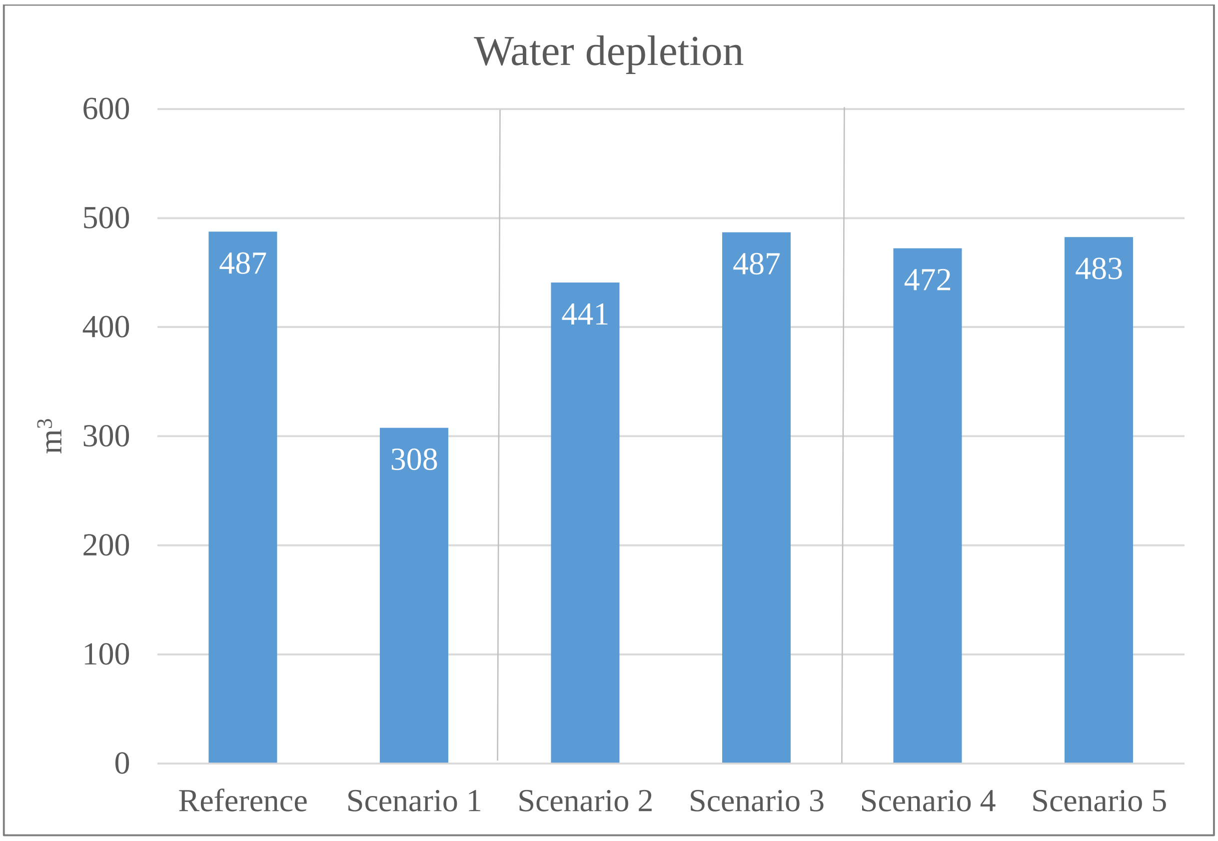


Figure 14: Water depletion caused by the functional unit (treatment of 1 ton dry matter of organic waste substrate), for the different scenarios

The share of water depletion between the different processes for each of the scenarios is presented in Figure 15. The highest impact for all scenarios is caused by Biogas upgrade to biomethane. For Scenario 1 to 5 follows Pretreatment and Digestion and Fuel substitution as responsible for the second and third largest share. For the Reference scenario, Transport of organic waste is responsible for the second largest share, followed by Pretreatment and Digestion and Fuel substitution. The reduction in water depletion is caused by one process for all scenarios, Bioresidual as substitution for artificial fertilizer.

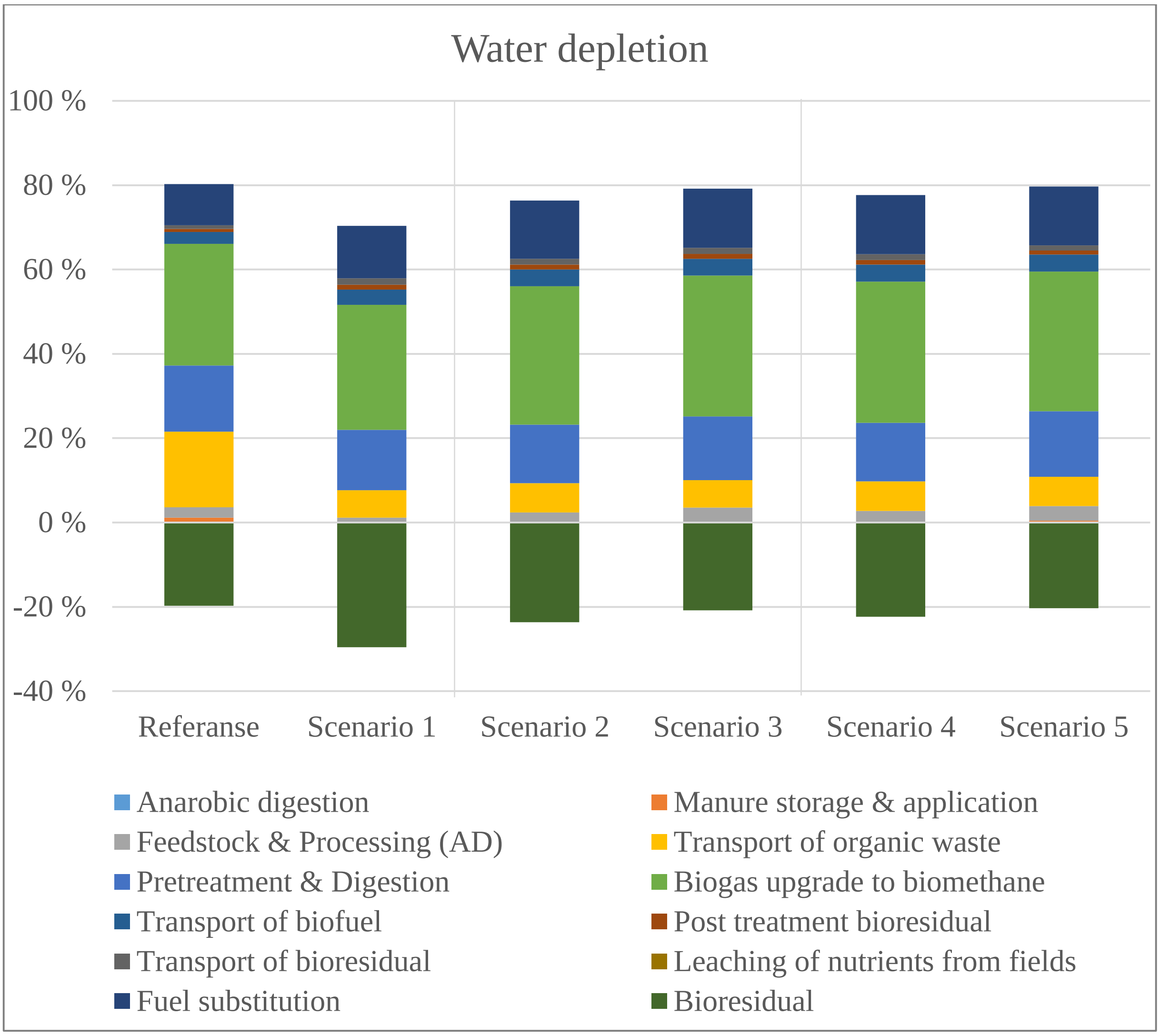


Figure 15: Share of water depletion caused by the different processes, for each scenario

4.2.4 Fossil depletion

Fossil depletion caused by the functional unit for the different scenarios is presented in Figure 16. All scenarios have a negative fossil depletion. Scenarios 1 to 5 have a similar reduction in the range 113 – 129 kg oil equivalents per ton; the Reference scenario stands out with a lower reduction of 45 kg oil equivalents per ton.

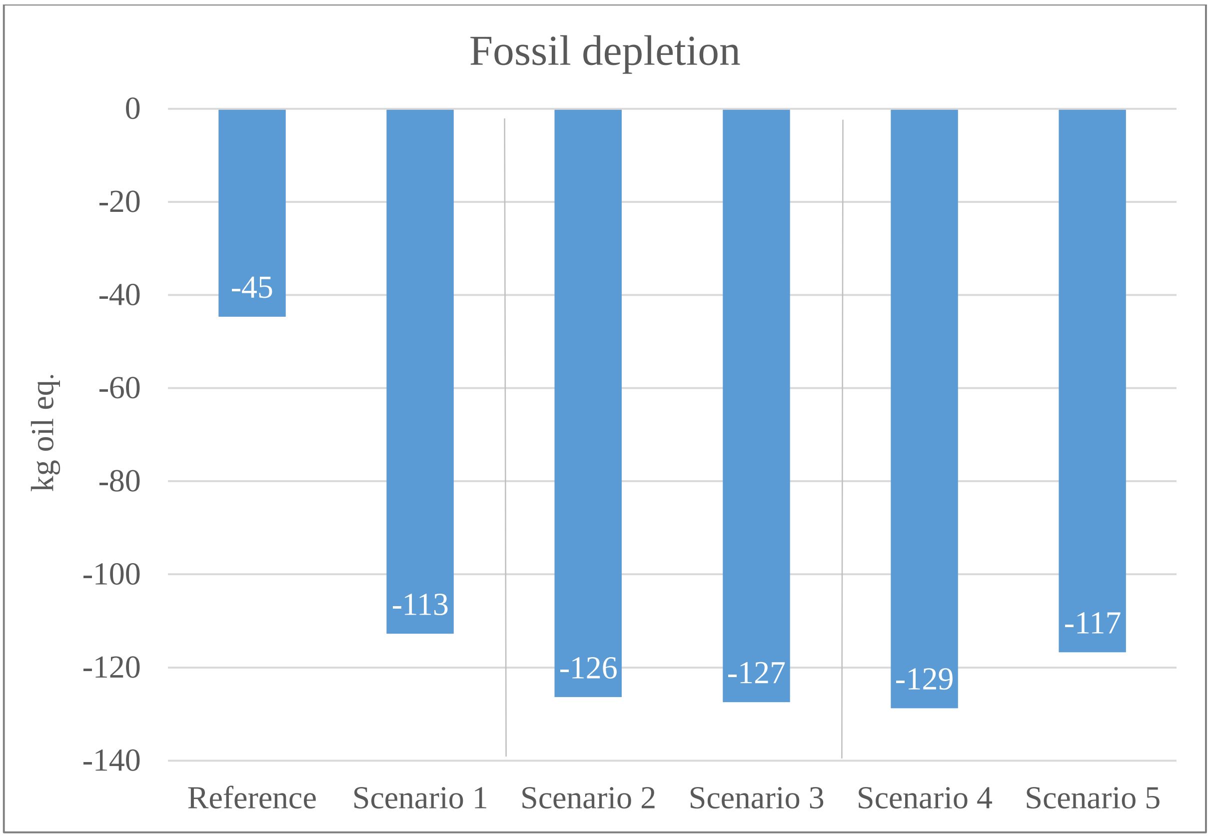


Figure 16: Fossil depletion caused by the functional unit (treatment of 1 ton dry matter of organic waste substrate), for the different scenarios

The share of the fossil depletion between the different processes for each of the scenarios is presented in Figure 17. The highest share of the depletion for all scenarios is due to the process Transport of organic waste; this is higher for the Reference scenario than the others because of the extra transport distance of the food waste to Sweden. Even though transport has a quite high share of impact, the results are a net fossil depletion impact reduction. This is mainly due to the Fuel substitution; the biofuel from the biogas production is assumed to substitute fossil fuel use in busses. It is also worth noting the share of fossil depletion reduction caused by Bioresidual as substitution of artificial fertilizer.

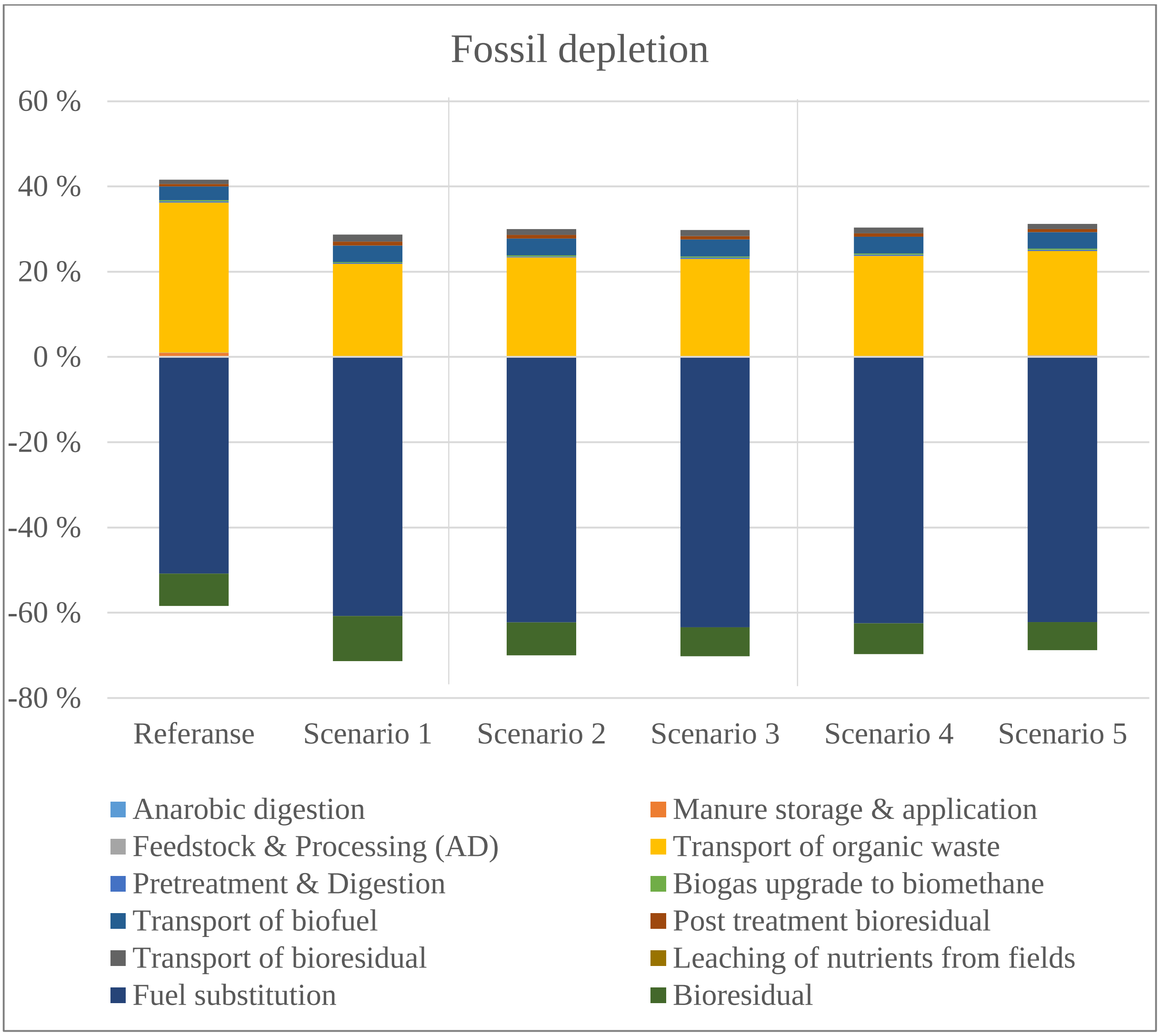


Figure 17: Share of fossil depletion caused by the different processes, for each scenario

4.3 Sensitivity analysis

Seven sensitivity analyses were carried out on all scenarios by use of the MFA model, while six sensitivity analyses were carried out on Scenario 2 by use of the LCA model. The results of the sensitivity analyses are presented below.

4.3.1 Outputs and requirements

Out of the seven sensitivity analyses carried out, only three influence the outputs and demand for water added:

- DMSM, dry matter of solid manure
- RSM and RLM, reject from solid and liquid manure
- DSOW and DM, degradability of solid organic waste and manure

However, all the sensitivities affected the energy yield.

The effect caused on the outputs from a change in dry matter content of solid manure from 30 % to 17 %, a reduction of 43 % is presented in Table 15. We can see that a reduction in the dry matter content of solid manure will affect the outputs in all scenarios, except for Scenario 5 in which manure is not processed at “The Magic Factory”.

Table 15: The sensitivity of the outputs from “The Magic Factory” by a 43 % reduction in dry matter content of solid manure compared to the Baseline

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Amount per ton DM for AD	Biofuel (CH_4)	1.2 %	0.7 %	5.2 %	0.6 %	-
	CO_2	1.6 %	0.9 %	6.7 %	0.8 %	-
	Bioresidual DM	-1.1 %	-0.8 %	-6.1 %	-0.7 %	-
	Bioresidual WW	-0.1 %	-0.1 %	-0.5 %	-0.1 %	-
	Water added	17.5 %	-10.3 %	-10.2 %	-6.6 %	-
Total amount per year	Biofuel (CH_4)	-1.6 %	-0.6 %	-4.4 %	-0.6 %	-
	CO_2	-1.2 %	-0.4 %	-3.1 %	-0.4 %	-
	Bioresidual DM	-3.8 %	-2.0 %	-14.7 %	-1.9 %	-
	Bioresidual WW	-2.9 %	-1.4 %	-9.6 %	-1.2 %	-
	Water added	13.9 %	-11.9 %	-18.6 %	-7.9 %	-

The output of Biofuel and CO_2 per ton dry matter for anaerobic digestion increases in all scenarios. These outputs nevertheless decrease when the total amount per year is investigated. The highest variation from the Baseline is seen for Scenario 3. The amount of bioresidual will decrease with a reduction of the dry matter of solid organic waste both per functional unit and on an annual basis. The highest decrease is seen for Scenario 3. As seen in the results, there is no demand for additional water for Scenario 1. We see from the sensitivity that a decreased dry matter in solid manure increased the overload of water following the substrate. For the other scenarios, we see a reduction in need for additional water both per functional unit and on an annual basis. The highest decrease is seen for Scenario 3.

The changes in outputs, caused by an exclusion of reject from manure, are presented in Table 16. An exclusion of reject from manure effects the output slightly for all scenarios except Scenario 5 in which solid manure is not included.

Table 16: The sensitivity of the outputs from "The Magic Factory" by a 100 % reduction in reject from manure compared to the Baseline

		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Amount per ton DM for AD	Biofuel (CH_4)	-0.8 %	-0.5 %	-0.9 %	-0.4 %	-
	CO_2	-0.9 %	-0.6 %	-1.2 %	-0.5 %	-
	Bioresidual DM	0.6 %	0.5 %	1.1 %	0.5 %	-
	Bioresidual WW	0.1 %	-	0.1 %	-	-
	Water added	-8.9 %	5.8 %	1.8 %	3.7 %	-
Total amount per year	Biofuel (CH_4)	0.8 %	0.4 %	0.9 %	0.3 %	-
	CO_2	0.6 %	0.3 %	0.6 %	0.2 %	-
	Bioresidual DM	2.2 %	1.4 %	2.9 %	1.3 %	-
	Bioresidual WW	1.7 %	0.9 %	1.9 %	0.8 %	-
	Water added	-7.3 %	7.0 %	3.7 %	4.6 %	-

The outputs of biofuel and CO_2 decreased per functional unit and increases on an annual basis, by a reduction in reject from manure. The variation from the Baseline is quite similar for all scenarios. The output of bioresidual in dry matter increases for all scenarios. The increase is highest for Scenario 3. The demand for addition of clean water is still absent for Scenario 1, we do however see that it is a reduction in amount of overload as result of the adjusted parameter. Scenarios 2, 3 and 4 will have an increased demand for additional water, and the highest increase is seen for Scenario 2.

There is a change in output from all scenarios compared to the Baseline by an increase of the degradability by 29 % for manure and 27 % for solid organic waste. These changes are shown in Table 17. We see that the changes are almost similar on basis of the functional unit and on an annual basis.

The change of the degradability results in a high increase in output of Biofuel and CO_2 for all scenarios, the increase is basically similar for all scenarios. The difference in output of bioresidual on dry matter basis varies a bit more. We do see a large decrease for all scenarios; the highest is seen for Scenario 5 and the lowest for Scenario 1. There is a small difference in water added per functional unit, but no difference on an annual basis.

Table 17: The sensitivity of the outputs from "The Magic Factory" by a 29 % and 27 % increase of degradability of manure and solid organic waste respectively compared to the Baseline

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Amount per ton DM for AD	Biofuel (CH_4)	27.3 %	27.2 %	27.2 %	27.1 %	27.0 %
	CO_2	27.3 %	27.2 %	27.2 %	27.1 %	27.0 %
	Bioresidual DM	-19.8 %	-26.4 %	-27.3 %	-27.3 %	-37.7 %
	Bioresidual WW	-1.8 %	-2.2 %	-2.2 %	-2.2 %	-2.6 %
	Water added	-0.5 %	1.0 %	0.2 %	0.7 %	0.3 %
Total amount per year	Biofuel (CH_4)	27.3 %	27.2 %	27.2 %	27.1 %	27.0 %
	CO_2	27.3 %	27.2 %	27.2 %	27.1 %	27.0 %
	Bioresidual DM	-19.8 %	-26.4 %	-27.3 %	-27.3 %	-37.7 %
	Bioresidual WW	-1.8 %	-2.2 %	-2.2 %	-2.2 %	-2.6 %
	Water added	-	-	-0.1 %	-	-

The energy yield for "The Magic Factory" was influenced by all the performed sensitivities. It was however a big difference in how much the energy yields was affected. The changes are presented in Table 18.

Table 18: The sensitivity of the energy yield for "The Magic Factory" by a change in different parameters compared to the Baseline

Sensitivity	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Dry matter solid manure	0.6 %	0.3 %	2.5 %	0.3 %	-
Reject manure	-0.5 %	-0.3 %	-0.5 %	-0.2 %	-
Heat demand biog. prod.	-0.7 %	-0.7 %	-0.7 %	-0.7 %	-0.6 %
Transport distance	-0.3 %	-0.4 %	-0.4 %	-0.4 %	-4.6 %
Collection distance	-1.0 %	-1.2 %	-1.2 %	-1.2 %	-1.5 %
Higher heating value	-0.9 %	-0.5 %	-	-0.4 %	-
Degradability	26.7 %	26.5 %	26.5 %	26.4 %	26.2 %

The highest effect of a change in dry matter for solid manure is seen for Scenario 3. The change in reject hardly has any effect on the energy yield. The change by these two parameters does however not affect the energy yield for Scenario 5 as it does not handle manure. We also see that an increase in heat demand of more than 200 % has a low impact on the energy yield. An increase of transport distances decreases the energy yield. We see that the collection distance has a much higher impact on the energy yield than the transport distance for Scenarios 1 to 4. The collection distance is increased with 10 % only, while the transport distance is doubled, yet the decrease in energy yield is about three times higher. However, for Scenario 5 we see that the transport distance has a much higher influence than the collection distance. The higher heating value for manure from pig does not affect the energy yield in Scenarios 3 and 5 as there is no input of pig manure in these scenarios. So we see that for the scenarios in which pig manure as a biogas substrate is included, there is a slightly negative effect. The change in degradability has a high impact on the energy yield for all scenarios.

4.3.2 Environmental impacts

The environmental impacts caused by the functional unit (treatment of 1 ton dry matter of organic waste substrate) and a shift in the parameters according to the sensitivities are studied with respect to the four impact categories:

- climate change
- human toxicity
- water depletion
- fossil depletion

The differences in climate change impact by the sensitivities are presented in Figure 18. All sensitivities have a net negative climate change impact and they all have a variation compared to the Baseline (Scenario 2). Two of the sensitivities cause a lower reduction than the Baseline. These are the two sensitivities representing increased transport- and collection distance for solid organic waste (TSOWt and TSOWc). Degradability (DSOW_DM) is the sensitivity that stands out with an almost doubled climate change impact reduction.

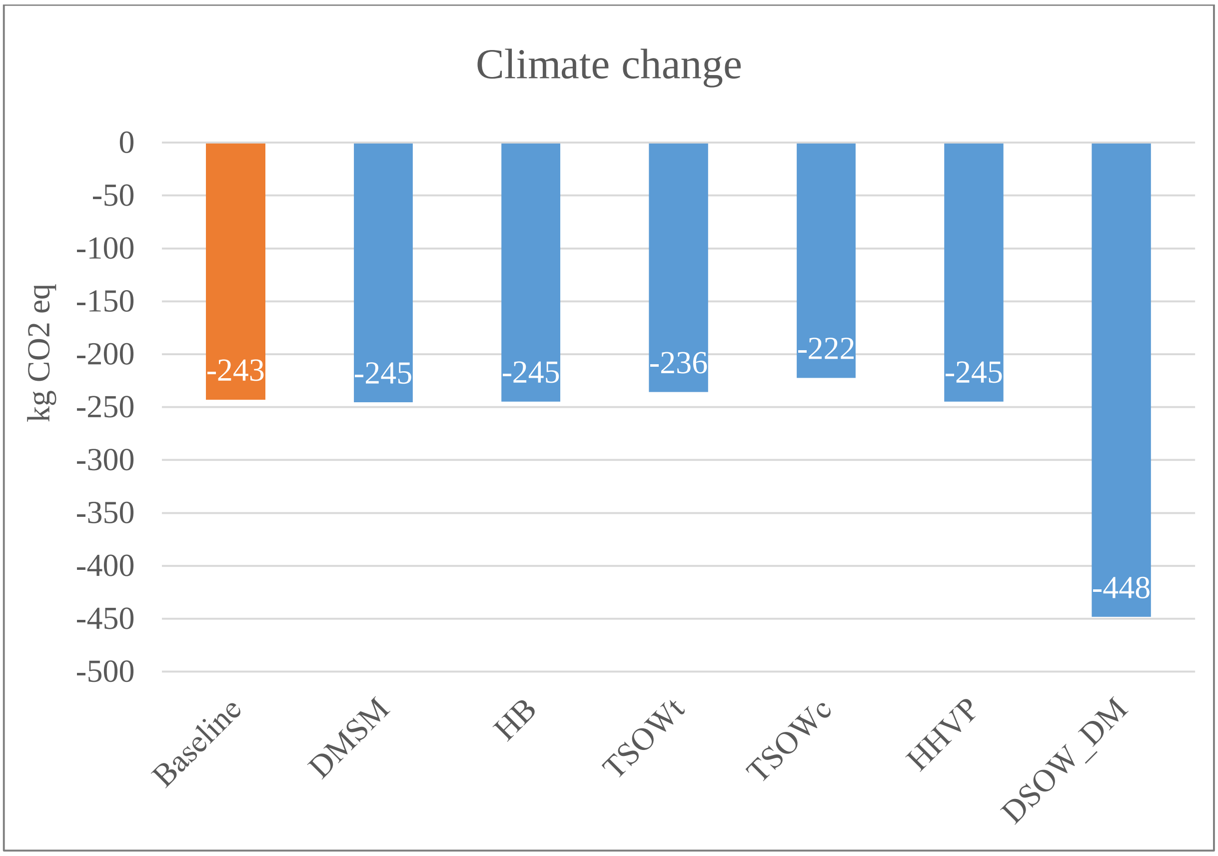


Figure 18: Climate change impact caused by the functional unit for Scenario 2, with different parameter adjustments making up a sensitivity analysis

The change in share of climate change impact caused by the different processes is presented in Figure 19. There is almost no change seen for most of the sensitivities. However, a small decrease in share from Fuel substitution is possible to spot for an increased collection distance for solid organic waste (TSOWc). The change for degradability (DSOW_DM) is mainly due to a reduction in share from Post treatment of Bioresidual, and an increased Fuel substitution.

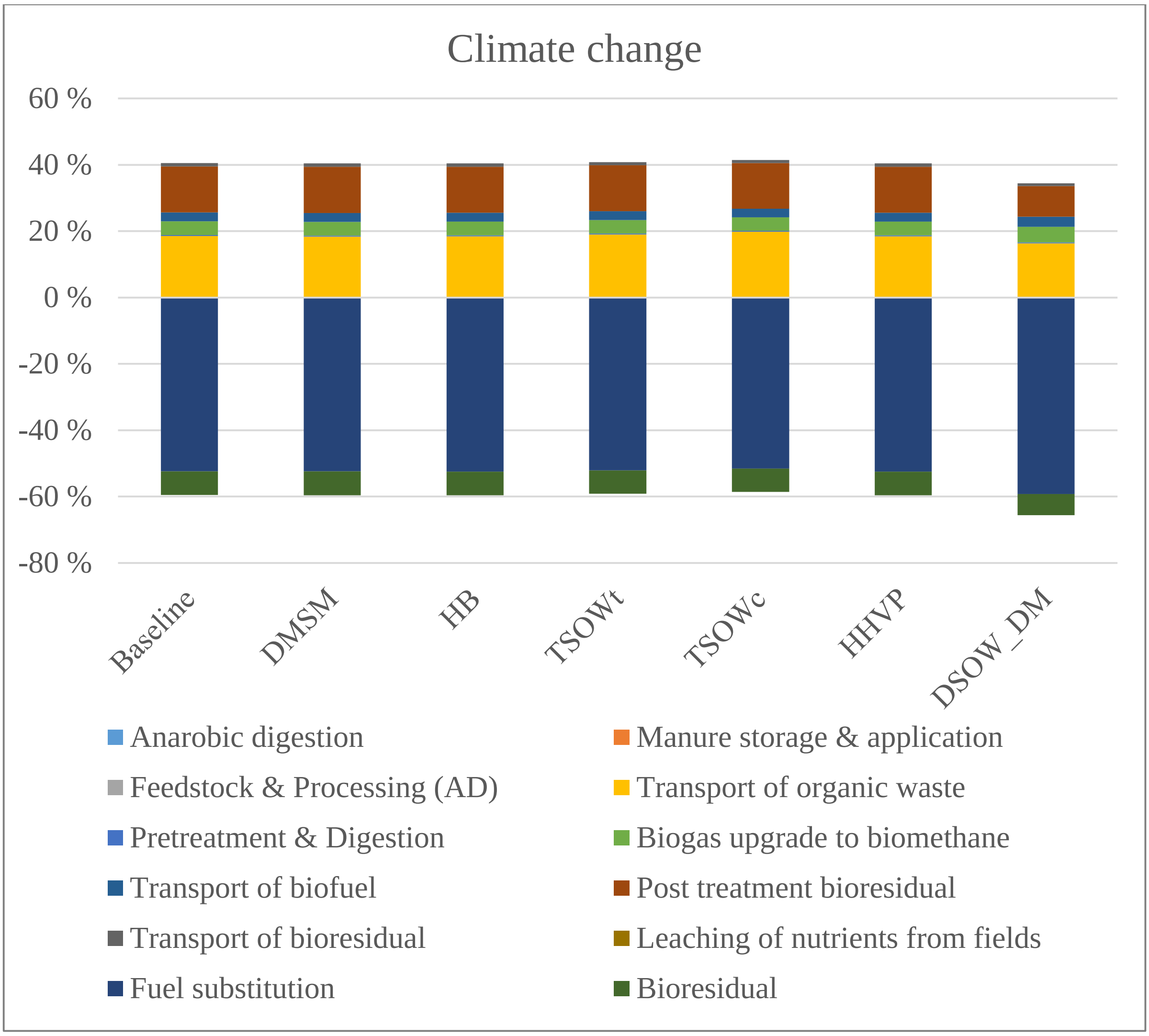


Figure 19: Share of climate change impact caused by the different processes, for the Baseline and each sensitivity

The differences in human toxicity impact by the sensitivities are presented in Figure 20. All sensitivities have a human toxicity impact and there is no difference in the impact from all sensitivities except transport distance for solid organic waste (TSOWt) and degradability (DSOW_DM). The change caused by an increased transport distance for solid organic waste is thus relatively low. The change in impact by the change in degradability is however substantial, a reduction of more than 40 %.

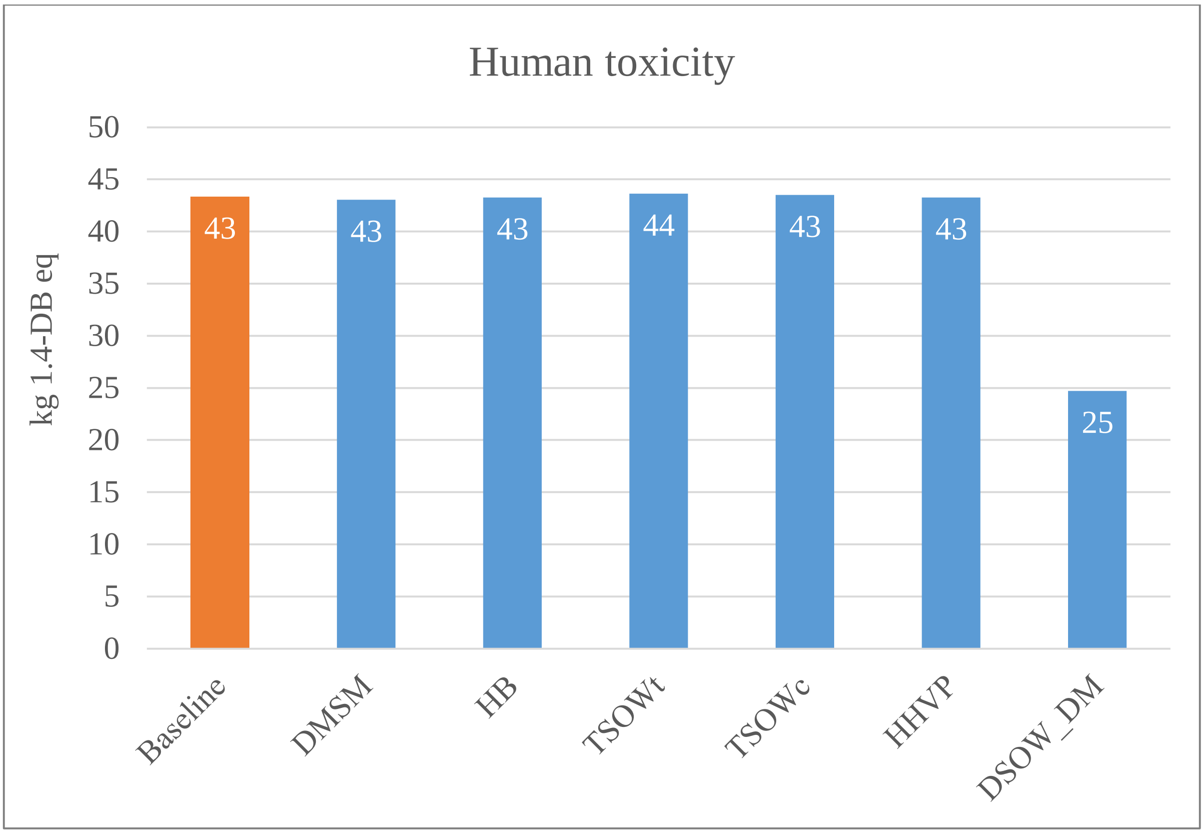


Figure 20: Human toxicity impact caused by the functional unit for Scenario 2, with different parameter adjustments making up a sensitivity analysis

The share of the human toxicity impact caused by the different processes for the different sensitivities is presented in Figure 21. We see that there is almost no difference in share from the different processes for most of the sensitivities. So, the reduction in human toxicity impact by an increased degradability is a result in a lower share form Post treatment of bioresidual and an increased Fuel substitution and Bioresidual, representing substitution of artificial fertilizer.

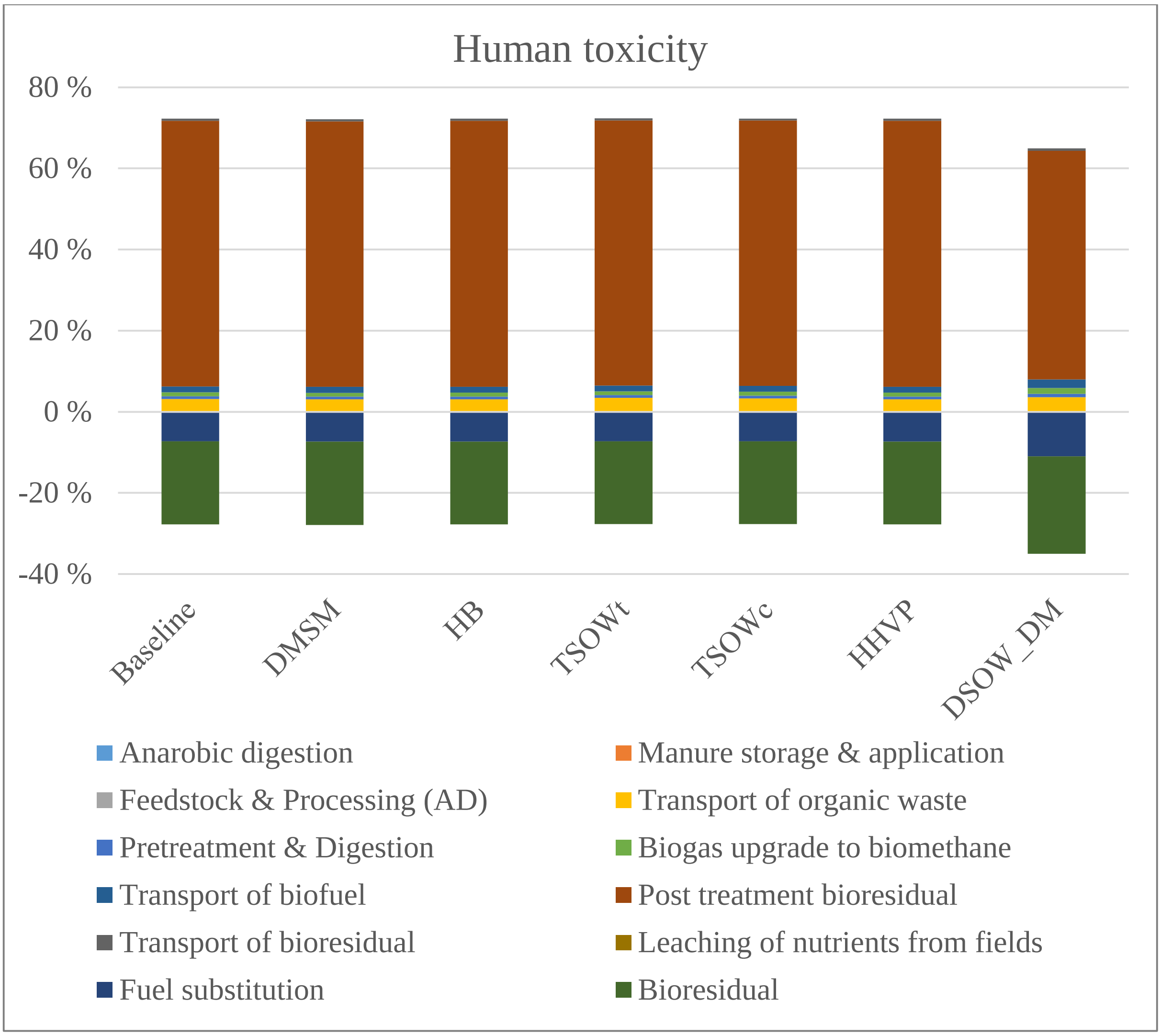


Figure 21: Share of human toxicity impact caused by the different processes, for the Baseline and each sensitivity

The differences in water depletion by the sensitivities are presented in Figure 22. The water depletion varies from the Baseline for all sensitivities. For three of them, there is a tiny reduction, while for the other three, there is an increase. So, there is a sensitivity only, which stands out with a significant difference, namely degradability (DSOW_DM), where water depletion is increased with 25 % compared to the Baseline.

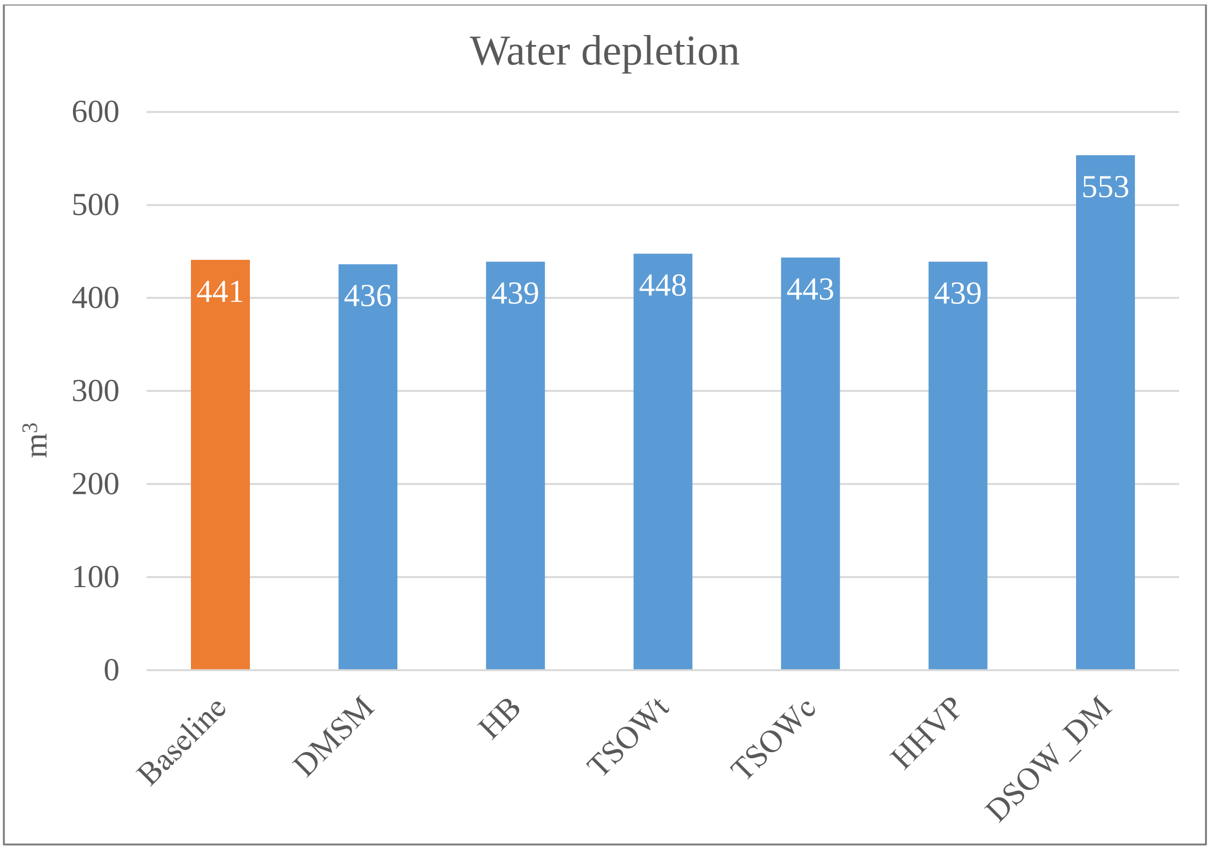


Figure 22: Water depletion caused by the functional unit for Scenario 2, with different parameter adjustments making up a sensitivity analysis

There is almost no difference in share from the different processes for the sensitivities, other than degradability (DSOW_DM), see Figure 23. The differences in share for degradability are to be seen in a reduction in share from Bioresidual, representing substitution of artificial fertilizer, along with an increased share in Biogas upgrade to biomethane.

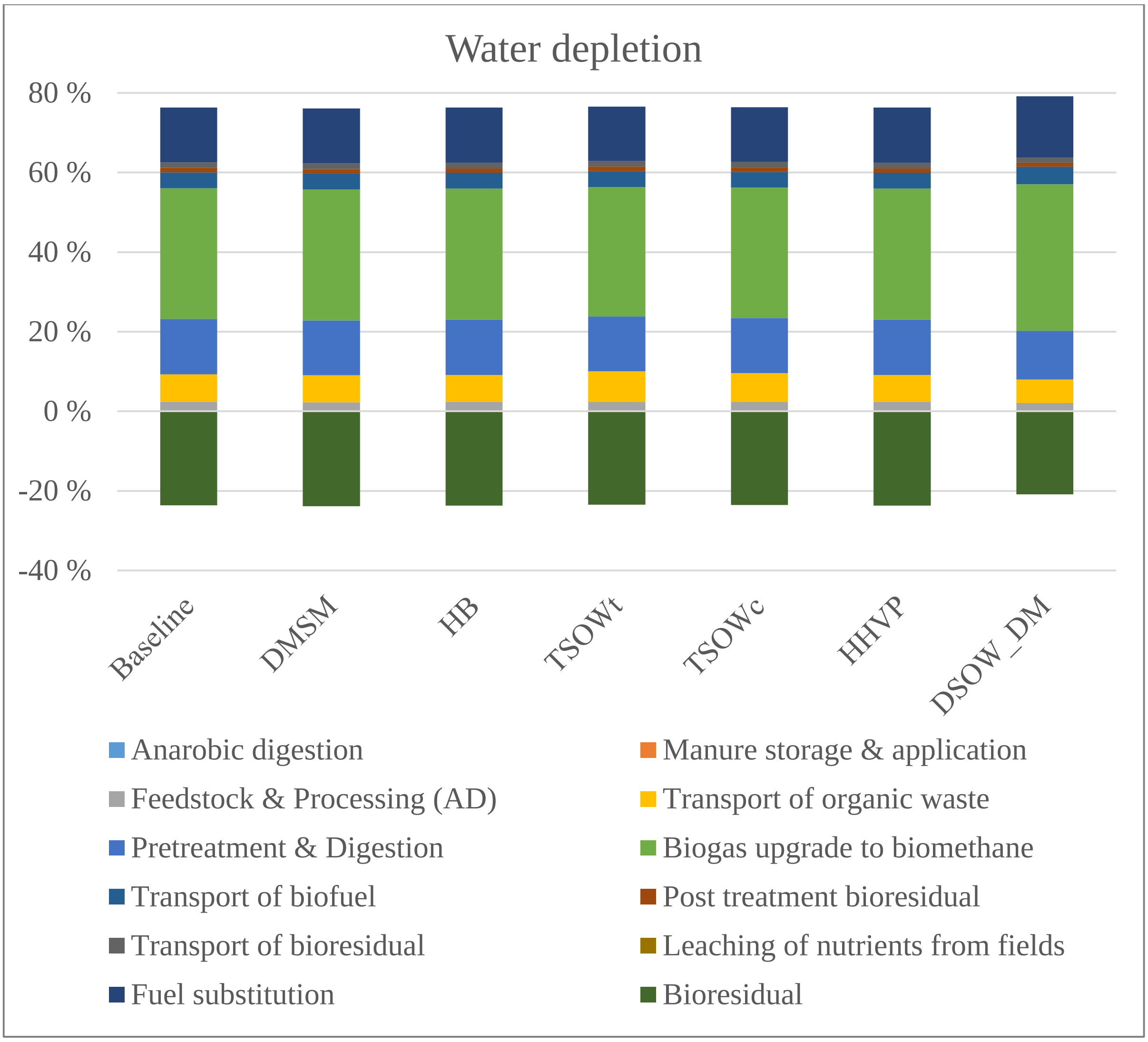


Figure 23: Share of water depletion caused by the different processes, for the Baseline and each sensitivity

The differences in fossil depletion by the sensitivities are presented in Figure 24. All sensitivities have a net negative fossil depletion, which varies from the Baseline. There is a reduction in saved fossil depletion for the sensitivities representing an increased transport; the highest reduction is seen for the collection (TSOWc,) which has a cage of almost 5 %. For the other sensitivities there is a saved fossil depletion compared to the Baseline; it is however only degradability (DSOW_DM) that has a significant difference. The saved fossil depletion by the increased degradability is about 40 %.

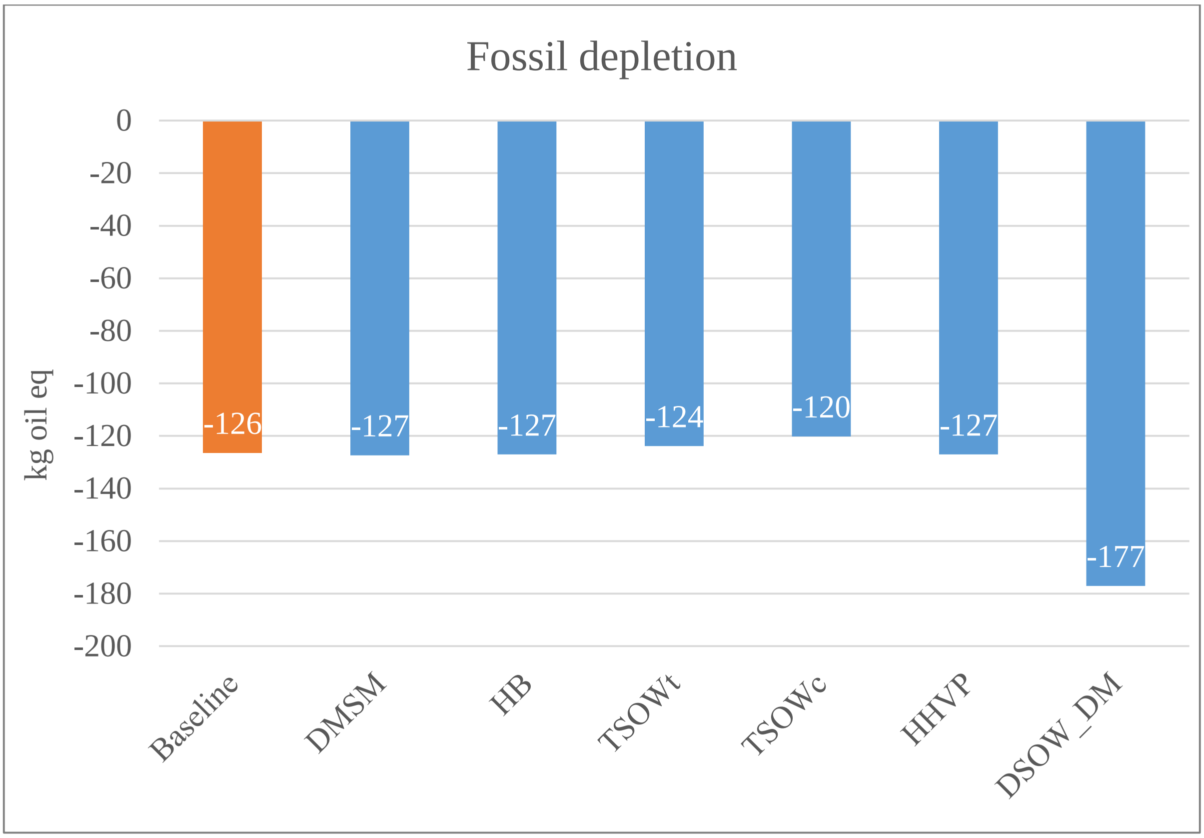


Figure 24: Fossil depletion caused by the functional unit for Scenario 2, with different parameter adjustments making up a sensitivity analysis

The share of the fossil depletion caused by the different processes for the different sensitivities is presented in Figure 25. The reduction in saved fossil depletion by a change in collection distance for solid manure (TSOWc), is mainly due to a reduced share from the process Fuel substitution and an increased share from Transport of organic waste. So, this is the opposite for degradability where there is an increased share from Fuel substitution and a decreased share for Transport of organic waste. It is worth noticing that the value for Fuel substitution has not been changed for the decrees in distance and eider is Transport of organic waste for degradation. The reason for the change of share is due to the change in value for the other processes. This impacts the share from all the other processes, but is only significant for the biggest ones.

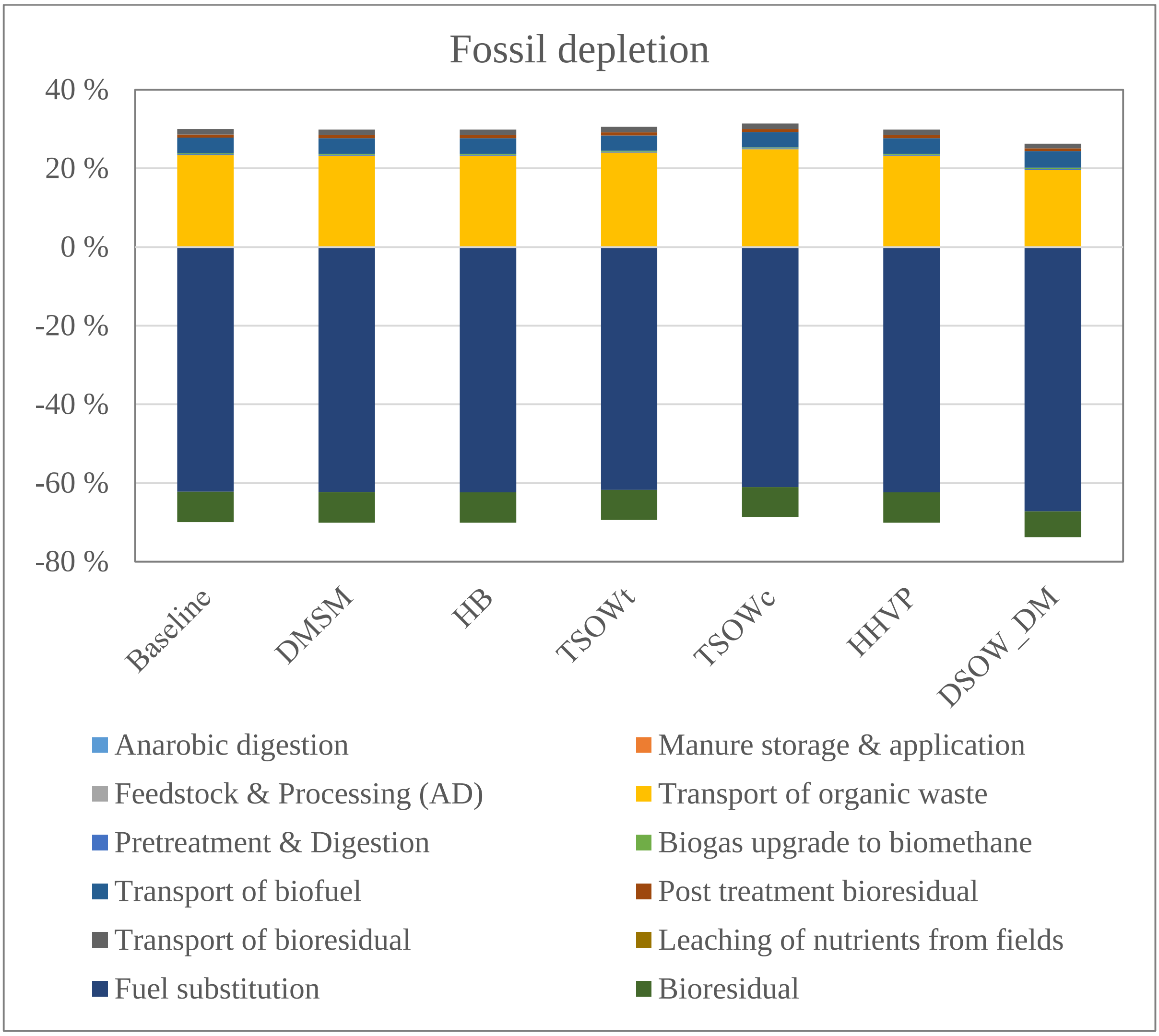


Figure 25: Share of fossil depletion caused by the different processes, for the Baseline and each sensitivity

5 Discussion

The main findings and achievements of this Thesis will be discussed in this chapter. The relevance of the findings related to the main objective of the Thesis and the research questions will be discussed along with the results in comparison with the existing literature, the strength and weaknesses of my work and the implications.

To refresh the issues for research, they are here repeated:

General research questions of relevance to this work are:

- What are previous studies telling us about climate benefits of biogas production from organic municipal waste in Norway?
- Are there any potential benefits of co-digesting organic waste with manure?

Case specific research questions are:

- What are the environmental benefits of establishing "The Magic Factory" compared to today's handling of the waste in the region to be served by this new factory?
- To what extent will the use of liquid manure instead of clean water as process water give environmental benefits?
- How will "The Magic Factory" assert itself environmentally compared to other biogas plants that do not treat such large amount of manure?

5.1 Outputs and requirements

The material flow analysis was used to establish the potential outputs and energy yield from "The Magic Factory" for the functional unit (1 ton dry matter for anaerobic digestion) and on an annual basis, based on the input established in the scenarios.

The outputs per functional unit vary between the different scenarios. The outputs of biofuel and CO_2 follow each other and we see that an increased output of biofuel also results in an increased output of CO_2. This indicates that the outputs are results of the total biogas produced, rather than the methane content in the biogas. This in fact is opposite to the outputs as the highest is for Scenario 1, 63.2 % and lowest for Scenario 5, 62.3 %; they are thus quite similar for all scenarios.

The reason why the scenario with the highest biofuel output has the lowest methane content is due to several factors. The output is based on dry matter content, volatile solids content, methane yield per ton volatile solids and degradability, while methane content is a separate value.

The calculations are therefore made so that the possible amount of biofuel (methane) is established. Then, by use of the methane content in the biogas, the total amount of biogas is established and thereafter the amount of CO_2. Some uncertainty is related to these calculations as there are different references for some of the values. However, the obtained parameters which are not case specific are taken from a commonly cited report in the literature referred to and should be applicable. The effect of the uncertainty is therefore assumed to be minor. The amount of dry matter in the bioresidual is also dependent on several factors that vary with the different substrates. This is because the Bioresidual represents the part of the fraction that is not entirely degraded by the treatment. This expresses the importance of the substrate mixture and that the outputs are dependent on the mixture of different waste fractions, just like described in the literature.

We see that Scenario 1 has a net overload of water; this is a bit misleading. The value represents the difference in water requirement and the water content of the incoming waste fractions. This would be correct if pretreatment was the only process demanding water, but for “The Magic Factory” there is also a demand for water in the biogas upgrading. It will therefore still be necessary to add water to the plant in Scenario 1, as the extra water following the substrate is not usable in the biogas upgrading where clean water is required. However, the demand of water in the biogas upgrading is quite low compared to the total demand and for Scenario 1 will be about 0.02 m^3 per functional unit and 200 m^3 on an annual basis. For the other scenarios, the share in demand of water from the biogas upgrading is 1 – 4 %. This portion is rather low and since this is a weakness only in cases where the incoming waste fractions has a quite high water content, it is assumed that the “misleading” has a low significance.

The energy yield varies with almost 10 % from Scenario 1 to Scenario 3, while the remaining scenarios have a quite similar energy yield. The energy yield is calculated based on the energy in the produced biofuel, the higher heating value of the substrates, the usage of energy in the plant and the usage of energy by transportation of the substrates and the Bioresidual. The main reason for the big difference is due to energy in the output, which is controlled by the amount of biofuel produced. This amount is somewhat lower for Scenario 1 compared to the other scenarios. This is because the share of dry matter from manure is higher for Scenario 1 than for the other scenarios and as manure has less methane content per ton volatile solids than solid organic waste. The opposite is the case for Scenario 5 where the substrate only consists of food waste. This shows that the types of waste fractions processed at “The Magic Factory” have a high influence on the energy yield. Still, as the liquid manure processed is a substitute for clean water (with no biogas potential) rather than a substrate, the energy yield can be assumed higher by assessing liquid manure as additional water.

The outputs are assumed by Greve Biogas AS to be 7.5 million Nm^3 biofuel, 150 000 tons Bioresidual and 4 500 tons CO_2 annually. The amount of biofuel established in this Thesis indicates that the assumed output is too high considering biofuel and Bioresidual and too low considering CO_2. Scenario 2 is the most represent able scenario as it handled the expected inputs of waste fractions to “The Magic Factory” in 2017. It has thus an output of only 4.9 million m^3 biofuel, 114 600 tons Bioresidual and 5 600 tons CO_2 annually. There is one assumption made that causes the output of biofuel to be a bit low. The biofuel in this Thesis is calculated as 100 % methane, but it would in reality be only 97 %. The amount of biofuel consequently is 3 % higher, or about 5 million m^3 biofuel. The variation in expected and calculated output could also be a result of some of the uncertain parameters; this will however be discussed more in detail in the sensitivity analysis, chapter 5.4.1 Outputs and requirements. The values calculated in this Thesis also show a biogas output that represents a considerably lower energy content than assumed by Raadal et al. (2008) to be the theoretical energy potential from food waste and manure in the Vestfold and Grenland region. Based on this, it could possibly be assumed that “The Magic Factory” can cover its demand for input from the Vestfold and Grenland region alone.

Greve Biogass AS expected the liquid manure to replace approximately 45 000 tons of clean drinking water. This is, according to the demand for water estimated by use of the MFA model, accomplished. Scenarios 2 and 3 handle the same amount of dry matter, but Scenario 2 uses liquid manure as substitute for clean water, resulting in a water demand almost 47 000 tons lower than the demand in Scenario 3. The same is seen for Scenario 4 when compared to Scenario 5. This shows that Greve Biogass AS is within their aim of reducing the need for clean drinking water, which is a good initiative in a world with an increasing demand for clean water.

5.2 General research questions

The previous studies considered for this Thesis concluded that the climate benefit from biogas production with organic waste in Norway is relatively low, assessing the waste treatment alone. This does however change when the possible usage of the products are included. The studies concluded that the maximum climate benefit from biogas produced from organic municipal waste in Norway is due to the possibility of substituting the use of fossil fuel in vehicles. The possibility of substituting artificial fertilizer with Bioresidual from the biogas production also may represent a climate benefit. The previous studies correspond well to the results achieved in this Thesis. As seen in the results, for two of the studied impact categories, climate change and fossil depletion, the maximum reduction in impact is as a result of fuel substitution, followed by substitution of artificial fertilizer by Bioresidual. For the other two impact categories, human toxicity and water depletion, the maximum reduction is a result of the fertilizer substitution.

The previous study, looking at biogas production in Trondheim, concluded that the environmental benefit related to biogas production from waste is highly dependent on the transport distance of the waste and the upgraded biogas. Transport to plant also stands out as a reason for the CO_2 equivalent emissions in the study performed by Østfoldforskning. This is in good consistency with the results obtained in this Thesis. Transport of organic waste stands out as the process with the highest impact on climate change and fossil depletion. The process also has an impact on human toxicity and water depletion. As seen in the results, transport of upgraded biogas is not included in this Thesis since the filling station will be located at “The Magic Factory”. This will accordingly increase the environmental benefits of “The Magic Factory”, taking previous studies into consideration.

Previous studies are in accordance that there is a benefit of co-digesting organic waste with manure. The studies considered all show that a high blending of organic waste with manure gives an increased methane yield. They indicate that the higher amount of organic waste, the higher methane yield, but there is a limit. A substrate consisting of organic waste only, has a lower methane yield than a mixture. The methane content is nevertheless not consistent with substrate mixture and the studies do not give any clear result as to the preferred substrate mixture for obtaining high methane content. Even though a benefit of co-digestion is seen, it is hard to determine an exact benefit. Therefore, it has not been calculated with a co-benefit of the mixture of the substrates at “The Magic Factory”. In the end it will be interesting to see if the real output of methane from an operational plant will be higher than calculated, due to this benefit.

5.3 Case specific research questions

Scenarios are compared in groups of two to answer the case specific research questions.

5.3.1 Environmental benefits of establishing “The Magic Factory”

The environmental benefits of establishing “The Magic Factory” are investigated by use of the Reference scenario and Scenario 1. The Reference scenario represents the current handling of the substrates; food waste is sent to Sweden for biogas production while manure is spread on farmland the traditional way. Scenario 1 represents the alternative treatment of both substrates by utilizing them for biogas production at “The Magic Factory”.

For all four impact categories, a benefit from Scenario 1 compared to the Reference scenario is seen. The maximum impact reduction is related to climate change: When using Scenario 1 instead of the Reference scenario, there is a change from climate change impact to climate change impact reduction. The shift is a result of several factors. We saw in the results that the process Manure storage and application is the main contributor to climate change impact for the Reference scenario, the share of impact from this process is significantly reduced in Scenario 1. This implicates that biogas production form manure is a more environmental friendly treatment than storage and spreading of manure the traditional way, when assessing climate change impact. Two processes are responsible for climate change impact reduction, namely Fuel substitution and Bioresidual (representing substitution of artificial fertilizer). The reduction from these processes is significantly increased in Scenario 1 compared to the

Reference scenario. The main reason for the big difference is due to the increased input, as the entire functional unit is utilized for biogas production. A higher input results in a higher output and a larger amount of biofuel and Bioresidual is available for substitution of fossil fuel and artificial fertilizer. It should also be noticed that the impact caused by Transport of organic waste in numbers is reduced with about 35 % from the Reference scenario to Scenario 1. This can however not be seen when the impacts are based on share from the different processes.

The reduction in human toxicity impact by a shift from the Reference scenario to Scenario 1 can be traced to several of the processes. The share caused by Transport of organic waste is clearly reduced at the same time as the processes that lead to a reduction of impacts, Bioresidual as substitution for artificial fertilizer and Fuel substitution, have a higher share.

Water depletion is reduced by a shift from the Reference scenario to Scenario 1. The largest change in share between the different processes is seen for Transport of organic waste, which is due to the reduced transport distance since the food waste does not require the 500 extra kilometer transport to the plant in Sweden. Another reason for the reduced water depletion in Scenario 1 is the increased reduction, a result of Bioresidual as substitution for artificial fertilizer. It is however surprising that the impact of Pretreatment and Digestion does not have a higher decrease, as there will be almost no need for additional water according to the output results. It could be several reasons for this, which is further discussed under chapter 5.3.2 Environmental benefits of the water choices, with expected load in 2017.

Both scenarios has a net reduction in fossil depletion, the reduction is more than 2.5 times higher for Scenario 1 than for the Reference scenario. The main reason seems to be the decreased Transport of organic waste; it is also an increase in the reduction due to Fuel substitution and use of Bioresidual instead of artificial fertilizer.

5.3.2 Environmental benefits of water choices, with expected load in 2017

The environmental benefits of substituting clean water as process water with liquid manure, is investigated by use of Scenarios 2 and 3. The two scenarios handle the same dry matter amount of both organic waste and manure. However, all manure in Scenario 3 is assumed to be solid, while Scenario 2 has a split between liquid and solid manure like the one scheduled for “The Magic Factory”.

Both scenarios have net reductions in climate change impact and the reductions are almost identical. It is a small shift in what process causes the highest reduction. The share of reduction from Fuel substitution is a bit higher for Scenario 3 than 2. Scenario 2 has a higher share of the reduction from the process Bioresidual, representing substitution of artificial fertilizer. It is therefore surprising that in Transport of organic waste there is not a more substantial difference between the two scenarios. The demand for transport will be higher for Scenario 2. In order to achieve the same amount of dry matter, a much higher amount of manure will need to be transported because of the lower dry matter of the manure. This surprising result could be a result of the functional unit. As the functional unit is 1 ton dry matter, the extra need for transport per functional unit will not be that high. Another aspect is that by using the EURO 5 standard for transport, the energy consumption per ton-kilometer is relatively low. Combined with the functional unit this is a possible reason for the low difference. When discussing transport, focus should also be on the possibility of return transport by the same vehicle. The Bioresidual will be a liquid fraction that is possible to transport by the same vehicle as the liquid manure. This makes it possible to assume that total transport, including substrates to "The Magic Factory" and return of Bioresidual, will be the lowest by usage of wet manure in the biogas production.

The difference in human toxicity impact between the two scenarios also is quite low. It is though a small difference between the two when considering the share from the different processes. In Scenario 3 the share from Pretreatment and Digestion is slightly higher than in Scenario 2, while Scenario 2 has a slightly higher reduction caused by Bioresidual, representing substitution of artificial fertilizer. These small differences just make Scenario 2 a bit better than Scenario 3.

For water depletion, there is a slightly higher difference between the two scenarios. Both has a net impact caused mainly by the process Biogas upgrade to biomethane followed by Pretreatment and Digestion. There is a slight difference in the share from Pretreatment and Digestion between the two scenarios. It is though surprising that the difference is not bigger, as Scenario 3 needs about 3.5 times more water added than Scenario 2, according to the MFA results. This surprising result could be a result of differences in the two models. The LCA model states a higher need for water added for Scenario 2 than the MFA model. Nevertheless, with the water demand from the LCA in mind, the difference in need between the two scenarios is significant to the degree that it should affect the water depletion more substantially. Another reason for the surprising results could be that the need for water added to the substrate accounts for a small part of the total water depletion in this process. It is however hard to determine the particular reason for the small difference, as the LCA model used has been developed by a fellow student. This makes it impossible to know the model, the equations, the assumptions and the aggregations well enough to determine the specific reason without going deeper into the model. This will be time consuming and outside the scope of this Thesis.

The main reason for the difference in water depletion between the two scenarios is due to a reduced share from the processes Pretreatment and Digestion, and Feedstock and Processing (AD), along with an increased reduction from Bioresidual.

The fossil depletion is negative for both scenarios and essentially equal. The tiny difference is thou a result of a slightly lower share from the process Fuel substitution for Scenario 2. This process does however stand as the main reason for the negative impact for both scenarios along with a share from Bioresidual, representing substitution of artificial fertilizer. The fossil depletion for both scenarios is mainly caused by the process Transport of organic waste. It is therefore surprising that the difference in this process between the two scenarios is not bigger, because of the higher need for transport in Scenario 2 due to the higher amount of manure necessary to fulfill the functional unit, as described above.

5.3.3 Environmental benefits of “The Magic Factory” compared to other biogas plants

Scenarios 4 and 5 have been applied to study if Greve Biogass AS has an environmental benefit compared to other biogas plants that do not treat such large amount of manure. Scenario 4 handles biogas production with co-digestion of food waste and manure, while Scenario 5 handles biogas production by utilization of only food waste.

Both scenarios have a reduction in climate change impact, but there is a big difference in the amount of reduction. Scenario 4 has a much lower climate change impact than Scenario 5. The main reason for the difference is the inclusion of manure in the biogas production; this makes the climate change impact from the process Manure storage and application non-existing. This process has however a great share of the impact from Scenario 5. The inclusion of manure in the biogas production also results in a higher reduction, caused by the processes Fuel substitution and Bioresidual for Scenario 4. This is, as described above, a result of the increased output following when a bigger part of the functional unit is utilized in the biogas production. Again, we see that for climate change impact, there is a benefit of utilizing manure for biogas production.

For human toxicity impact there is a small difference between the two scenarios and the inclusion of manure in biogas production. The difference is in favor of Scenario 4. This is a result of the lower share of impact from the process with the highest share Post treatment Bioresidual, and the higher reduction caused by the process Bioresidual compared to Scenario 5.

Water depletion has a slight difference between the scenarios, and Scenario 4 has the lower. This is due to the lower share from the process Pretreatment and Digestion and it is as assumed, as Scenario 4 has an input of wet manure. The wet manure will make the need for addition of water lower than for Scenario 5, it is like already described, surprising that the difference is not bigger. It is also a smaller share in the impact caused by Feedstock and Processing (AD) for Scenario 4 compared to Scenario 5. However, the water depletion from Transport of organic waste and Biogas upgrade to biomethane is biggest for Scenario 4. The main difference in the total water depletion is therefore associated with the reduction in water depletion where the share is due to the process Bioresidual, representing substitution of artificial fertilizer and are biggest for Scenario 4.

Both scenarios have a net reduction in fossil depletion. The reduction is biggest for Scenario 4. This is a result of the increased output, as described earlier, resulting in a higher amount for Fuel substitution and Bioresidual. It is surprising that the difference in Transport of organic waste is not bigger. Since Scenario 4 demands a transport of manure to the plant, Scenario 5 does not demand this as the manure is spread directly. This could be because of the short transport distance for manure and the low energy demand by transport according to the EURO 5 standard.

5.4 Sensitivity analysis

The sensitivity analysis was used to study the impacts in adjustment of the uncertain parameters used in the MFA and LCA models. The results of the sensitivity analysis will be further discussed in this chapter.

5.4.1 Outputs and requirements

The different outputs from “The Magic Factory” changes with three of the performed sensitivities: decreased dry matter content of solid manure, exclusion of reject from solid- and liquid manure and increased degradability of all substrates.

The reason for the difference in output of Biofuel and CO_2 by a changed dry matter content of solid manure is the share of dry matter from the different substrates. As the total amount of each substrate is set according to the scenario descriptions, the share of dry matter from solid manure will decrease with a decreased dry matter content, and then the share of dry matter from the other substrates will increase. 1 ton dry matter when studied for anaerobic digestion, that ton (based on the share of dry matter) will contain more solid organic waste than in the Baseline. As solid organic waste has a higher output of methane per ton volatile solids than manure, the output of methane and CO_2 will increase. However, for the total annually amount, the maximum load of the wet weight for the different substrates are set. As a result, the total amount of dry matter will decrease with a decrease in dry matter content of one of the substrates. As a result of a decrease in total dry matter, there will be a decrease in total output. This will be the reversed when the reject from manure is excluded, since the total amount of dry matter from manure will increase. The biggest impact is seen in Scenario 3 due to the handling of the largest amount of solid manure in this scenario. A change in the total amount of dry matter into the anaerobic digestion from solid manure therefore will have the most substantial effect for this scenario. The higher the share of dry matter from solid manure, the higher the change in outputs by a shift in these two parameters will be.

Followed by the reduction in dry matter content of solid manure there is a reduction in output of Bioresidual per functional unit. This is due to the higher degradation of the digested substrate. With an increased share of solid organic waste, there will be an increase in volatile solids. The degradability is based on the volatile solids and so more substrate will be degraded and less left as Bioresidual. On yearly basis, the amount of substrate through the biogas plant will decrease and by this decrease the amount of Bioresidual. This will be reverse when the reject from manure is excluded. When there is no reject, the total amount of dry matter from manure will increase since manure has a lower volatile solids content than solid organic waste.

The reduced need for additional water when the dry matter of solid manure is decreased is because more water will follow with the substrate. This extra amount of water therefore will be available to substitute additional process water.

An increased need for additional water as a result of the reduced reject is due to the increased amount of organic matter available for anaerobic digestion. As the reject is assumed as part of the dry matter, the amount of dry matter will decrease after the reject is sorted out. However, when this part does not exist, the amount of organic dry matter per unit is increased although the same amount of water is present. To obtain the desired dry matter content of the mixed substrate before it enters into the biogas production, it will be an increased demand for addition of water. The reason for Scenario 2 to have the maximum increase in water demand is that it is the scenario containing the most liquid manure. Liquid manure basically is the source of water in the substrate mixture; when it is then an increased dry matter from this fraction, there will in total be less water available per ton dry matter.

The changes in outputs of biofuel and CO_2, caused by a change in degradability, are almost similar on the basis of the functional unit and on an annual basis. The reason for this is that the inputs to the plant stays constant regardless of an adjustment of the parameter. The share of dry matter from the different substrates therefore is similar for both units. There is a big change in outputs as a result of this adjustment. This indicates that this parameter is of importance for "The Magic Factory"; it can therefore be important to include the result from this sensitivity in further work as this is a degradability rate based on a value Greve Biogass AS aims for. This increase of the degradability also increases the output to the point that the assumed outputs by Greve Biogass are almost fully achieved. The outputs from Scenario 2 by this increase will be of about 6.2 million m^3 biofuel and 7 000 ton CO_2 annually.

The substantial decrease in output of Bioresidual on a dry matter basis when the degradability is increased is because more of the dry matter is converted to biogas. The small change in wet weight of Bioresidual shows that the water amount in the substrate in the biogas production is the same; hence the amount of water is the same. The reduction therefore purely is a result of the decreased amount of dry matter in the outgoing Bioresidual.

The difference in need for water added because of an increased degradability is surprising. As the input of substrates or composition of the substrate is not affected by the degradability, it would thus be likely that there would be no change in water added. The change seems however to be a result of the functional unit, as there is no change per year for other than Scenario 3.

All parameters adjusted in the sensitivity analysis affects the energy yield. A change in dry matter for solid manure results in the most substantial impact on Scenario 3. The reason for this is that Scenario 3 has the highest input of solid manure. A decrease in dry matter on an annual basis implies a reduced energy level for the feedstock; this reduction is consequently bigger than the reduction in annual energy out of "The Magic Factory" and then we see an increased energy yield. The small change in energy yield because of this parameter tells us that the uncertainty connected to the dry matter of the solid manure will not affect the energy yield of the plant significantly.

The exclusion of reject hardly has an effect on the energy yield from the plant. It is of almost no significance that Greve Biogass AS has left this parameter out of their estimates. The biggest impact for Scenarios 1 and 3 is seen for the energy yield. The reason is that manure constitutes the major share of dry matter for Scenario 1, when Scenario 3 has the biggest share of solid manure, which again in the Baseline is assumed to have a higher reject than liquid manure.

The small impact on energy yield, due to a large increase of heat demand from biogas production, is because of the low share that heat demand has of the total energy demand. The energy demand by heat is just a part of the total process energy; at the same time as process energy itself is quite low compared to energy in feedstock and energy demand by transport.

The reason for collection distance to have a higher impact on energy yield than transport distance is higher diesel consumption demand for collection. This is likely because the vehicle will run with varying speed and have many stops and starts. Nevertheless, the high impact on energy yield by transport distance for Scenario 5 is due to the high amount of solid organic waste. In this scenario, the whole share of the substrate is solid organic waste and it is assumed that all of it has a doubled transport distance; this will double the transport for all the substrates.

The small decrease in energy yield by an increased higher heating value for pig manure is due to the increased energy in feedstock while there is no change in biofuel produced from "The Magic Factory". The reason for this change not to be bigger is that pig manure only represents a share of the total substrate. However, the bigger this share is, the bigger the impact. This is why we see the biggest decrease for Scenario 1.

The big impact caused by the increased degradability is because bigger amount of biofuel is produced, with the same input of energy. This shows that the degradability is important to the result and it will consequently be important to facilitate the methane bacteria to degrade the substrate as much as possible. This could be achieved by adding substances, as Greve Biogas AS intends to do by adding ferric chloride, or by maintaining a steady composition of substrates that the bacteria likes.

5.4.2 Environmental impacts

For all sensitivities there is a small change in environmental impacts when compared to the Baseline. The two sensitivities concerning increased driving distances cause an all over negative change. Increased transport of solid organic waste (TSOWt) will have a negative impact compared to the Baseline for all four impact categories, while an increased collection distance (TSOEc) will have so for all four, except human toxicity. The reason for the negative change due to these sensitivities is the emissions caused by the use of fossil fuel by vehicles, and that an increased use of fossil fuels to get the substrates to “The Magic Factory” will make the profit by fuel substitution less.

The sensitivities carried out on dry matter content of solid manure (DMSL), heat demand in biogas production (HB) and higher heating value pig manure (HHVP) has a positive change. The differences compared to the Baseline are small, but positive for all impact categories except for human toxicity for which there is no difference. The small variations from the Baseline for these sensitivities demonstrate that the consequence of the uncertainty of these parameters is rater low. This is positive and confirms that the results from this Thesis are plausible.

One sensitivity stands out with a much bigger difference from the Baseline than the other sensitivities, the one sensitivity studying the two parameters: degradability of solid organic waste and manure (DSOW and DM). For all the four impact categories, the environmental impacts vary considerably from the Baseline. There is a positive change for climate change on 84 %. This is due to the increased amount of biofuel produced, because of the increased degradability. An increased amount of biofuel means that more fossil fuel can be substituted. This also results in a reduced amount of Bioresidual, which again needs less treatment. The decreased human toxicity impact is 42 %; this decrease also is a result of the shift in outputs to a higher amount of biofuel for substitution and a lower amount of Bioresidual in need of treatment. However, for water depletion, the increased degradability works out negative; the depletion is increased with 25 %. An increased amount of biofuel means that a bigger amount of biogas is produced and the technology used for biogas upgrading has a demand for water. The bigger the amount required for the upgrading, the bigger the need for water. So, the need for water will increase for all processes that have a demand for water dependent on the amount of biogas or biofuel/biomethane, like Transportation of biofuel and Fuel substitution. The environmental impact of fossil depletion will improve 40 % with this increase in degradability. This is again a result of the increased amount of biofuel available for substitution.

The results of the LCA sensitivity indicate that out of the uncertain parameters, degradability is the one with the highest environmental impact. It will be of great importance to determine this as exact as possible, to be able to make well-founded decisions; and to continue assessing the right values.

5.5 Strength and weaknesses

All calculations are based on the assumption that 1 m^3 biogas substrate is similar to 1 ton. This would be correct if the substrate only consisted of water, but it is likely that the dry matter will somehow have a higher weight. The assumption is based on Møller et al. (2012). As this value is used for other projects, the uncertainty of the assumption should be acceptable for this Thesis.

As previously discussed, there are some uncertainties related to the calculations of output of methane content in the MFA model. The uncertainty exists because the parameters used to calculate the output of biofuel and CO_2 are based on different sources. The methane produced from the different waste fractions is calculated based on case specific data. The amount of biogas produced is calculated based on the methane produced and the methane contents for the different fractions collected in Carlsson and Uldal (2009). Further on, the output of methane is calculated based on the weighted average of methane content for the different waste fractions. This makes the output of methane a bit higher than by adding up the methane produced from the different fractions. This difference is very modest, constituting about 1 %. The difference is so small that it is deemed not to influence the results of this Thesis. The report of Carlsson and Uldal (2009) is commonly cited in other literature and should therefore be supposed to hold a high quality and be applicable.

There is, as described previously, a weakness in the MFA model related to the water demand. The problem is only an issue when the incoming waste fractions have a weighted average of dry matter content lower than 15 %. This is a relatively unrealistic scenario, as the plant will demand a quite high amount of food waste (with a DM content of about 33 %) to ensure a biogas substrate that the methane bacteria likes, for reaching a sufficient biogas production. This model weakness is considered neither to make particular challenges nor affect the results largely.

The MFA model builds on the assumption that the biofuel consists of 100 % methane, which is more likely to be 97 %. The results can therefore be assumed to be of by about 3 %, making the output of biofuel about 3 % too low and the output of CO_2 about 3 % too high. This weakness results in a small moderation in the outputs of the preferred fractions. The deviation is deemed within what is acceptable for this Thesis.

Most of the parameters are case specific and are set close to the values presented in the literature. However, some of the parameters varies from the literature to such a degree that they could represent a model weakness if they do not turn out as expected. There is already carried out a sensitivity analysis for the parameter with the deviation that constitutes the highest impact, degradability. The parameter used in the model is the value collected from the literature, but as seen in the sensitivity this is a parameter with a high influence and therefore should be kept in mind and adjusted for when utilizing the model. A case specific parameter applied, but which varies substantially from the literature is the need for energy for heating of the substrate for the biogas production. The case specific data is based on the assumption that there will be no need for heating during the summer, which leads to a relatively low annual energy demand. For case specific energy demand to meet the specific heat capacity of water, the annual average temperature in the waste fractions need to be o 20.26 °C. This is rater unlikely to happen. It is demonstrated by use of the sensitivity analysis that this parameter has a low influence on the results and the weakness is therefore deemed to be acceptable for this Thesis. Greve Biogass AS should be made aware that they might have a bigger need for energy than anticipated.

Among other case specific parameters, the methane yield per ton volatile solids according to the literature vary for solid organic waste and solid manure. Greve Biogass AS assumes 550 m^3 CH^4 / ton VS of solid organic waste (Sørby 2015b), while Carlsson and Uldal (2009) estimate 461 m^3 CH^4 / ton VS. The latter is based on organic municipal waste, while the value from Greve Biogass in all likelihood is based on a mixture with solid organic industrial waste. A big difference is also demonstrated for the value for solid manure from cattle where Greve Biogass AS build upon 150 m^3 CH^4 / ton VS (Sørby 2015b), while Carlsson and Uldal (2009) state 213 m^3 CH^4 / ton VS. The difference in the numbers is however believed to be for the better, as the difference apparently is adapted to the specific waste fractions to be produced by "The Magic Factory". The difference between Greve Biogas AS and the literature therefore must be seen to strengthen the results reached by use of the model.

5.6 Further work

The outcome of the report could be used by Greve Biogass to make updated decisions on effective waste composition to estimate the effect of adjustments and as a basis for justifying their project plan. When "The Magic Factory" is fully up-and-running, it might be fruitful to study the effect of co-digestion. This could be performed by comparing the outputs to the theoretical results reached in this Thesis, which does not build on a co-benefit. The values used in this Thesis should also be discussed and adjusted in the light of the results of the digestion test, which is currently carried out on the specific waste fractions.

The MFA model should be further developed and completed with inclusion of liquid industrial waste as a part of the biogas substrate for all the flows. The composition of the liquid industrial waste needs to be established. To make the environmental analysis more accurate, it would also be productive to determine the composition of the industrial share of the solid organic waste.

It will further be of interest to study the flows of phosphor and nitrogen inside the system and to determine the availability of these substances for plants. It would also be of great use to have determined the difference in plant availability in the Bioresidual compared to manure spread directly as fertilizer the traditional way. Moreover, estimates should be made and confirmed of how much artificial fertilizer could be saved by establishing "The Magic Factory". When the Bioresidual has been studied, a sensitivity analysis should also be carried out investigating the environmental effect of the heavy metal concentration in the Bioresidual, to establish to which extent the LCA results would be affected by a Bioresidual classified in category 1 instead of category 0.

It would also be productive to further study the transport distances, since the sensitivity analysis carried out on transport, resulted in that transport to some extent has an environmental impact. Likewise, a sensitivity analysis of the transport of manure to determine the environmental benefit by including manure is justified only when the plant and the farms are located relatively close to each other.

This Thesis is a part of the BIOTEMARE research project at NTNU, in collaboration between Norway and Poland to devise technologies for energy and material recovery of organic waste. It is desirable for this Thesis to point out issues and possibilities of importance for the Project and to contribute additional information.

6 Conclusion

The objective of this Thesis was set to carry out a material flow analysis and a life cycle assessment studying the specific choices made regarding the operation of "The Magic Factory". It was of interest to examine results from environmental systems analysis regarding resource efficiency and potential life cycle environmental impacts of the plant, and in particular to determine the critical variables affecting the results and in what respect, such as the effect of variations in substrate mixture and transportation distances.

The analysis shows that the outputs and resource efficiency are dependent on substrate mixture and transportation distances. A slightly higher output and energy yield by a plant processing solid manure instead of liquid manure and by a plant processing only food waste instead of a substrate mixture containing manure, is demonstrated. This is when a co-digestion benefit is not accounted for.

The specific choices made regarding the operation of "The Magic Factory" is studied from an environmental perspective. The analysis concludes that the environmental benefit of establishing "The Magic Factory" is positive as seen from all four studied impact categories. The environmental benefit of establishing "The Magic Factory" is significant and the decision on establishment well-reasoned. The principal positive result is due to reduced impacts by including manure in the biogas production and cease spreading it directly the traditional way, the reduced transport distance of food waste and the increased amount of biofuel available for substitution of fossil fuel.

The effect of the choice of substituting clean water with liquid manure varies with the impact categories. The substitution is preferable when considering human toxicity and water depletion, while usage of solid manure would be preferable considering climate change impact and fossil depletion. However, the analysis does not include the possibility for return of Bioresidual on the same vehicle which transports liquid manure. It is not possible to ascertain that one impact category is of more or less importance than other categories, unless establishing what environmental aspect that is of the highest significance. Nevertheless, as the water depletion is the only impact category that stands out with a significant difference between the two options, the substitution of clean water with liquid manure is assumed as the preferable choice.

Most biogas plants in Norway do not include such large share of manure as planned for "The Magic Factory". The analysis demonstrates that the choice of processing such a large amount of manure is environmentally beneficial. The inclusion of manure is positive for all four impact categories, mainly due to the reduced emissions from manure spread directly as fertilizer, and the increased possibility for substitution of fossil fuel and artificial fertilizer that follows when a higher share of potential substrates are utilized.

Based on the sensitivity analysis, it is possible to conclude that of the uncertain parameters, degradability is the one that has the highest impact on both outputs and efficiency. The highest impact on demand for additional water is for dry matter content of solid manure. Transport distances, especially collection distance will also have a significant impact on the efficiency.

Degradability is also one of the uncertain parameters implying the highest environmental impact. An increase in the range of the one studied in the sensitivity analysis, will have a significant effect on the environmental impacts. This shows that it is of importance to establish the value of this parameter as precise as possible. A change in transport distances will also have effects on the environmental impacts to a level worth noticing. It should therefore be taken into account when considering what waste fractions to be processed.

The conclusion of this Thesis is that the environmental impact will benefit substantially by the establishment of "The Magic Factory", by substituting clean water with liquid manure and by including a significant amount of manure in the biogas production. The establishment of the plant and the choices made also are preferable as the goal set by Klimakur 2020 of using 30 % of the manure in the region for biogas production, is achieved. The choices to substitute clean water with liquid manure and to include manure in the biogas production do however seem to have a negative effect on the outputs, this is thus when there is not accounted for a co-digestion benefit.

Greve Biogass AS is recommended to use the results of this Thesis as a support of the choices already made. The company could also use the Thesis as an information input to the Government and other interested parties about "The Magic Factory", the possible substrates and the environmental impacts of the plant. The results could be used as a tool and basis for decision making for other biogas plants. The BIOTENMARE project could use the results as a basis for a potential technology for recovering energy and materials in organic waste and as a background for demonstrating how the technological choices have influenced a specific case.

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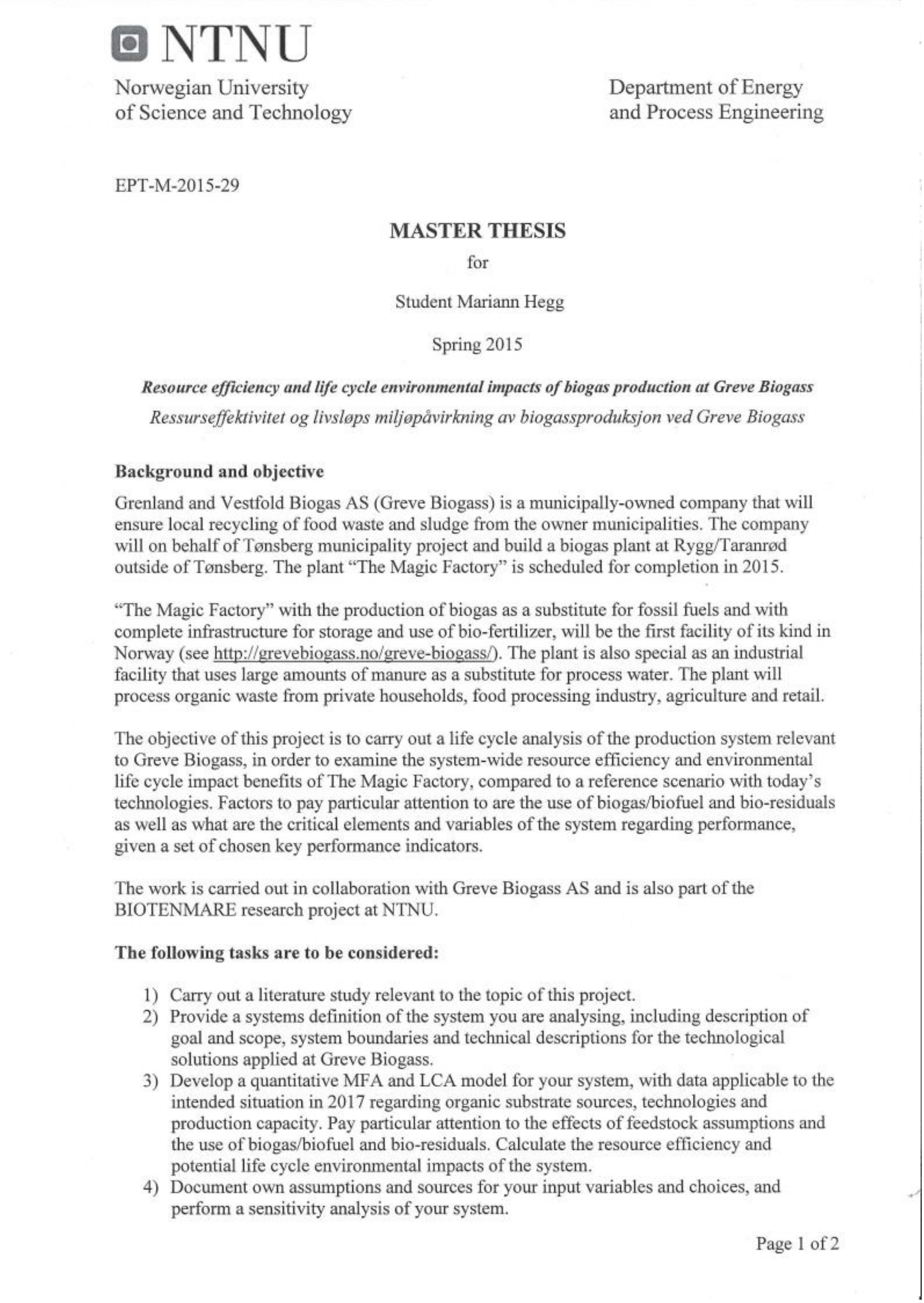
Appendix 1 – Thesis assignment text



NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2015-29

MASTER THESIS

for

Student Mariann Hegg

Spring 2015

Resource efficiency and life cycle environmental impacts of biogas production at Greve Biogass

Ressurseffektivitet og livsløps miljøpåvirkning av biogassproduksjon ved Greve Biogass

Background and objective

Grenland and Vestfold Biogas AS (Greve Biogass) is a municipally-owned company that will ensure local recycling of food waste and sludge from the owner municipalities. The company will on behalf of Tønsberg municipality project and build a biogas plant at Rygg/Taranrød outside of Tønsberg. The plant "The Magic Factory" is scheduled for completion in 2015.

"The Magic Factory" with the production of biogas as a substitute for fossil fuels and with complete infrastructure for storage and use of bio-fertilizer, will be the first facility of its kind in Norway (see http://grevebiogass.no/greve-biogass/). The plant is also special as an industrial facility that uses large amounts of manure as a substitute for process water. The plant will process organic waste from private households, food processing industry, agriculture and retail.

The objective of this project is to carry out a life cycle analysis of the production system relevant to Greve Biogass, in order to examine the system-wide resource efficiency and environmental life cycle impact benefits of The Magic Factory, compared to a reference scenario with today's technologies. Factors to pay particular attention to are the use of biogas/biofuel and bio-residuals as well as what are the critical elements and variables of the system regarding performance, given a set of chosen key performance indicators.

The work is carried out in collaboration with Greve Biogass AS 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 the technological solutions applied at Greve Biogass.
3) Develop a quantitative MFA and LCA model for your system, with data applicable to the intended situation in 2017 regarding organic substrate sources, technologies and production capacity. Pay particular attention to the effects of feedstock assumptions and the use of biogas/biofuel and bio-residuals. 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.

Page 1 of 2

5) Discuss the overall findings of your work, agreement with literature and comparison with other biogas plants in Norway, 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, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed 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 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 2015

Olav Boll

Olav Bolland
Department Head

H. Brattebø

Helge Brattebø
Academic Supervisor

Contact person at Greve Biogass AS: Assistant Manager Ivar Sørby.

Appendix 2 – Biogas yields as results of co-digestion of food waste and manure

The different biogas yields, as results of co-digestion of food waste and manure from the studies disused in chapter 2.5.2 Co-digestion of food waste and manure, are presented in Table I.

Table I: Biogas yields and methane contents derived from different mixtures of manure and organic waste from previous studies. The numbers in green indicates the highest number in the particular study.

VS Ratio food/manure		**GPR**		**Biogas yield**		**Methane yield**		**Methane content**	**Days**	**Reference**
food	manure									
	100 %					78	m3/ton VS	72 %	73	Macias-Corral et al. 2008 [3]
[1] 91 %	9 %					194	m3/ton VS	72 %	151	Macias-Corral et al. 2008 [3]
[1] 100 %						31	m3/ton VS	73 %	113	Macias-Corral et al. 2008 [3]
	100 %			331	L/kgVS	218	L/kgVS	66 %	20	El-Mashad & Zhang 2010
32 %	68 %			411	L/kgVS	251	L/kgVS	61 %	20	El-Mashad & Zhang 2010
48 %	52 %			504	L/kgVS	293	L/kgVS	58 %	20	El-Mashad & Zhang 2010
100 %				520	L/kgVS	256	L/kgVS	49 %	20	El-Mashad & Zhang 2010
	100 %	[4] 0.79	L/L·day					59 %	13	Li et al. 2009
50 %	50 %	1.48	L/L·day					62 %	13	Li et al. 2009
75 %	25 %	2.56	L/L·day					62 %	13	Li et al. 2009
85 %	15 %	3.97	L/L·day					63 %	13	Li et al. 2009
	[7] 100 %			804	ml/day	210	m3/ton VS	56 %	30	Alvarez & Lidén 2007
[10] 34 %	67 %			1 211	ml/day	320	m3/ton VS	53 %	30	Alvarez & Lidén 2007
[8] 50 %	50 %			1 467	ml/day	320	m3/ton VS	50 %	30	Alvarez & Lidén 2007
[9] 66 %	33 %			1 359	ml/day	320	m3/ton VS	56 %	30	Alvarez & Lidén 2007
[11] 84 %	17 %			1 602	ml/day	350	m3/ton VS	51 %	30	Alvarez & Lidén 2007
[5] 100 %				297	ml/day	60	m3/ton VS	45 %	30	Alvarez & Lidén 2007
[6] 100 %				316	ml/day	2	m3/ton VS	2 %	30	Alvarez & Lidén 2007
100 %						546	Nm^3/tonVS [2]	57 %	20	Huing & Solli 2012

[1] Food waste is not only food waste but a mixture of OFMSW
OFMSW = organic fraction of municipal solid waste (62% paper, 23 % food waste and 15 % yard clippings)

[2] VS content of waste 28.1 %

[3] Article unclear, different numbers given in text and table, looks like a mix up in table

[4] Calculated based on the values in the article

[5] Digestion of only solid cattle and swine slaughterhouse waste (57.1 % rumen, 33.5 % blood and 9.4 % pig's paunch waste)

[6] Digestion of only fruit and vegetable waste

[7] Solid cattle and swine manure (71 % cattle manure and 29 % swine manure)

[8] 50 % Solid cattle and swine manure (71 % cattle manure and 29 % swine manure) and 50 % fruit and vegetable waste

[9] 33 % solid cattle and swine slaughterhouse waste (57.1 % rumen, 33.5 % blood and 9.4 % pig's paunch waste), 33 % fruit and vegetable waste and 33 % solid cattle and swine manure (71 % cattle manure and 29 % swine manure)

[10] 17 % solid cattle and swine slaughterhouse waste (57.1 % rumen, 33.5 % blood and 9.4 % pig's paunch waste), 17 % fruit and vegetable waste and 67 % solid cattle and swine manure (71 % cattle manure and 29 % swine manure)

[11] 17 % solid cattle and swine slaughterhouse waste (57.1 % rumen, 33.5 % blood and 9.4 % pig's paunch waste), 67 % fruit and vegetable waste and 17 % solid cattle and swine manure (71 % cattle manure and 29 % swine manure)

Appendix 3 – Work drawings from Greve Biogass AS

3A - Pretreatment

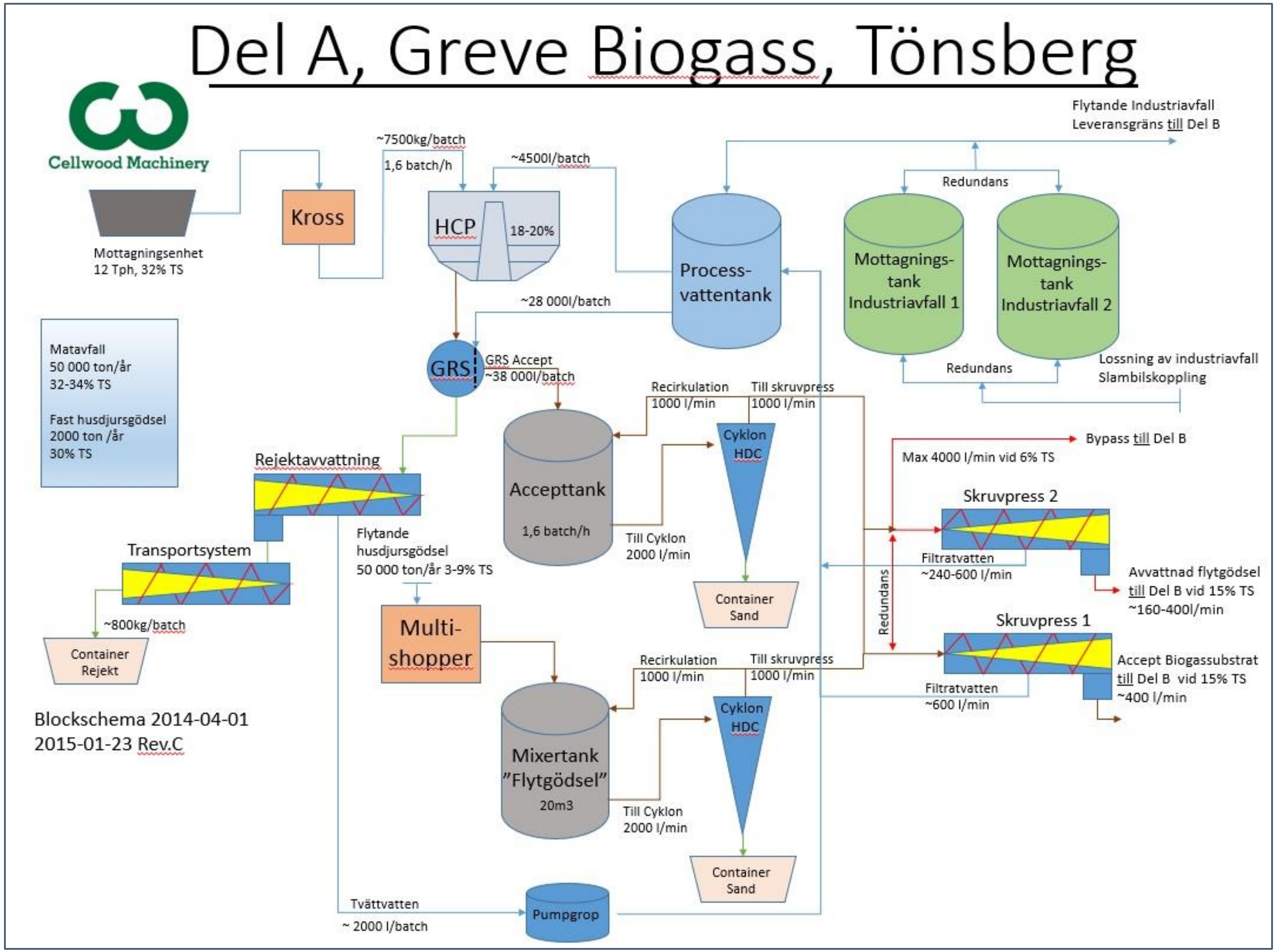


Figure I: Block diagram showing the pretreatment at "The Magic Factory" with assumed values (Sørby 2015a). *(HCP – High Consistency Pulper, GRS – Grubbens Reject Separator, HCD – High Density Cleaner* (Cellwood Machinery 2014)

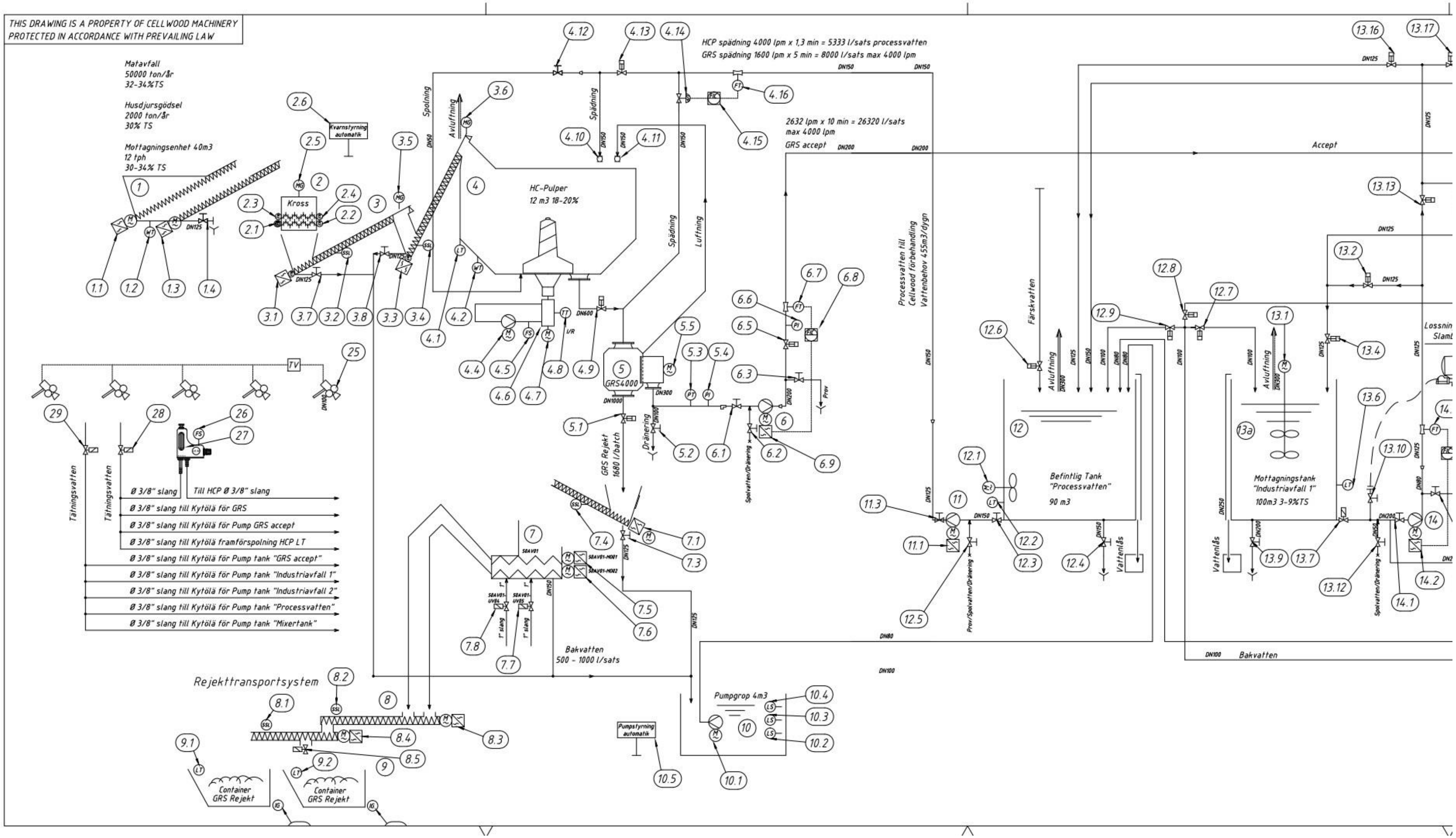


Figure II_a: Technical Process Flow Sheet describing the pretreatment at “The Magic Factory” (Sørby 2015a) *(The drawing is split into three for higher picture resolution)*

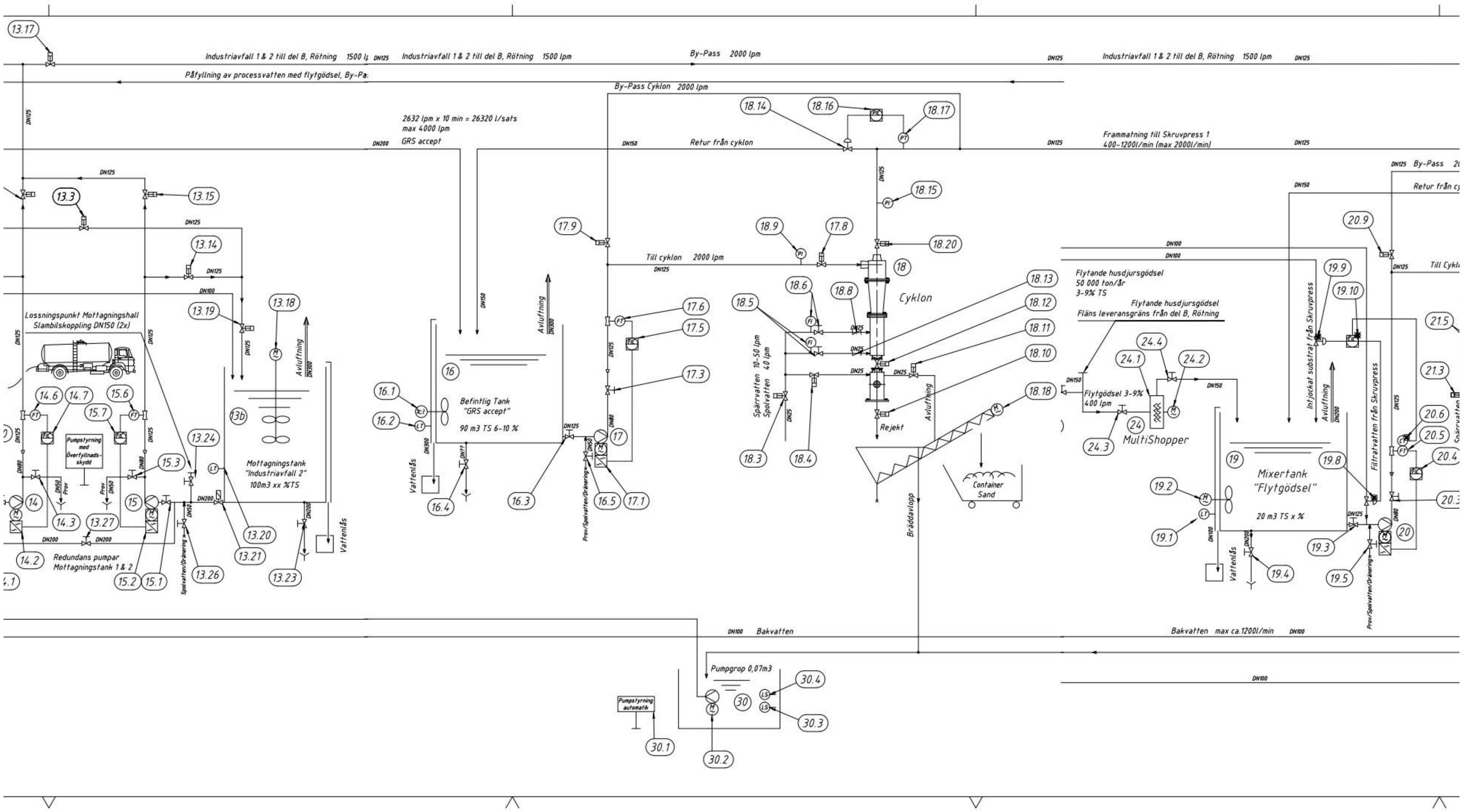


Figure II_b: Technical Process Flow Sheet describing the pretreatment at “The Magic Factory” (Sørby 2015a) (The drawing is split into three for higher picture resolution)

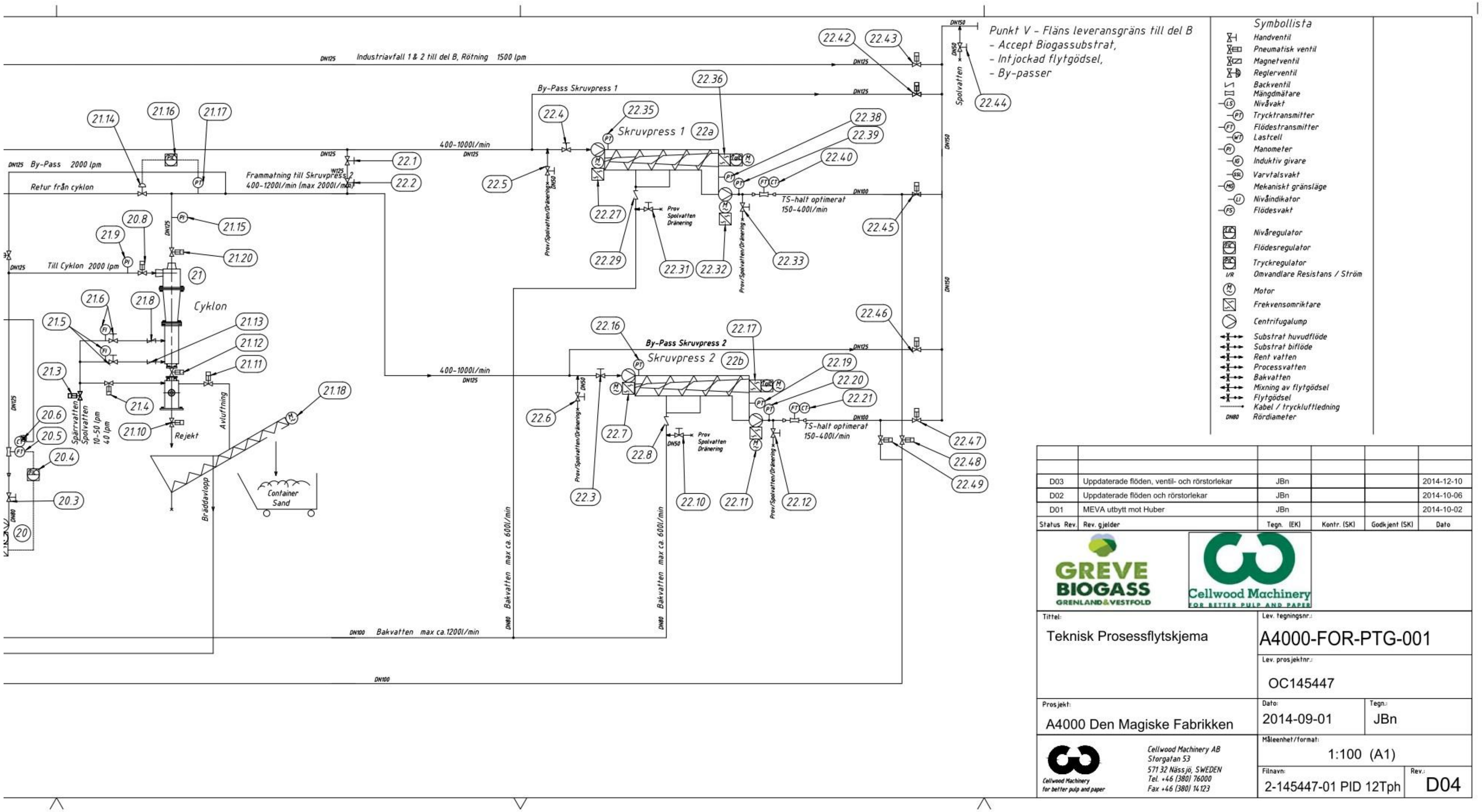


Figure II_c: Technical Process Flow Sheet describing the pretreatment at "The Magic Factory" (Sørby 2015a) (The drawing is split into three for higher picture resolution)

3B – Sanitation and Biogas Production

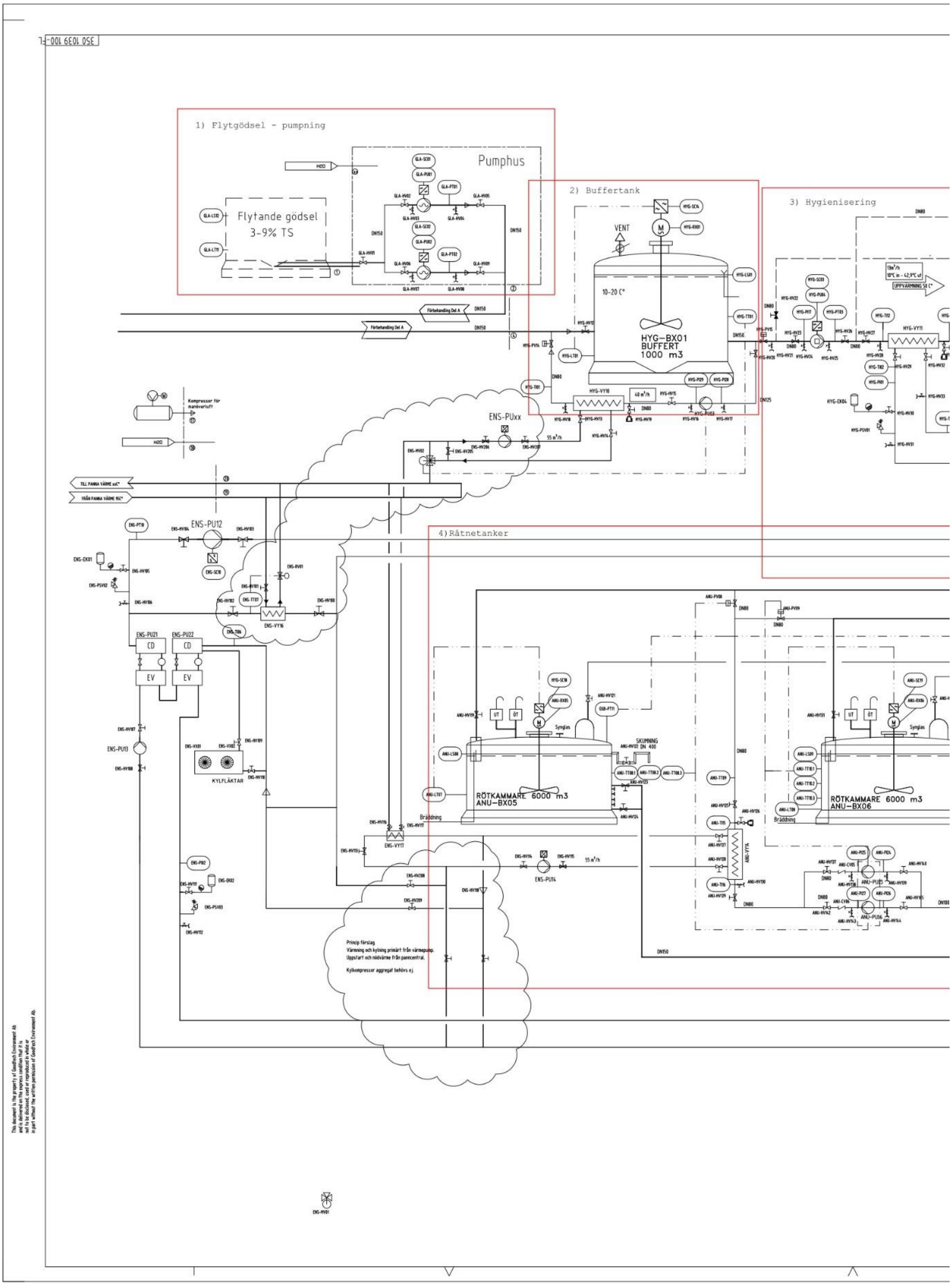


Figure III_a: Technical Process Flow Sheet describing the sanitation and biogas production at "The Magic Factory" (Sørby 2015a) (The drawing is split into two for higher picture resolution)

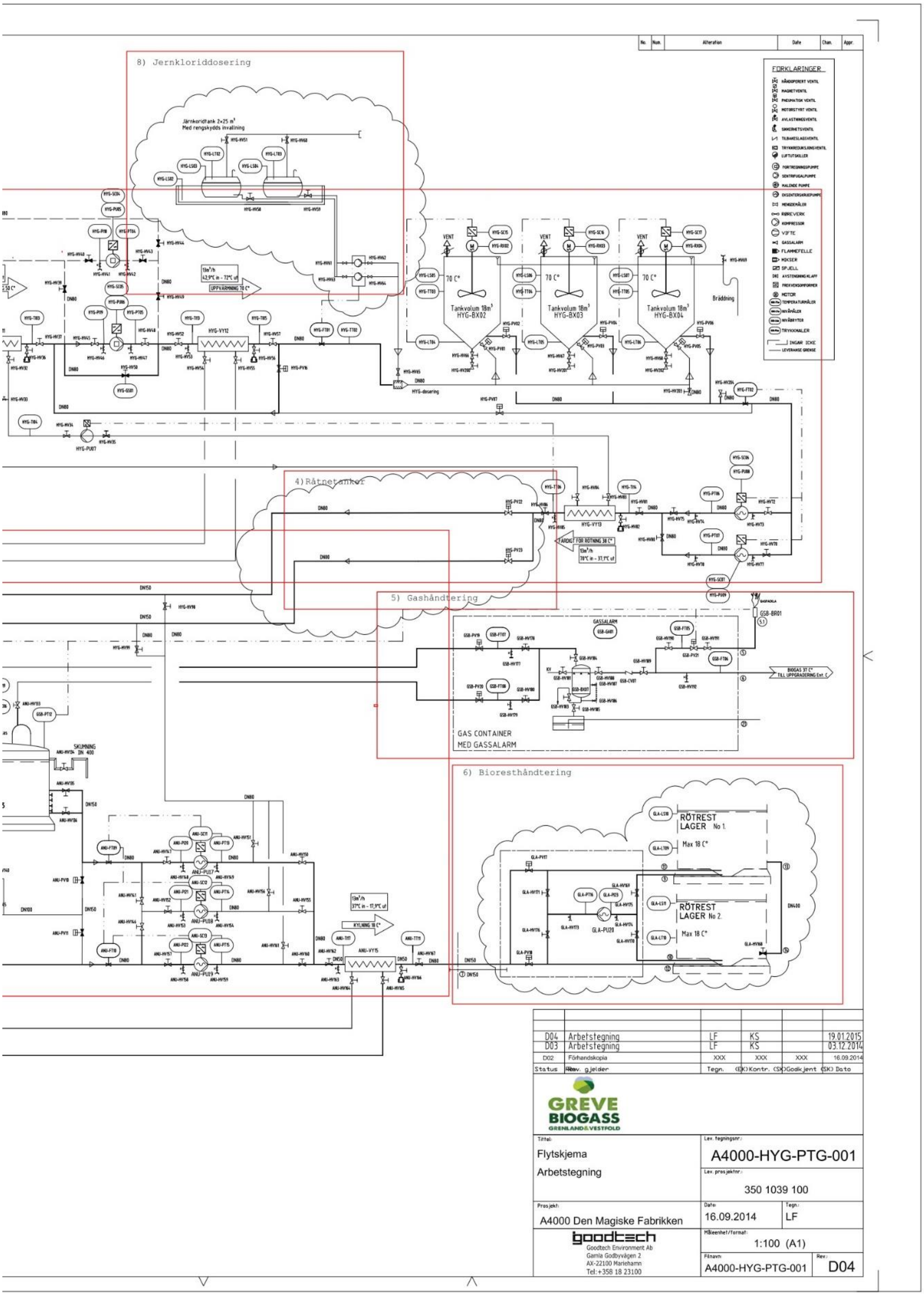


Figure III_b: Technical Process Flow Sheet describing the sanitation and biogas production at "The Magic Factory" (Sørby 2015a) (The drawing is split into two for higher picture resolution)

3C – Biogas Upgrading

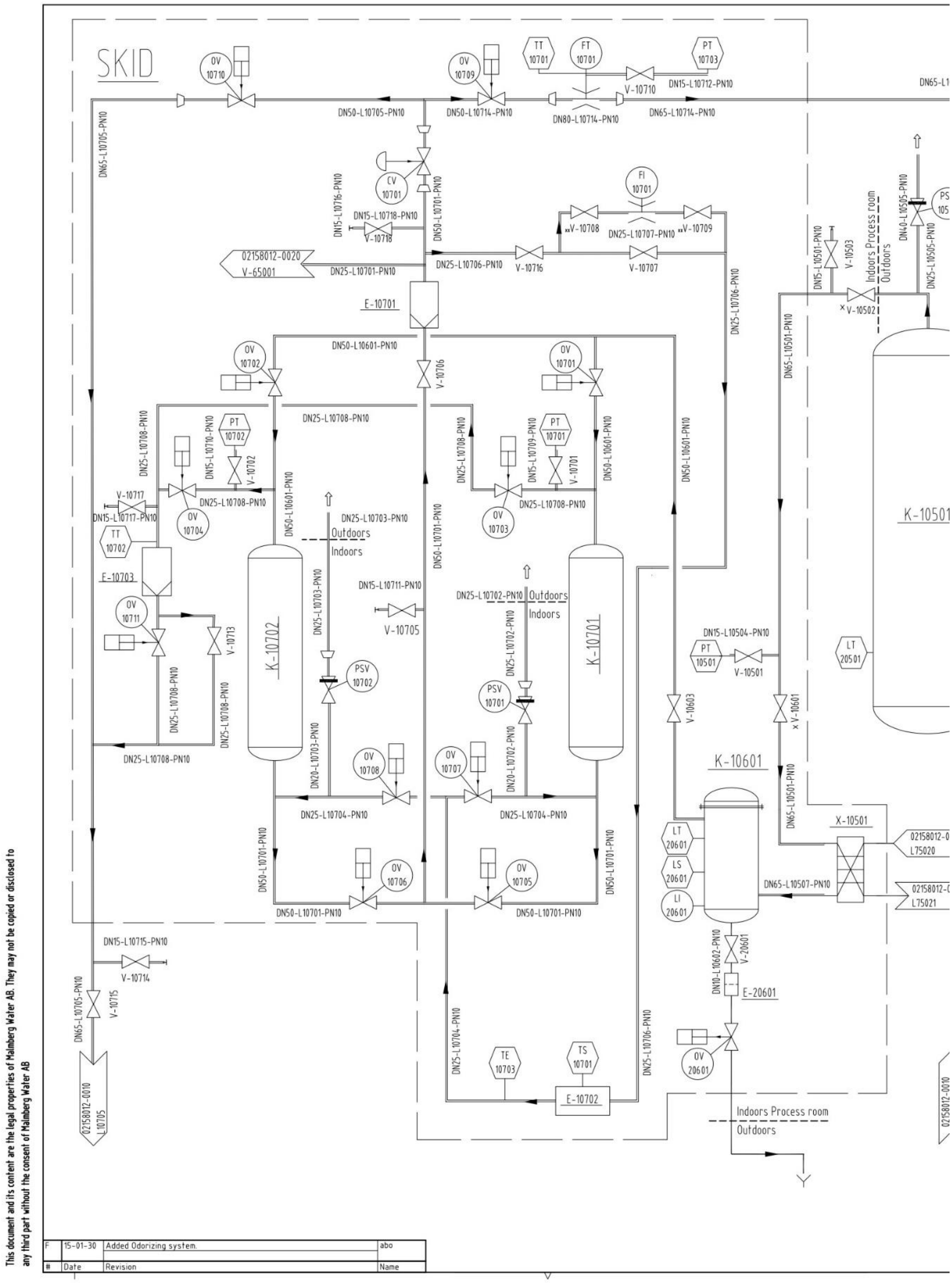


Figure IV_a: Technical Process Flow Sheet describing the biogas upgrading at "The Magic Factory" (Sørby 2015a) (The drawing is split into two for higher picture resolution)

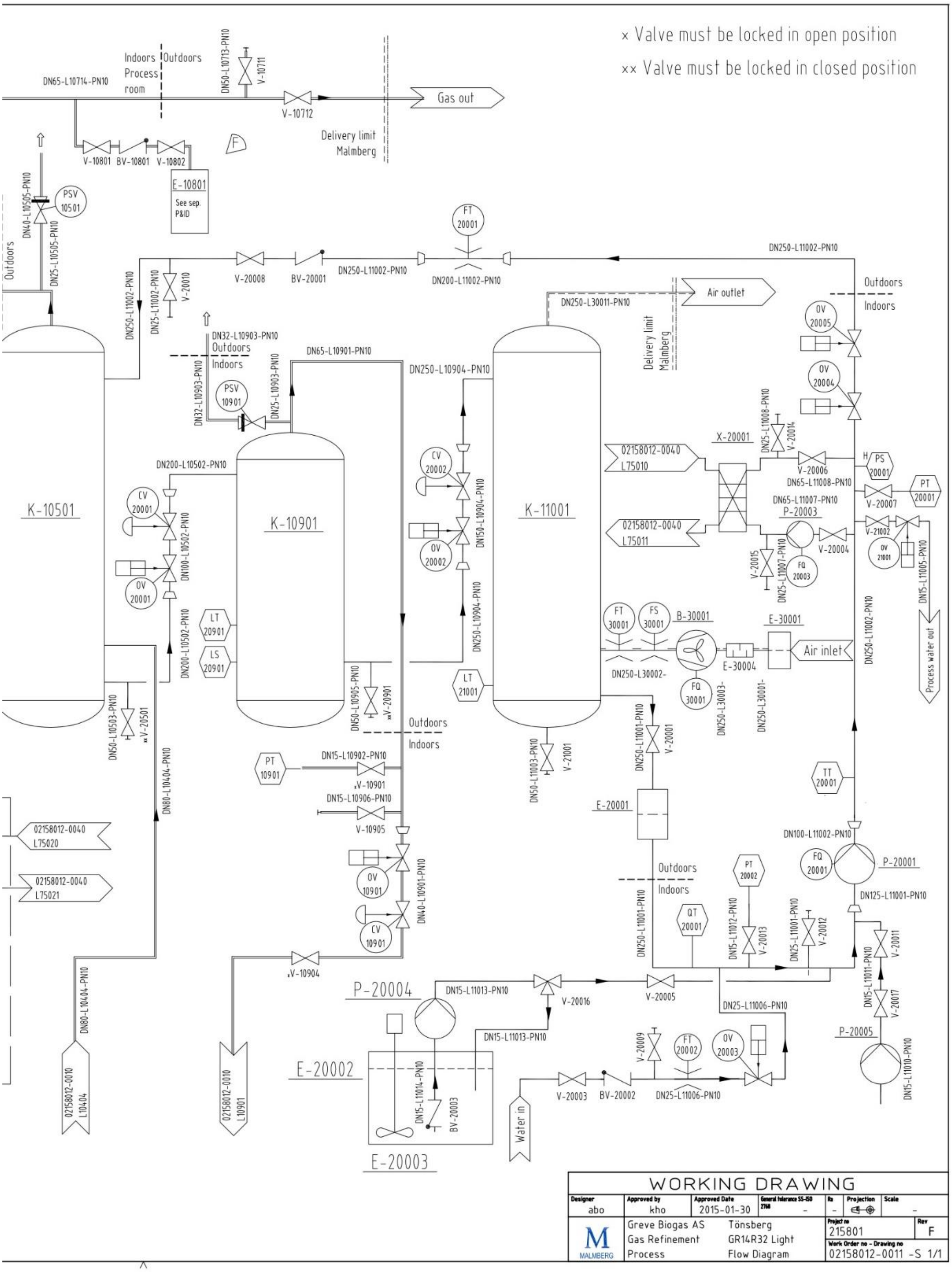
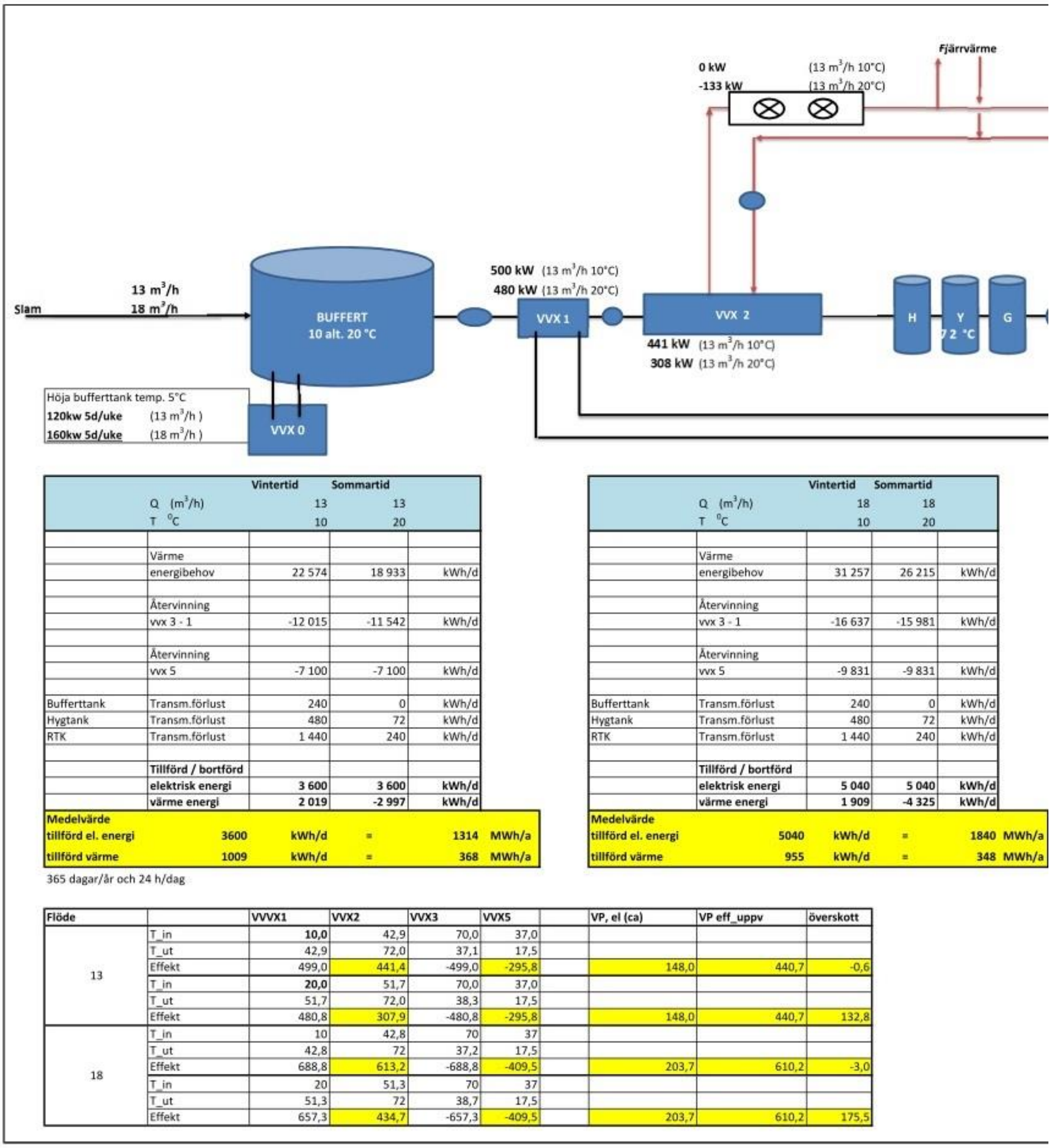


Figure IV_b: Technical Process Flow Sheet describing the biogas upgrading at "The Magic Factory" (Sørby 2015a) (The drawing is split into two for higher picture resolution)

Appendix 4 – Energy Balance section B



		Vintertid	Sommartid	
	Q (m³/h)	13	13	
	T °C	10	20	
	Värme			
	energibehov	22 574	18 933	kWh/d
	Återvinning			
	vvx 3 - 1	-12 015	-11 542	kWh/d
	Återvinning			
	vvx 5	-7 100	-7 100	kWh/d
Bufferttank	Transm.förlust	240	0	kWh/d
Hygtank	Transm.förlust	480	72	kWh/d
RTK	Transm.förlust	1 440	240	kWh/d
	Tillförd / bortförd			
	elektrisk energi	**3 600**	**3 600**	**kWh/d**
	värme energi	**2 019**	**-2 997**	**kWh/d**

Medelvärde					
tillförd el. energi	**3600**	**kWh/d**	**=**	**1314**	**MWh/a**
tillförd värme	**1009**	**kWh/d**	**=**	**368**	**MWh/a**

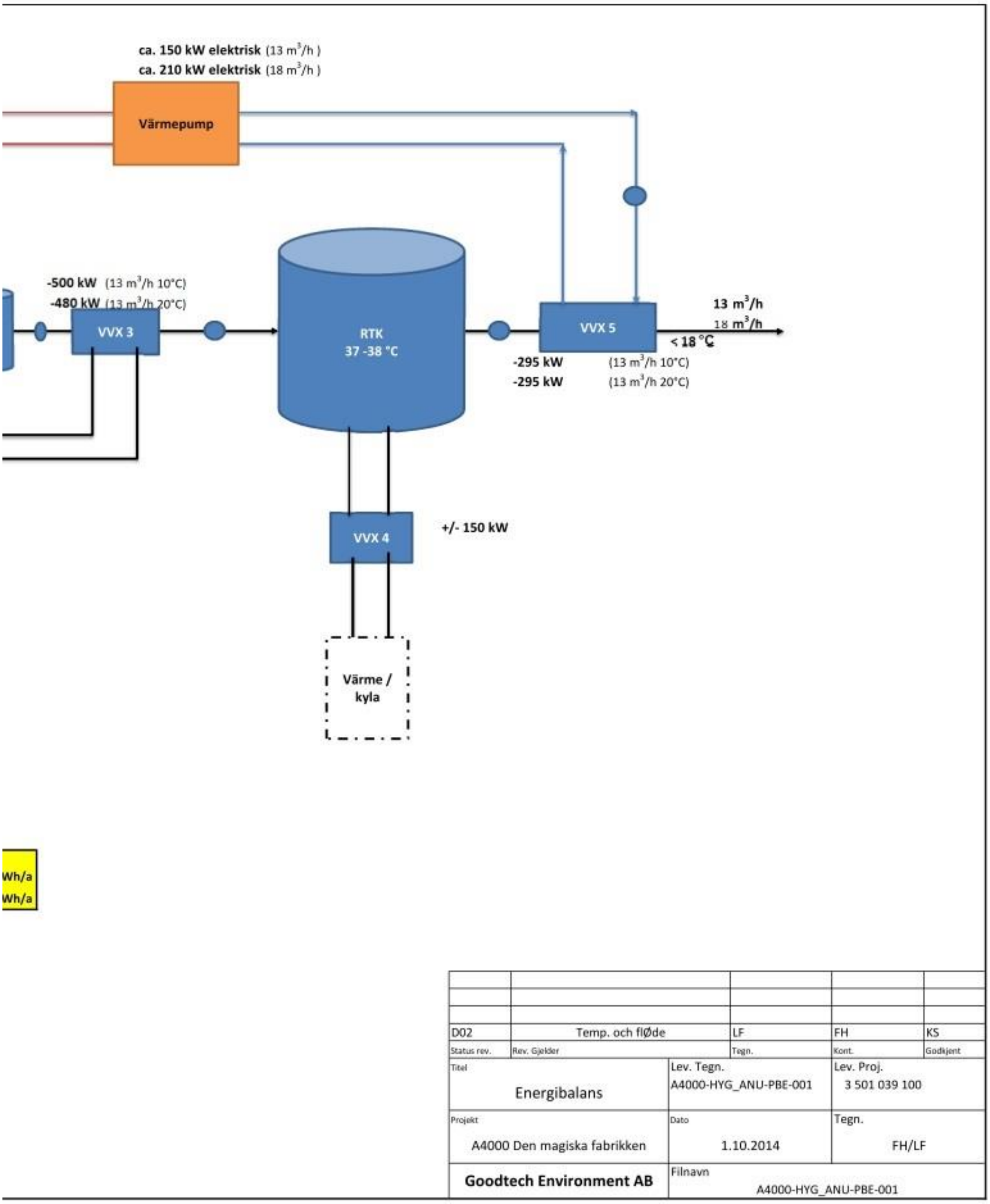
365 dagar/år och 24 h/dag

		Vintertid	Sommartid	
	Q (m³/h)	18	18	
	T °C	10	20	
	Värme			
	energibehov	31 257	26 215	kWh/d
	Återvinning			
	vvx 3 - 1	-16 637	-15 981	kWh/d
	Återvinning			
	vvx 5	-9 831	-9 831	kWh/d
Bufferttank	Transm.förlust	240	0	kWh/d
Hygtank	Transm.förlust	480	72	kWh/d
RTK	Transm.förlust	1 440	240	kWh/d
	Tillförd / bortförd			
	elektrisk energi	**5 040**	**5 040**	**kWh/d**
	värme energi	**1 909**	**-4 325**	**kWh/d**

Medelvärde					
tillförd el. energi	**5040**	**kWh/d**	**=**	**1840**	**MWh/a**
tillförd värme	**955**	**kWh/d**	**=**	**348**	**MWh/a**

Flöde		**VVVX1**	**VVX2**	**VVX3**	**VVX5**		**VP, el (ca)**	**VP eff_uppv**	**överskott**
13	T_in	**10,0**	42,9	70,0	37,0				
	T_ut	42,9	72,0	37,1	17,5				
	Effekt	499,0	441,4	-499,0	-295,8		148,0	440,7	-0,6
	T_in	**20,0**	51,7	70,0	37,0				
	T_ut	51,7	72,0	38,3	17,5				
	Effekt	480,8	307,9	-480,8	-295,8		148,0	440,7	132,8
18	T_in	10	42,8	70	37				
	T_ut	42,8	72	37,2	17,5				
	Effekt	688,8	613,2	-688,8	-409,5		203,7	610,2	-3,0
	T_in	20	51,3	70	37				
	T_ut	51,3	72	38,7	17,5				
	Effekt	657,3	434,7	-657,3	-409,5		203,7	610,2	175,5

Figure V_a: Energy balance for the sanitation and biogas upgrading at the Magic (Sørby 2015a) *(The drawing is split into two for higher picture resolution)*



D02	Temp. och flØde	LF	FH	KS
Status rev.	Rev. Gjelder	Tegn.	Kont.	Godkjent

Titel Energibalans	Lev. Tegn. A4000-HYG_ANU-PBE-001	Lev. Proj. 3 501 039 100
Projekt A4000 Den magiska fabrikken	Dato 1.10.2014	Tegn. FH/LF
Goodtech Environment AB	Filnavn A4000-HYG_ANU-PBE-001	

Figure V_b: Energy balance for the sanitation and biogas upgrading at the Magic (Sørby 2015a) *(The drawing is split into two for higher picture resolution)*

Appendix 5 – LCA model description

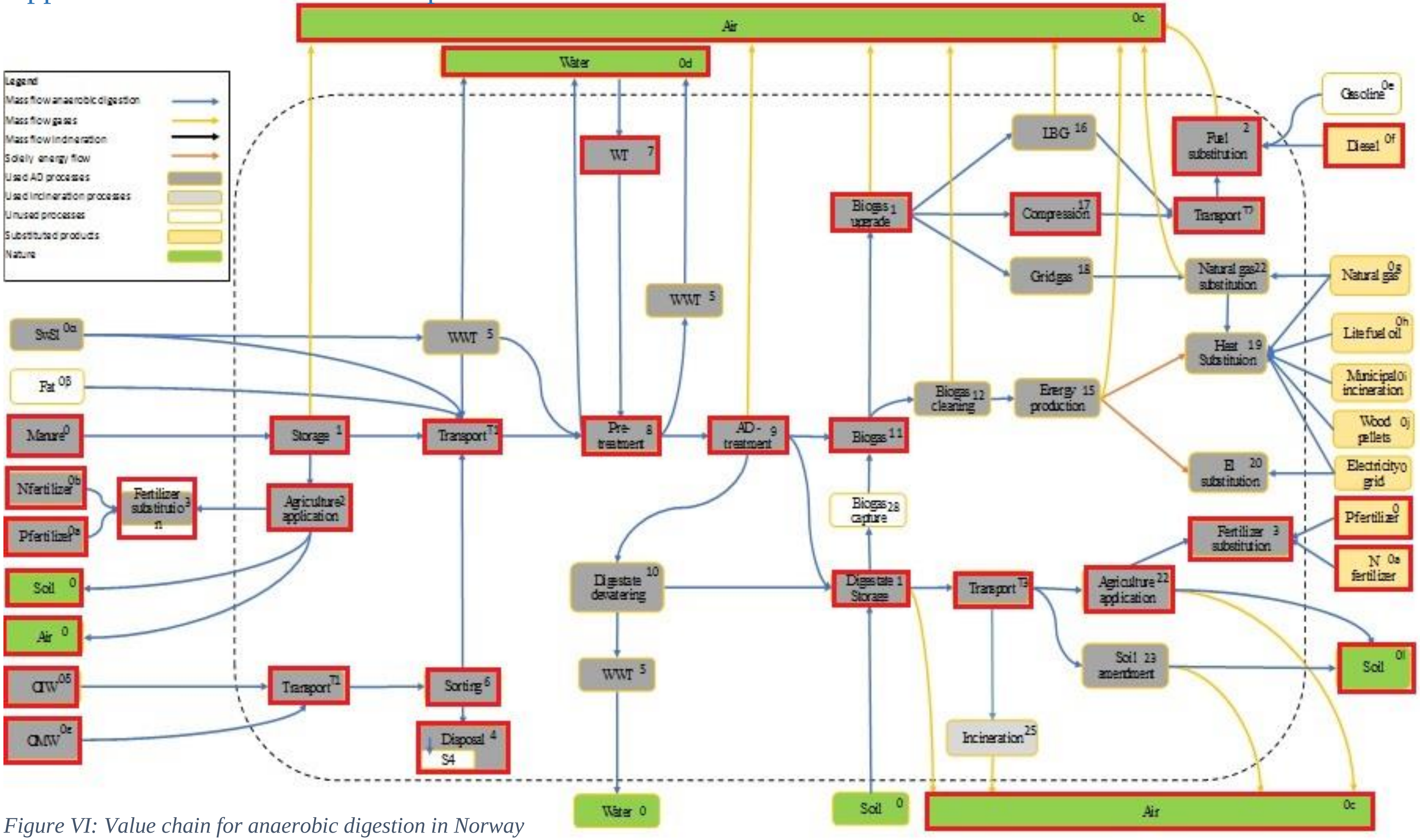


Figure VI: Value chain for anaerobic digestion in Norway
(Saxegård 2015, modified by author). *Processes highlighted, with a red box, marks the processes included in the system handled in this Thesis*

Appendix 6 – List of processes and flows in MFA model

The biogas production at "The Magic Factory" is aggregated into 20 processes in the MFA model, presented in Table II. The mass flows between the different processes are calculated per functional unit, 1 ton organic waste substrate for anaerobic digestion. Both the wet weight and the dry weight for each flow is established, this is presented in Table III. The temperatures in the mass flows are established for section B, Table IV, along with the energy used in all three sections, Table V. The mass flows and the energy used is based on the inputs for Scenario 2, the most realistic scenario considering a fully running plant in 2017.

All tables should be seen together with the flow chart in chapter 3.4 Model development, or Appendix 7.

Table II: Processes used in the MFA model

Processes	**pro. nr.**
Transportation	1
Receiving unit solid fractions	2
Receiving unit liquid OIW	3
Receiving unit liquid manure	4
Pretreatment solid fractions	5
Process water	6
Pretreatment liquid manure	7
Buffer tank	8
Heat exchanger 1	9
Heat exchanger 2	10
Sanitation (HYG)	11
Heat exchanger 3	12
Anaerobic Digestion	13
Upgrading of gas	14
Heat exchanger 5	15
Transportation and storage of bioresidual	16
Heat exchanger 0	17
Heat exchanger 4	18
Heat pump	19
Heat boiler	20

Table III: Mass flows established in the MFA model, blue symbolize demand for additional water, green symbolizes the placement of the functional unit (1 ton organic waste substrate for anaerobic digestion)

Mass flow name	from	to	Flow abbreviation	Mass flow (tons ww)	tonn DM
Feedstock, SOW	0	1	A_0,1_a	2.08	0.69
Feedstock, SM	0	1	A_0,1_b	0.23	0.07
Feddstock, LOIW	0	1	A_0,1_c	0.00	0.00
Feddstock, LM	0	1	A_0,1_d	5.77	0.35
Freshwater	0	6	A_0,6	-1.32	
Ferric chloride	0	11	A_0,11	0.03	
Water	0	14	A_0,14	0.02	
Solid organic waste	1	2	A_1,2_a	2.08	0.69
Solid manure	1	2	A_1,2_b	0.23	0.07
Liquid organic industrial waste	1	3	A_1,3	0.00	0.00
Liquid manure	1	4	A_1,4	5.77	0.35
Solid organic waste	2	5	A_2,5_a	2.08	0.69
Solid manure	2	5	A_2,5_b	0.23	0.07
Industrial waste as process water	3	6	A_3,6	0.00	0.00
Industrial waste as substrate	3	8	A_3,8	0.00	0.00
Liquid manure	4	7	A_4,7	5.77	0.35
Reject	5	0	A_5,0	0.09	0.09
Solid fractions as substrate	5	8	A_5,8	4.43	0.66
Dilution	6	5	A_6,5	2.20	0.00
Reject	7	0	A_7,0	0.01	0.01
Backwater	7	6	A_7,6	3.52	0.00
Liquid manure as substrate	7	8	A_7,8	2.24	0.34
Biogas substrate	8	9	A_8,9	6.67	1.00
*Biogas substrate for temp. regulation	8	17	A_8,17	*	*
Biogas substrate	9	10	A_9,10	6.67	1.00
Biogas substrate	10	11	A_10,11	6.67	1.00
Biogas substrate	11	12	A_11,12	6.69	1.00
Biogas substrate	12	13	A_12,13	6.69	1.00
Biogas	13	14	A_13,14		0.42
Bioresidual	13	15	A_13,15	6.27	0.58
*Biogas substrate for temp. regulation	13	18	A_13,18	*	*
Biofuel (methane)	14	0	A_14,0_a		0.16
Carbon Dioxide	14	0	A_14,0_b		0.26
Methane lost through upgrading	14	0	A_14,0_c		0.002
Bioresidual	15	16	A_15,16	6.27	0.58
Bioresidual	16	0	A_16,0	6.27	0.58
*Biogas substrate for temp. regulation	17	8	A_17,8	*	*
*Biogas substrate for temp. regulation	18	13	A_18,13	*	*

* The biogas substrate are in these flows send through a heat exchanger for temperature regulation, the flows can be seen as an internal stirring and are therefore not calculated. The energy use in the processes are however included in the yearly energy demand.

Temperature in flows:

Table IV: Temperature in flows in section B. All flows in bold are flows heating the substrate

Temperature flow name	from	to	Flow abbreviation	Temp °C
District heating for heat pump	0	19	T_0,19	2.6
Heating req. by heat boiler	0	20	T_0,20	5
Temp. in Industrial waste as substrate	3	8	T_3,8	15
Temp. in Solid fractions as substrate	5	8	T_5,8	15
Temp. in Liquid manure as substrate	7	8	T_7,8	15
Temp. in Biogas substrate	8	9	T_8,9	20
Temp. in Biogas substrate	9	10	T_9,10	50.4
Temp. in Biogas substrate	10	11	T_10,11	72
Temp. in Biogas substrate	11	12	T_11,12	70
Heat recovery from biogas substrate	12	9	T_12,9	30.4
Temp. in Biogas substrate	12	13	T_12,13	38
Temp. in Bioresidual	13	15	T_13,15	38
Temp. in Bioresidual	15	16	T_15,16	18
Heat recovery from bioresidual	15	19	T_15,19	19
Temp. added to biogas substrate	17	8	T_17_8	5
Temp. added to biogas substrate	19	10	T_19,10	21.6
Temp. added by heat boiler	20	17	T_20,17	5
Temp. added by heat boiler	20	18	T_20,18	0

Table V: Energy use in the different sections

Section	Energy use in kWh (baced on 1 ton for AD)
A - Pretreatment	177.84
B - Biogas Production	95.47
C - Gas purification	106.10

Appendix 7 – Flowchart MFA model

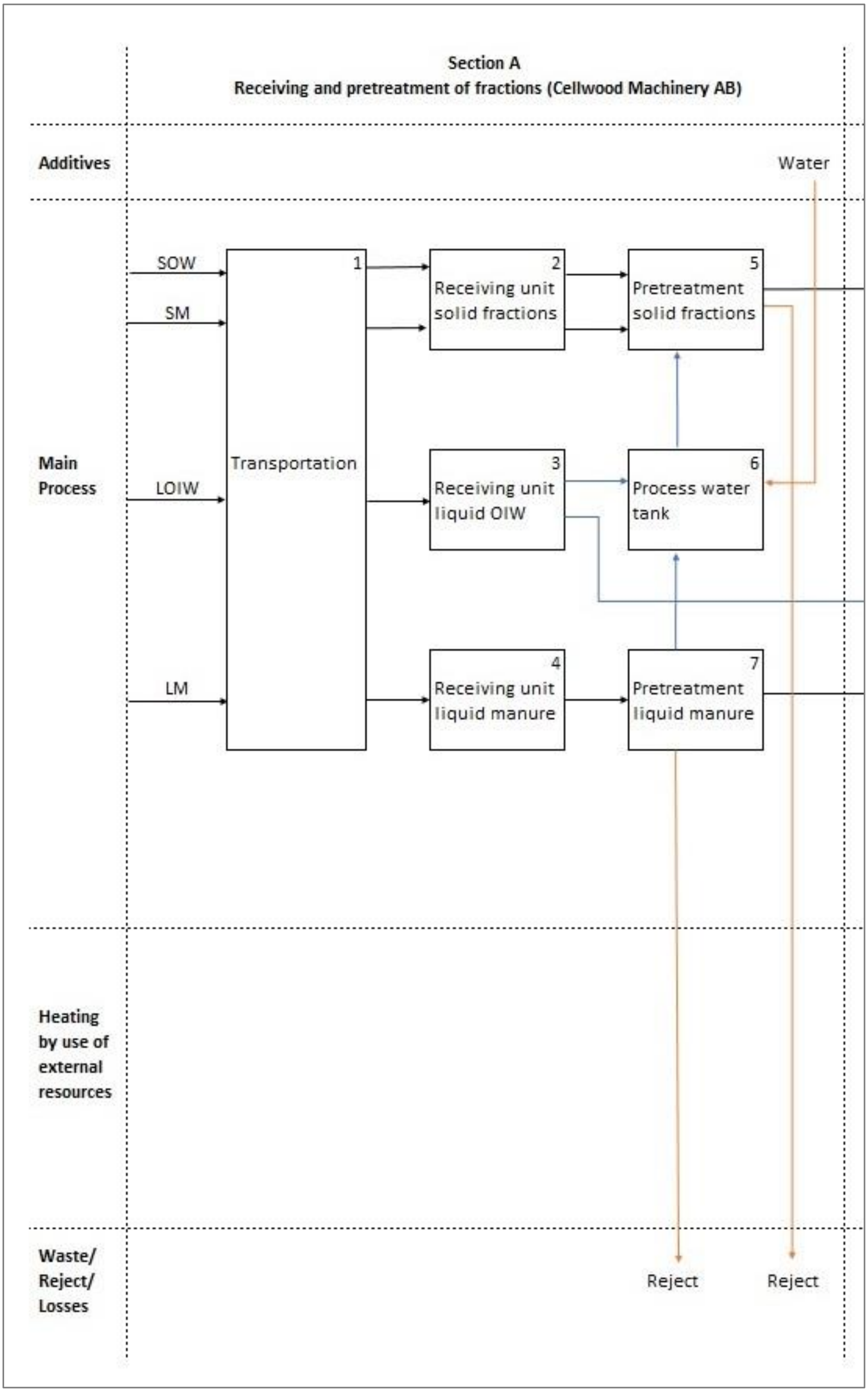


Figure VII: Flow chart section A, black arrows mass flow through "The Magic Factory", red arrows additives and waste/reject/losses, blue arrows flows of process water

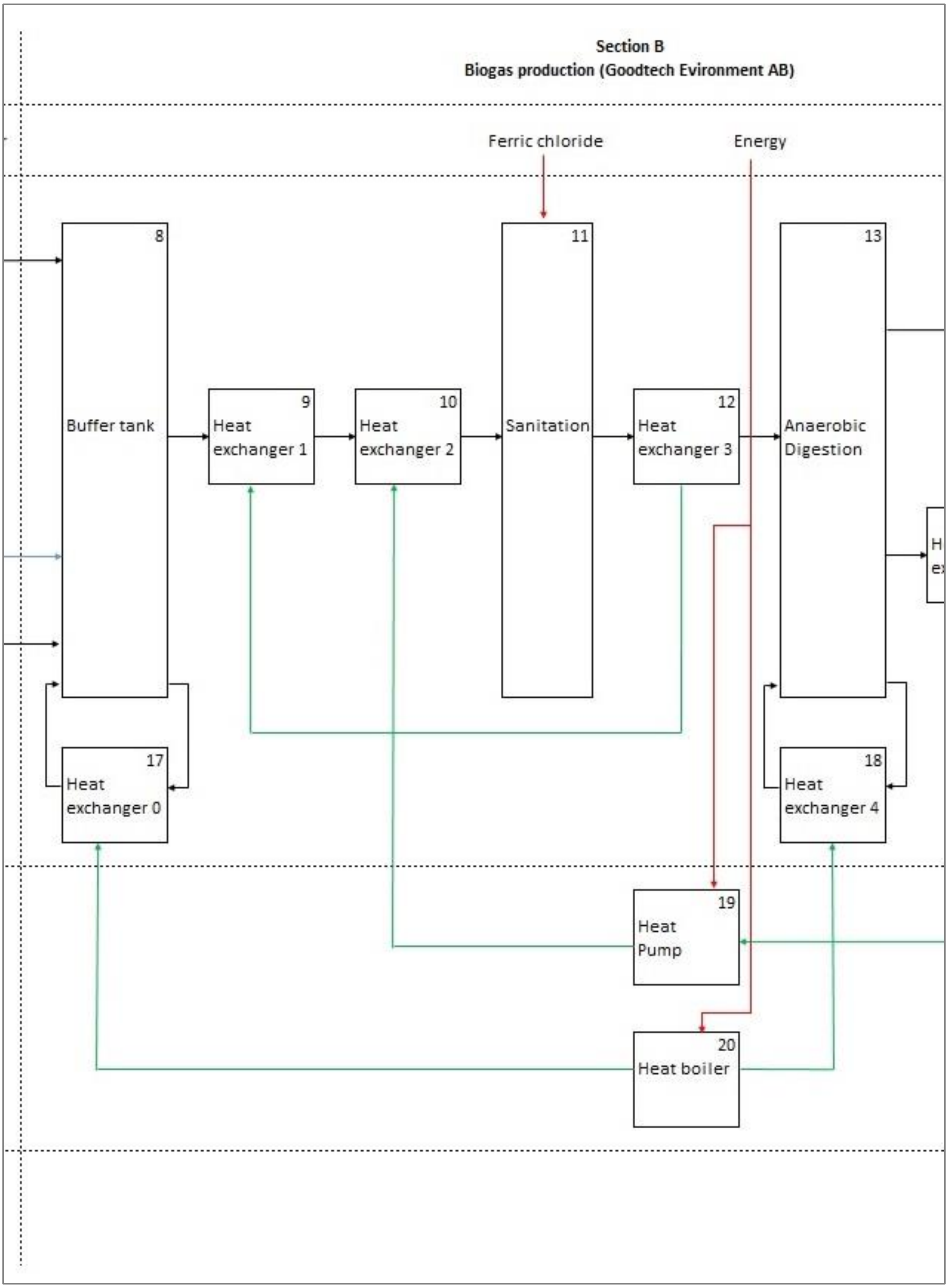


Figure VIII: Flow chart section B until anaerobic digestion, black arrows mass flow through "The Magic Factory", red arrows additives and waste/reject/losses, blue arrows flows of process water, green arrows energy

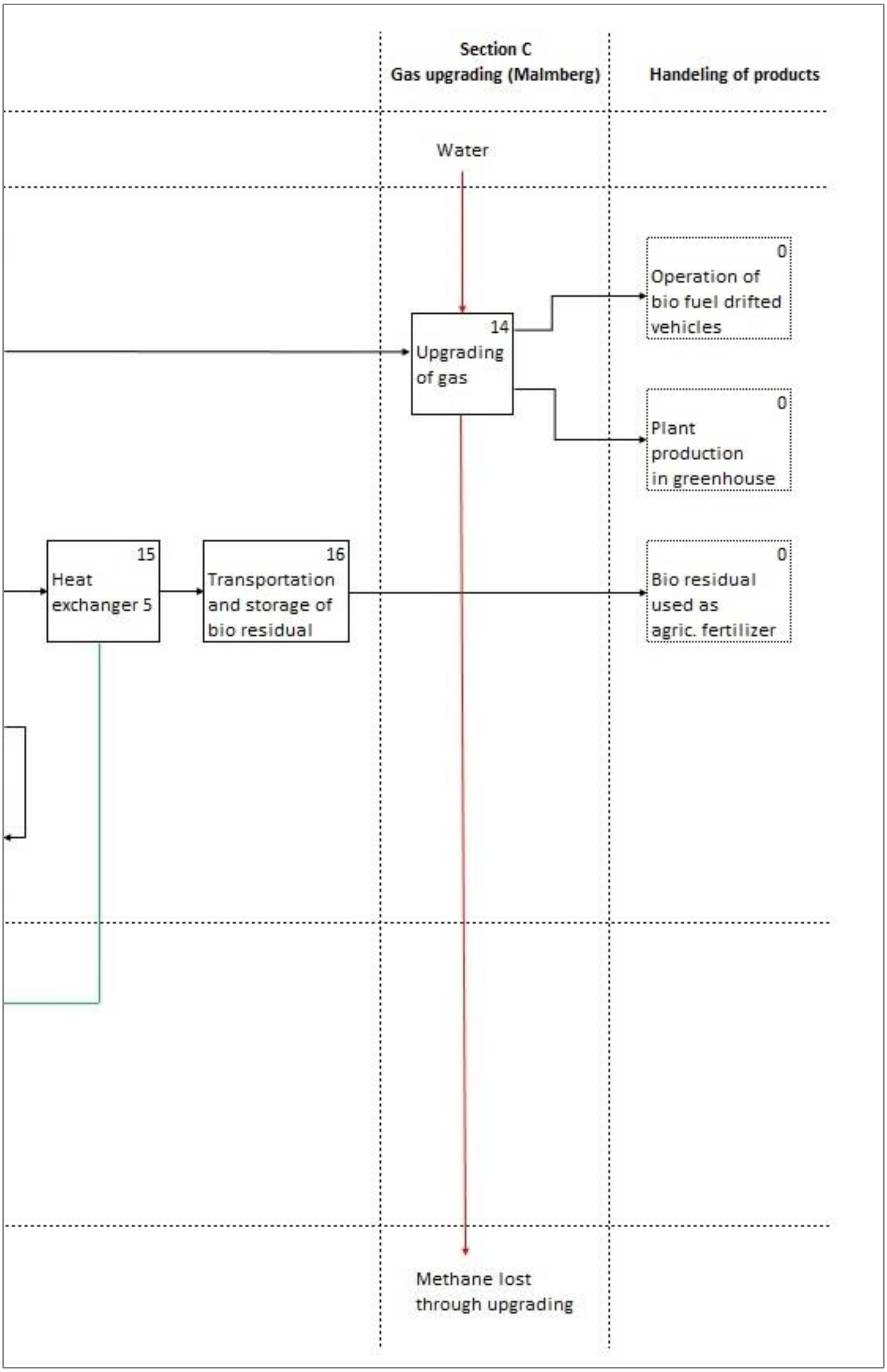


Figure IX: Flow chart section B from anaerobic digestion and section C, black arrows mass flow through "The Magic Factory", red arrows additives and waste/reject/losses, blue arrows flows of process water, green arrows energy

Appendix 8 – Data from previous student work

The total amount of feasible organic waste, from the Vestfold and Grenland region, is calculated to 362.22 - 388.22 tons/week (18 835.44- 20 187.44 tons/year), dependent on what value used for stores. The actual potential is probably higher as neither all enterprises as nor governmental operated large-scale households/restaurants are included. The results for each category are presented in Table VI.

The amounts, composition and location of the organic waste are determined by use of the Register of Enterprises, proff.no, key figures from Østfoldforskning and data collected through interviews. Previous customers of Norsk Biogassubstrat AS (NBGS) are considered additionally.

Table VI: Total amount of organic waste from different types of food industry located in the Vestfold and Grenland region

Category		Amount of organic waste (tons/year)	
		Based on data from interviews	Based on key figures from Østfoldforskning
Production		780	-
Trade	Kiosks and gas stations	11.44	-
	Stores	1 300	2 652
Large-scale households/ restaurants	Privately operated	-	8 528
	Government operated	Not possible to calculate, due to lack of data	
Customers of NBGS	Vestf. and Gr. region	8 216	-
Total		**18 835.44 - 20 187.44**	

Appendix 9 – Parameter list for LCA model

The parameter list embedded in the LCA model is presented with explanations in Table VII. The complete table, included explanations, is collected directly from the model in SimaPro and the student who developed the model sat it up.

Table VII: All parameter embedded in the LCA model with explanations

DM_AD	1	Functional unit, should always contain a value >0
Incineration	0	Applied when Incineration case is being applied to extract the correct MFA results found below in the calculated parameters!
OWc_AD	0.9	Insert numeric % of the optimal water content in the anaerobic digester
OWc_I	0.6	Insert numeric % optimal water content in incinerated organic waste; Ecoinvent 2.2
Recycle_W_AD	0	Insert numeric % of water reused in the anaerobic digester from the dried bioresidual, if dewatered; Insert value (numeric %)
Manure	0.5	Insert numeric % manure of the total DM of organic waste
Fat	0	Insert numeric % Fat of the total DM of organic waste
OMW	0.131	Insert numeric % Organic Municipal Waste of the total DM of organic waste
OIW	0.321	Insert numeric % Organic Industrial Waste of the total DM of organic waste
SwSl	0.048	Insert numeric % Sewage sludge of the total DM of organic waste
ProductX	0	Insert numeric % self adjusted product of the total DM of organic waste
AD_SL	0.12	Numeric % of CH4 produced from the total remaining biogas potential in the bioresidual; Amon et al 2006, derived form digestate emission / by methane yield for cattle and is given in Numeric % of this actual loss
Storage_Emission_BD	0	Numeric % of the methane yield in manure pre digested during post storage of manure; insert value (Numeric %)
Codigestion_Benefit	1	Numeric % of the co-digestion methane yield benefit; Lyng et al. 2011, Ariunbaatar et al 2014 (+11.9% at 155C Pt); 1=100= no change [>1= increase, (=1)=no change, <1= negative change]
N_Adjustment	1	Numeric % change to find N sensitivity ; 1=100= no change [>1= increase, (=1)=no change, <1= negative change]
Optic_sorting	0	Optical sorting technology; Turn on by applying 1, then turn off the other by giving them value 0

Inorganic_OMW	0.5	Numeric % of indigestible material (waste) that is sorted out from Organic municipal waste and sent to incineration; Jørgensen (2015)
Inorganic_OIW	0.25	Numeric % indigestible material (waste) that is sorted from Organic industrial waste and sent to incineration; Jørgensen (2015)
Lr_ADg	0	Numeric % loss of methane (CH4) in the anaerobic digester
Lr_Sorting	0	Numeric % during sorting OMW and OIW to remove inorganic waste such as plastic, metals, sand ect. Jøregensen (2015)
Lr_LBG	0.018	Numeric % loss of methane by converting biomethane to LBG; Bauer et al. (2013)
Lr_DW	0.05	Numeric % of DM lost to the dewatered reaction after dewatering of bioresidual; Jørgensen (2015)
N_DM	0.1	Numeric % of N that is found in the solid fraction of the bioresidual; Poeschl et al 2012a: Helm, 2010
P_DM	0.7	Numeric % of Phosphorus that is found in the solid fraction of the bioresidual; Poeschl et al 2012a: Amon et al. 2007
NH3_Inhi	0	Implementation of NH3 inhibition in storage tanks for bioresidual; Turn on by applying 1, then turn off the other by giving them value 0; Gjødselsforskriften §10
NH3_Red	0.65	Numeric % of the NH3 inhibition in storage tanks for bioresidual, Luostarinen et al. (2011)
ST	0	Tight storage technology for bioresidual, only CH4 inhibiting, se Lr_ST for reduction value; Turn on by applying 1, then turn off the other by giving them value 0; Luostarinen et al. 2011
SC	0	Cover over storage technology for bioresidual, only CH4 inhibiting, se Lr_SC for reduction value; Turn on by applying 1, then turn off the other by giving them value 0; Luostarinen et al. 2011
Lr_SC	0.65	Numeric (%) loss reduction Storage cover ; Luostarinen et al. 2011
Lr_ST	0	Numeric (%) loss reduction storage tight ; Luostarinen et al. 2011
Sp_Bat	0	Best available technology for NH3 emission reduction during spreading. Turn on by applying 1, then turn off the other by giving them value 0; Luostarinen et al. 2011
Spr_NH3	0	Numeric % reduced NH3 emission when applying best available technology (BAT); Loustarinen et al. 2011
MDF	0	Manure applied directly as fertilizer; Turn on by applying 1, then turn off the other by giving them value 0

Digestate_Use_Wet	0	Untreated bioresidual containing both processing water and remaining inorganics and undigested VS; Turn on by applying 1, then turn off the other by giving them value 0
Digestate_Use_Dry	1	Dewatered bioresidual containing a share of process water, inorganics and VS. Dewatered water to WWT; Turn on by applying 1, then turn off the other by giving them value 0
Digestate_Use_Separated	0	Dewatered bioresidual containing a share of process water, inorganics and VS. Dewatered water is also applied for fertilization purposes; Turn on by applying 1, then turn off the other by giving them value 0
Digestate_Use_Compost	0	Composted bioresidual by addition of uncontaminated soil and dewatered to fit the optimal water-content for compost (see: Compost_Soil); Turn on by applying 1, then turn off the other by giving them value 0
Biomethane_Use_Grid	0	Biomethane applied in a gas grid system; Turn on by applying 1, then turn off the other by giving them value 0
Biomethane_Use_Bus	1	Biomethane applied as bus fuel, substituting diesel; Turn on by applying 1, then turn off the other by giving them value 0
Biomethane_Use_gasoline_car	0	Biomethane applied as car fuel, substituting gasoline; Turn on by applying 1, then turn off the other by giving them value 0
Biomethane_Use_diesel_car	0	Biomethane applied as car fuel, substituting diesel; Turn on by applying 1, then turn off the other by giving them value 0
LBG_Use_Bus	0	Liquid biomethane applied as bus fuel, substituting diesel; Turn on by applying 1, then turn off the other by giving them value 0
LBG_Use_Gasoline_car	0	Liquid biomethane applied as car fuel, substituting gasoline; Turn on by applying 1, then turn off the other by giving them value 0
LBG_Use_diesel_car	0	Liquid biomethane applied as car fuel, substituting diesel; Turn on by applying 1, then turn off the other by giving them value 0
CO2_Capture_Cyrogenic	0	Capture and purification of CO2 from the Cryogenic biogas cleaning technology; Bauer et al. 2013; Turn on by applying 1, then turn off the other by giving them value 0
CO2_Capture_Cyrogenic_Effectivity	0.25	Capture efficiency of the CO2 from Cryogenic biogas cleaning; Give value in Numeric %; Bauer et al. 2013
Bm_Compression200	1	Compression of biomethane to storage tanks, 200 bar; Turn on by applying 1, then turn off the other by giving them value 0; Bauer et al. 2013

Bm_Compression300	0	Compression of biomethane to storage tanks, 300 bar; Turn on by applying 1, then turn off the other by giving them value 0; Bauer et al. 2013
Bm_Compression45_50	0	Compression of biomethane to gas grid network, 45 - 50 bar; Turn on by applying 1, then turn off the other by giving them value 0; Bauer et al. 2013
E_Use_Diesel_car	2.864	MJ/ km; (BMW 1 series, 2008) 1.79 MJ / km =(0.05l/km*36.2MJ/l) or (0.08l/km*36.2MJ/l) =2.864 MJ/km accounted for the extra weight of biogas tanks.
E_Use_Gasoline_car	3.24	MJ/ km; (Peugeot 307 2002) 2.268 MJ / km =(0.07l/km*32.4MJ/l) or (0.1l/km*32.4MJ/l) =3.24 MJ/km accounted for the extra weight of biogas tanks.
E_Use_Bus	15.185	MJ / vkm; Hung & Solli 2011
Person_Bus	12	Persons per bus on average in Norway; M. Simonsen 2012, Toutain et al. 2008
l_LBG_Nm3	1.7	liter LBG per Nm3 biomethane; Bauer et al. 2013
Torch	0	Numeric % of biogas being torched at biogas-plant; add value that is true for the given case in Numeric %
UpT_Cleaning	0	Cleaning of biogas to meet H2S, SO2 and H2O requirements for CHP utilization; Bauer et al. 2013
UpT_WS	1	Upgrading technology Water scrubber; Turn on by applying 1, then turn off the other by giving them value 0; Water Scrubbing; Bauer et al. 2013
UpT_ChS	0	Upgrading technology Chemical scrubber; Turn on by applying 1, then turn off the other by giving them value 0; Chemical scrubber
UpT_PSA	0	Upgrading technology Pressure Swing Absorption; Turn on by applying 1, then turn off the other by giving them value 0; Pressure Swing Absorption
UpT_Membrane	0	Upgrading technology Membrane separation; Turn on by applying 1, then turn off the other by giving them value 0; Membrane filtering system
UpT_Cyrogenic	0	Upgrading technology Cryogenic separation; Turn on by applying 1, then turn off the other by giving them value 0; Cryogenic separation
HM_0	0	Heavy metal concentration class zero - Agriculture non restrictions; Gjødselsforskriften §27
HM_1	1	Heavy metal concentration class one - Agriculture restricted to maximum spreading:5cm/ 10 yr, Gjødsels forskriften §27
HM_2	0	Heavy metal concentration class two - Agriculture restricted to maximum spreading:5cm/ 10 yr, Gjødselsforskriften §27

HM_3	0	Heavy metal concentration class three - non agriculture or cover landfill, Gjødselsforskriften §27
Lr_CH4_Cleaning	0.02	Methane loss to atmosphere in Numeric by biogas cleaning % ; No data found! so an assumption where cleaning = Water scrubbing have been applied
Lr_Ch4_UpT_WS	0.02	Methane loss to atmosphere in Numeric by water scrubbing % ; Baurer et al. 2013
Lr_Ch4_UpT_ChS	0.001	Methane loss to atmosphere in Numeric % by chemical scrubbing ; Baurer et al. 2013
Lr_Ch4_UpT_PSA	0.02	Methane loss to atmosphere in Numeric % by Pressure swing absorption; Baurer et al. 2013
Lr_Ch4_UpT_Membrane	0.03	Methane loss to atmosphere in Numeric % by membrane separation ; Baurer et al. 2013
Lr_Ch4_UpT_Cyrogenic	0.05	Methane loss to atmosphere in Numeric % by cryogenic separation ; Baurer et al. 2013
Lr_CO2_Cleaning	0.02	Carbon dioxide loss to atmosphere in Numeric by biogas cleaning % ; No data found! so an assumption where cleaning = Water scrubbing have been applied
Lr_CO2_UpT_WS	0.98	Carbon dioxide loss to atmosphere in Numeric % by using water scrubber ; Baurer et al. 2013
Lr_CO2_UpT_ChS	0.998	Carbon dioxide loss to atmosphere in Numeric % by using chemical scrubber ; Baurer et al. 2013
Lr_CO2_UpT_PSA	0.98	Carbon dioxide loss to atmosphere in Numeric % by using ressure swing absorption ; Baurer et al. 2013
Lr_CO2_UpT_Membrane	0.8	Carbon dioxide loss to atmosphere in Numeric % by using membrane separation; Baurer et al. 2013
Lr_CO2_UpT_Cyrogenic	1	Carbon dioxide loss to atmosphere in Numeric % by using cryogenic separation ; Baurer et al. 2013
Digestate_Dry_DM	0.3	Numeric % of dry matter content in dry bioresidual ; Sande et al. 2008
Compost_Soil	0.3	Numeric % of dry bioresidual content in compost ; Sande et al. 2008
DMC_Cattle	0.09	Dry matter content of cattle manure; Carlsson & Uldal 2009
DMC_Pig	0.08	Dry matter content of pig manure; Carlsson & Uldal 2009
DMC_Fat	0.9	Dry matter content of fried fat; Carlsson & Uldal 2009
DMC_OMW	0.33	Dry matter content of organic municipal waste; Carlsson & Uldal 2009
DMC_Animal_Fat	0.04	Dry matter content of animal fats; Carlsson & Uldal 2009
DMC_Fish_Waste	0.42	Dry matter content fish wastes; Carlsson & Uldal 2009
DMC_Resturant_Waste	0.27	Dry matter content restaurant waste; Carlsson & Uldal 2009

DMC_Slaughter_Blood	0.1	Dry matter content of blood from slaughter house ; Carlsson & Uldal 2009
DMC_Slaughter_Entrails	0.16	Dry matter content of entrails from slaughter house ; Lyng et al. 2011
DMC_Slaughter_Offal	0.3	Dry matter content of offal from slaughter house ; Carlsson & Uldal 2009
DMC_Diary	0.2	Dry matter content of average dairy products ; Carlsson & Uldal 2009
DMC_Fruit_Vegetable	0.15	Dry matter content average from fruits and vegetables ; Carlsson & Uldal 2009
DMC_SwSl	0.17	Dry matter content; Carlsson & Uldal 2009 , Stian Wadahl (2014) (DMC 15 - 17%), Tore Fløan (2015) (40%)
DMC_ProductX	0.17	Dry matter content; Insert own measured value for total mix
VS_Cattle	0.8	Volatile solids of DM cattle manure ; Carlsson & Udal 2009
VS_Pig	0.8	Volatile solids of DM pig manure ; Carlsson & Udal 2009
VS_Fat	1	Volatile solids of DM fired fats ; Carlsson & Udal 2009
VS_OMW	0.85	Volatile solids of DM organic municipal waste ; Carlsson & Udal 2009
VS_Animal_Fat	0.95	Volatile solids of DM animal fats ; Carlsson & Udal 2009
VS_Fish_Waste	0.98	Volatile solids of DM fish wastes ; Carlsson & Udal 2009
VS_Resturant_Waste	0.87	Volatile solids of DM restaurant wastes ; Carlsson & Udal 2009
VS_Slaughter_Blood	0.95	Volatile solids of DM blood form slaughter houses ; Carlsson & Udal 2009
VS_Slaughter_Entrails	0.83	Volatile solids of DM entrails form slaughter houses ; Lyng et al. 2011, s.22
VS_Slaughter_Offal	0.83	Volatile solids of DM offal form slaughter houses; Carlsson & Udal 2009
VS_Diary	0.82	Volatile solids of DM diary average ; Hamelin et al. 2014
VS_Fruit_Vegetable	0.95	Volatile solids of DM average from fruits and vegetables ; Carlsson & Udal 2009
VS_SwSl	0.8	Volatile solids of DM sewage sludge ; Wadahl 2014
VS_ProductX	0.9	Volatile solids of DM ; Insert own meassured value for total mix
Share_Cattle	0.7	Numeric % DM share of cattle manure in the average manure mix ; Calculated from Morken et al. 2008
Share_Pig	0.3	Numeric % DM share of pig manure in the average manure mix ; Calculated from Morken et al. 2008
Share_Fat	1	Numeric % DM share of fried fats in the average fat mix ; Calculated from Morken et al. 2008

Share_OMW	1	Numeric % DM share of organic municipal waste in the average organic municipal waste mix ; Calculated from Morken et al. 2008
Share_Animal_Fat	0	Numeric % DM share of animal fat waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Fish_Waste	0.49	Numeric % DM share of fish waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Resturant_Waste	0.1481	Numeric % DM share of restaurant waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Slaughter_Blood	0	Numeric % DM share of blood from slaughterhouse waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Slaughter_Offal	0.245	Numeric % DM share of offal from slaughterhouse waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Slaughter_Entrails	0	Numeric % DM share of entrails from slaughterhouse waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Diary	0.117	Numeric % DM share of diary average waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
Share_Fruit_Vegetable	0	Numeric % DM share of average from fruits and vegetable waste in the average organic industrial waste mix ; Calculated from Morken et al. 2008
CH4_Share_Pig	0.65	Methane share in Numeric % of the produced biogas from cattle manure ; Carlsson & Udal 2009
CH4_Share_Cattle	0.65	Methane share in Numeric % of the produced biogas from pig manure ; Carlsson & Udal 2009
CH4_Share_Fat	0.68	Methane share in Numeric % of the produced biogas from fried fats ; Carlsson & Udal 2009
CH4_Share_OMW	0.63	Methane share in Numeric % of the produced biogas from organic municipal wastes ; Carlsson & Udal 2009
CH4_Share_Animal_Fat	0.6	Methane share in Numeric % of the produced biogas from animal fats ; assumed from qualitative data ; Morken et al. 2008 , Carlsson & Udal 2009
CH4_Share_Fish_Waste	0.71	Methane share in Numeric % of the produced biogas from fish wastes ; Calrsson & Udal 2009
CH4_Share_Resturant_Waste	0.63	Methane share in Numeric % of the produced biogas from restaurant wastes ; Carlsson & Udal 2009

CH4_Share_Slaughter_Blood	0.63	Methane share in Numeric % of the produced biogas from blood from slaughter house waste ; Carlsson & Udal 2009
CH4_Share_Slaughter_Entrails	0.63	Methane share in Numeric % of the produced biogas from entrails from slaughter house waste; Lyng et al. 2011
CH4_Share_Slaughter_Offal	0.68	Methane share in Numeric % of the produced biogas from offal from slaughter house waste ; Carlsson & Udal 2009
CH4_Share_Diary	0.59	Methane share in Numeric % of the produced biogas from diary average Hamelin et al. 2014
CH4_Share_Fruit_Vegetable	0.6	Methane share in Numeric % of the produced biogas from average from fruits and vegetable waste ; Carlsson & Udal 2014
CH4_Share_SwSl	0.6	Methane share in Numeric % of the produced biogas from sewage sludge ; Wadahl 2014
CH4_Share_ProductX	0.6	Methane share in Numeric % of the produced biogas ; Insert own measured value for total mix
MY_Cattle	213	Methane yield; m3/ ton volatile solids (VS) cattle manure ; Carlsson & Udal 2009
MY_Pig	268	Methane yield; m3/ ton VS pig manure ; Carlsson & Udal 2009
MY_Fat	757	Methane yield; m3/ ton VS fried fats ; Carlsson & Udal 2009
MY_OMW	461	Methane yield; m3/ ton VS organic municipal waste ; Carlsson & Udal 2009
MY_Animal_Fat	682	Methane yield; m3/ ton VS animal fats ; Carlsson & Udal 2009
MY_Fish_Waste	930	Methane yield; m3/ ton VS fish waste ; Carlsson & Udal 2009
MY_Resturant_Waste	461	Methane yield; m3/ ton VS restaurant waste ; Carlsson & Udal 2009
MY_Slaughter_Blood	547	Methane yield; m3/ ton VS blood from slaughterhouse ; Carlsson & Udal 2009
MY_Slaughter_Entrails	688	Methane yield; m3/ ton VS entrails from slaughterhouse ; Lyng et al. 2011
MY_Slaughter_Offal	664	Methane yield; m3/ ton VS offal from slaughterhouse ; Hamelin et al. 2014
MY_Diary	277	Methane yield; m3/ ton VS diary average ; Carlsson & Udal 2009
MY_Fruit	666	Methane yield; m3/ ton VS average fruits and vegetable ; Carlsson & Udal 2009
MY_SwSl	336	Methane yield; m3/ ton VS sewage sludge ; Wadahl 2014
MY_ProductX	500	Methane yield; m3/ ton VS ; Insert own meassured value for total mix
DS_Cattle	0.504	Remaining solids in Numeric % of DM cattle manure ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009

DS_Pig	0.504	Remaining solids in Numeric % of DM pig manure ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Fat	0	Remaining solids in Numeric % of DM fried fats ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_OMW	0.46	Remaining solids in Numeric % of DM organic municipal waste ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Animal_Fat	0.05	Remaining solids in Numeric % of DM animal fat ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Fish_Waste	0.36	Remaining solids in Numeric % of DM fish wastes; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Resturant_Waste	0.3	Remaining solids in Numeric % of DM restaurant wastes ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Slaughter_Blood	0.38	Remaining solids in Numeric % of DM blood from slaughterhouse ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Slaughter_Entrails	0.48	Remaining solids in Numeric % of DM entrails from slaughterhouse ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Slaughter_Offal	0.46	Remaining solids in Numeric % of DM offal from slaughterhouse ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Lyng et al. 2011, s.22
DS_Diary	0.53	Remaining solids in Numeric % of DM average dairy products ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_Fruit_Vegetable	0.46	Remaining solids in Numeric % of DM average fruit and vegetable waste ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Hamelin et al. 2014
DS_SwSl	0.6	Remaining solids in Numeric % of DM sewage sludge ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Carlsson & Udal 2009
DS_ProductX	0.5	Remaining solids in Numeric % of DM ; Remaining solids = 1 - (VS * Degradability coefficient of VS) ; Insert own measured value for total mix
N_Cattle	44.8	kg N/ ton DM cattle manure; Poeschl et al. 2012a

N_Pig	99.38	kg N/ ton DM pig manure; Karlengen et al 2012
N_Fat	35	kg N/ ton DM fat; assumed the same as for animal fat ; Poeschl et al. 2012a via Helm 2009
N_OMW	40	kg N/ ton DM organic municipal waste; Poeschl et al. 2012a via Helm 2009
N_Animal_Fat	35	kg N/ ton DM animal fat; Poeschl et al. 2012a via Helm 2009
N_Fish_Waste	39.23	kg N/ ton DM fish waste; Gebauer & Eikebrokk 2005
N_Resturant_Waste	6	kg N/ ton DM restaurant waste; Carlsson & Udal 2009
N_Slaughter_Blood	15	kg N/ ton DM slaughter house blood; Alvarez & Lidén 2007; (15 for cattle blood and 8.3 for pig blood) table 2 in the given paper
N_Slaughter_Entrails	25	kg N/ ton DM slaughter house entrails; Lyng et al. 2011 s. 22
N_Slaughter_Offal	59	kg N/ ton DM slaughter house offal; Lyng et al. 2011 s. 21
N_Diary	8.06	kg N/ ton DM diary products; Hamelin et al. 2014
N_Fruit_Vegetable	0	kg N/ ton DM Fruit and vegetables; Alvarez & Lidén 2007
N_SwSl	17.5	kg N/ ton DM sewage sludge ; Yara 2011
N_ProductX	0	kg N/ ton DM ; Insert own measured value for total mix
P_Cattle	4.56	kg P/ ton DM cattle manure ; Poeshl et al. 2012a via Helm 2009
P_Pig	13.98	kg P/ ton DM pig manure ; Karlengen et al. 2012
P_Fat	3.8	kg P/ ton DM frying fat Assumed the same as separated fats ; Poeshl et al. 2012a via Helm 2010
P_OMW	0.59	kg P/ ton DM organic municipal waste ; Poeshl et al. 2012a via Helm 2010
P_Animal_Fat	3.8	kg P/ ton DM animal fat ; Poeshl et al. 2012a via Helm 2010
P_Fish_Waste	1.1	kg P/ ton DM fish wastes ; Carlsson & Udal 2009 , Genauer & Eikebrokk 2005
P_Resturant_Waste	0.9	kg P/ ton DM restaurant wastes ; Poeshl et al. 2012a via Helm 2010
P_Slaughter_Blood	0.1	kg P/ ton DM blood from slaughterhouse ; Alvarez & Lidén 2007
P_Slaughter_Entrails	10.5	kg P/ ton DM entrails from slaughterhouse ; Lyng et al. 2011 s. 22
P_Slaughter_Offal	40	kg P/ ton DM offal from slaughterhouse waste ; Lyng et al. 2011 s. 21
P_Diary	1.12	kg P/ ton DM average dairy products ; Hamelin et al. 2014
P_Fruit_Vegetable	0	kg P/ ton DM average of fruits and vegetable waste ; Alvarez & Lidén 2007
P_SwSl	16	kg P/ ton DM sewage sludge ; Yara 2011
P_ProductX	0	kg P/ ton DM ; Insert own measured value for total mix

Digestate_ava_P	1	Plant availability phosphorus (P) for digested organic wastes ; Lyng et al 2011
Digestate_ava_N	0.85	Plant availability nitrogen (N) for digested organic wastes ; Luostarinen et al 2011, s41
Manure_ava_P	1	Plant availability phosphorus (P) for manure; Lyng et al 2011
Manure_ava_N	0.3	Plant availability nitrogen (N) for manure; Luostarinen et al 2011, s 41
HHV_Cattle	15358	MJ / ton DM cattle manure Higher heating value (HHV) ; Annamali & Sweeten 1987, calculated the average for all manure types in table 1, s 1206
HHV_Pig	15358	MJ / ton DM pig manure (HHV) ; Assumed the same as for Cattle manure ; Annamali & Sweeten 1987
HHV_Fat	37550	MJ / ton DM frying fat (HHV) ; Metha & Anand 2009
HHV_OMW	18500	MJ / ton DM organic municipal waste (HHV) ; Wirsenius 2000
HHV_Animal_Fat	35550	MJ / ton DM animal fat (HHV) ; Assumed tha same as for fat - 2000 MJ so as to account for the impurity ; qualitative assumption , Carlsson & Udal 2009
HHV_Fish_Waste	20000	MJ / ton DM fish waste (HHV); Wirsenius 2000
HHV_Resturant_Waste	18500	MJ / ton DM; Wirsenius 2000
HHV_Slaughter_Blood	18000	MJ / ton DM blood from slaughterhouse; Assumed same as Offal , Wirsenius 2000
HHV_Slaughter_Entrails	18000	MJ / ton DM entrails from slaughterhouse; Assumed same as Offal , Wirsenius 2000
HHV_Slaughter_Offal	17500	MJ / ton DM offal from slaughterhouse ; Wirsenius 2000
HHV_Diary	15650	MJ / ton DM average dairy products: 3.13 kj/ wet wheight yougurt; Matvaretabelen.no
HHV_Fruit_Vegetable	17000	MJ / ton DM average fruit and vegetable waste: Assumed the same as for uneaten food , Wirsenius 2000
HHV_SwSl	15000	MJ / ton DM sewage sludge ; Fryba et al. 2014
HHV_ProductX	0	MJ / ton DM ; Insert own measured value for total mix
Pl_Avg	0.1	Phosphorus loss (P) during digestion, assumed 10% for all substrates ; Möller & Müller 2012 , Hospido et al. 2005 (Sewage sludge)
Molar_Mass_CH4	0.7143	kg/Nm3 ; Mass density for CH4 per m3 - found by applying the ideal gas law m/V = (P*M)/(R*T)
Molar_Mass_CO2	1.9642	kg/Nm3 ; Mass density for CO2 per m3 - found by applying the ideal gas law m/V = (P*M)/(R*T)
SHC	4.18	MJ/ (ton*C) ; Specific heat capacity for water - assumed the same from water and organic material ; Coultry et al. 2013

FSH	14	Celsius, organic waste substrate temperature in Celcius in to treatment plant, pasteurization start temperature ; Jørgensen 2015, Bauer et al.2013
AFSH	44	Celsius, organic waste substrate temperature in Celcius after heat recovery, pasteurization start temperature ; Jørgensen 2015 ; Calculator follows in Appendix XX
PH	70	Pasteurization treatment heat for one hour; Jørgensen 2015, Ecopro (2015), Morken et al. 2008 ; Calculator follows in Appendix XX
Temp_Incinerated_Water	120	Temperature absorbed by the water within the incinerated material - resulting in a lesser energy output than the HHV suggests ; Jørgensen 2015
Lr_HP	0.05	Loss rate Heating Pretreatment ; Hamelin et al. 2014
HV_W	2260	MJ/ton water to steam - energy requirements in conversion from liquid to gaseous state ; Heat of vaporization of water; Wikipedia: "Enthalpy of vaporization"
Energy_Methane	37.5	MJ/Nm3 ; energy density methane (CH4) per m3; Morken et al. 2008
Energy_Efficiency_e_CHP	0.12	Energy efficiency for electricity in biogas combined heat and power plant (CHP), biogas utilization : Hung & Solli 2011
Energy_Efficiency_H_CHP	0.8	Energy efficiency for heat in CHP, biogas utilization ; Hung & Solli 2011
Energy_Efficiency_e_Incineration	0	Energy efficiency for electricity production in incineration plant ; Hung & Solli 2011
Energy_Efficiency_H_Incineration	0.8	Energy efficiency for heat production in incineration plant ; Hung & Solli 2011
kWh_to_MJ	3.6	MJ converted to kWh
Share_Fly_ash	0.1	Dry matter that goes to fly ash ; Boesch et al. 2014
Share_HM_Fly_ash	0.3	Amount of heavy metals that foes to fly ash ; Boesch et al. 2014
Share_Bottom_ash	0.9	Dry matter that goes to fly ash ; Boesch et al. 2014
Share_HM_Bottom_ash	0.7	Amount of heavy metals that foes to fly ash ; Boesch et al. 2014
Cd0	0.4	mg/kg DM bioresidual Cadmium (Cd) class 0; Gjødselsforskriften §10
Cd1	0.8	mg/kg DM bioresidual Cadmium (Cd) class 1; Gjødselsforskriften §10
Cd2	2	mg/kg DM bioresidual Cadmium (Cd) class 2; Gjødselsforskriften §10
Cd3	5	mg/kg DM bioresidual Cadmium (Cd) class 3; Gjødselsforskriften §10
Pb0	40	mg/kg DM bioresidual Lead (Pb) class 0; Gjødselsforskriften §10
Pb1	60	mg/kg DM bioresidual Lead (Pb) class 1; Gjødselsforskriften §10

Pb2	80	mg/kg DM bioresidual Lead (Pb) class 2; Gjødselsforskriften §10
Pb3	200	mg/kg DM bioresidual Lead (Pb) class 3; Gjødselsforskriften §10
Hg0	0.2	mg/kg DM bioresidual Mercury (Hg) class 0; Gjødselsforskriften §10
Hg1	0.6	mg/kg DM bioresidual Mercury (Hg) class 1; Gjødselsforskriften §10
Hg2	3	mg/kg DM bioresidual Mercury (Hg) class 2; Gjødselsforskriften §10
Hg3	5	mg/kg DM bioresidual Mercury (Hg) class 3; Gjødselsforskriften §10
Ni0	20	mg/kg DM bioresidual Nickel (Ni) class 0; Gjødselsforskriften §10
Ni1	30	mg/kg DM bioresidual Nickel (Ni) class 1; Gjødselsforskriften §10
Ni2	50	mg/kg DM bioresidual Nickel (Ni) class 2; Gjødselsforskriften §10
Ni3	80	mg/kg DM bioresidual Nickel (Ni) class 3; Gjødselsforskriften §10
Zn0	150	mg/kg DM bioresidual Zinc (Zn); Gjødselsforskriften §10
Zn1	400	mg/kg DM bioresidual Zinc (Zn); Gjødselsforskriften §10
Zn2	800	mg/kg DM bioresidual Zinc (Zn); Gjødselsforskriften §10
Zn3	1500	mg/kg DM bioresidual Zinc (Zn); Gjødselsforskriften §10
Cu0	50	mg/kg DM bioresidual Copper (Cu); Gjødselsforskriften §10
Cu1	150	mg/kg DM bioresidual Copper (Cu); Gjødselsforskriften §10
Cu2	650	mg/kg DM bioresidual Copper (Cu); Gjødselsforskriften §10
Cu3	1000	mg/kg DM bioresidual Copper (Cu); Gjødselsforskriften §10
Cr0	50	mg/kg DM bioresidual Chromium (Cr); Gjødselsforskriften §10
Cr1	60	mg/kg DM bioresidual Chromium (Cr); Gjødselsforskriften §10
Cr2	100	mg/kg DM bioresidual Chromium (Cr); Gjødselsforskriften §10
Cr3	150	mg/kg DM bioresidual Chromium (Cr); Gjødselsforskriften §10
E_Sorting	4.16	kWh electricity (e-)/ ton sorted organic waste; Jørgensen 2015, Composed of Sorting (3.12) and crushing (1.04).
E_Pasteurization	1.733	kWh (e-) /ton pasteurized organic waste; Jørgensen 2015
E_AD	2.08	kWh (e-)/ton organic waste to treatment; Jørgensen 2015

E_Dewatering	2.4	kWh (e-)/m3 bioresidual slurry to dewatering ; Rehl & Müller 2011
E_WT	0.4288	kWh (e-)/ m3 (ton) cleaned water to treatment system ; Ecoinvent 3.0
E_WWT	0.3997	kWh (e-)/ m3 waste water to waste water treatment plant (WWTP) ; Ecoinvent 3.0
E_Spreading_Dry	0.16	kWh (diesel) / ton spread dry fertilizer (Water content >25%) ;
E_Spreading_Wet	0.8	kWh (diesel) / ton spread wet fertilizer (Water content <75%) ;
E_Tanking	0.16	kWh (e-) / m3 tanking of biomethane ; Soli et al.2011
E_Cleaning	0	kWh (e-)/m3 raw biogas cleaned ; Bauer et al. 2013
E_UpT_WS	0.23	kWh (e-) /m3; Bauer et al. 2013
E_UpT_ChS	0.13	kWh (e-) /m3; Bauer et al. 2013
E_UpT_PSA	0.25	kWh (e-) /m3 ; Bauer et al. 2013
E_UpT_Membrane	0.3	kWh (e-) /m3; Bauer et al. 2013
E_UpT_Cyrogenic	0.4564	kWh (e-)/m3; Bauer et al. 2013
H_UpT_ChS	1.96	MJ heat (H)/m3; Bauer et al. 2013
E_LBG_Process	0.75	kWh (e-)/m3; Bauer et al. 2013
E_Compression45_50	0.16	kWh (e-)/m3 biomethane compressed to 45 - 50 bar ; Bauer et al. 2013
E_Compression200	0.21	kWh (e-)/m3 biomethane compressed to 20 bar ; Bauer et al. 2013
E_Compression300	0.25	kWh (e-)/ m3 biomethane compressed to 300 bar ; Bauer et al. 2013
E_Incineration	65.7	kWh (e-)/ ton waste Hospido et al. 2005
E_CHP	0.04	% of total energy content in
km_Manure	50	Average transport distance for manure to plant ; Part of the assumption in the LCA model
km_Fat	50	Average transport distance for frying fat to plant ; Part of the assumption in the LCA model
km_OMW	19	Average transport distance for organic municipal waste to plant ; Part of the assumption in the LCA model
km_OMWc	0	Average transport distance for organic municipal waste to plant ; Part of the assumption in the LCA model collected at regional storage and transported by Euro 5 transport lorry
km_OIW	50	Average transport distance for organic industrial waste to plant ; Part of the assumption in the LCA model
km_SwSl	0	Average transport distance for sewage sludge to plant ; Part of the assumption in the LCA model
km_ProductX	0	Average transport distance for self defined organic waste mix to plant ; Part of the assumption in the LCA model
km_Dg	50	Average transport distance for bioresidual to application area ; Part of the assumption in the LCA model

km_Compost	50	Average transport distance for composted bioresidual to application area ; Part of the assumption in the LCA model
km_Bm_LBG	10	Average transport distance for liquid biogas (LBG) to filling station ; Part of the assumption in the LCA model
km_Fly_Ash	250	Average transport distance for fly ash to hazardous landfill ; Part of the assumption in the LCA model
km_Bottom_Ash	1	Average transport distance for bottom ash to land fill ; Part of the assumption in the LCA model
Diesel_Consumption	0.022	kg diesel / tkm or (43,1 MJ diesel / tkm) ; Ecoinvent 3.0 ; MJ / kg diesel https://snl.no/energivare
E_Transport_EUR5	1.056	MJ diesel per tkm: Energy per transport unit
E_Transport_Municipal_Collection	16.12	MJ diesel per tkm: Energy per transport unit
Share_NH4	0.75	Numeric % share of nitrogen (N) bound as NH4 - N in the bioresidual ; Bernstad & Jansen 2011 via Svensson et al. 2004, Britto & Kronzucker 2002
Share_NO3	0.018	Numeric % share of nitrogen (N) bound as NO3 - N in the bioresidual ; Bernstad & Jansen 2011 via Svensson et al. 2004
Share_N_Org	0.232	Numeric % share of nitrogen (N) bound as organic N - N in the bioresidual ; Bernstad & Jansen 2011 via Svensson et al. 2004
N_N2	1	Mass (kg) of N per N-compound; Bernstad & Jansen 2011
N_N2O	0.636	Mass (kg) of N per N-compound; Bernstad & Jansen 2011
N_NH3	0.824	Mass (kg) of N per N-compound; Bernstad & Jansen 2011
NH3_dig	0.96	Numeric % of N-total loss converted to ammonia (NH3) ; Bernstad & Jansen 2011
N2O_dig	0.02	Numeric % of N-total loss converted to dinitrogen monoxide (N2O) ; Bernstad & Jansen 2011
Nl_Waste	0.17	Numeric % of N-total loss from digested organic waste ; Bernstad & Jansen 2011, table 5, their reference Sonesson (1996) (17.0% loss)
Nl_Manure	0.179	Numeric % of N-total loss from untreated manure ; Bernstad & Jansen 2011, table 5, their reference Sonesson (1996) (17.9% loss)
Nl_Manure_Dig	0.218	Numeric % of N-total loss from digested manure; Bernstad & Jansen 2011, table 5, their reference Sonesson (1996) (21.8% loss)
Nl_undig_NH3	0.99	Numeric % production of ammonia (NH3) from undigested manure relative to digested manure ; Assumed from Amon et al. 2006

Nl_dig_NH3	1	Numeric % production of ammonia (NH_3) from digested manure relative to digested manure ; Assumed from Amon et al. 2006
Nl_sepa_NH3	1.78	Numeric % production of ammonia (NH_3) from digested and separated manure relative to digested manure ; Assumed from Amon et al. 2006
Nl_dig_N2O	1	Numeric % production of dinitrogen monoxide (N_2O) from undigested manure relative to digested bioresidual ; Calculated from Amon et al. 2006
Nl_undig_N2O	0.77	Numeric % production of dinitrogen monoxide (N_2O) from undigested manure relative to digested bioresidual ; Calculated from Amon et al. 2006
Nl_sepa_N2O	1.19	Numeric % production of dinitrogen monoxide (N_2O) produced from separated bioresidual relative to digested bioresidual ; Calculated from Amon et al. 2006
Nl_dig_N2	1	Numeric % production of dinitrogen (N_2) from digested bioresidual relative to digested bioresidual ; Calculated from Amon et al. 2006
Nl_undig_N2	1	Numeric % production of dinitrogen (N_2) from undigested manure relative to digested bioresidual ; Calculated from Amon et al. 2006
Nl_Sepa_N2	1	Numeric % production of dinitrogen (N_2) from separated bioresidual relative to digested bioresidual ; Calculated from Amon et al. 2006
Storage_Untreated_NH3	0.18	Numeric % ammonia (NH_3) produced by storage of untreated manure ; Calculated from Amon et al. 2006
Storage_Sepa_Dry_NH3	0.71	Numeric % ammonia (NH_3) produced by storage of dewatered bioresidual ; Calculated from Amon et al. 2006
Storage_Sepa_Wet_NH3	0.1	Numeric % ammonia (NH_3) produced by storage of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006
Storage_Digested_NH3	0.04	Numeric % ammonia (NH_3) produced by storage of digested organic wastes substrates ; Calculated from Amon et al. 2006
Storage_Untreated_N2O	0.84	Numeric % dinitrogen monoxide (N_2O) produced by storage of untreated manure ; Calculated from Amon et al. 2006
Storage_Sepa_Dry_N2O	0.31	Numeric % dinitrogen monoxide (N_2O) produced by storage of dewatered bioresidual ; Calculated from Amon et al. 2006
Storage_Sepa_Wet_N2O	0.46	Numeric % dinitrogen monoxide (N_2O) produced by storage of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006

Storage_Digested_N2O	0.91	Numeric % dinitrogen monoxide (N2O) produced by storage of digested organic wastes substrates; Calculated from Amon et al. 2006
Storage_Untreated_CH4	1	Numeric % methane (CH4) produced by storage of untreated manure ; Calculated from Amon et al. 2006
Storage_Sepa_Dry_CH4	0.215	Numeric % methane (CH4) produced by storage of dewatered bioresidual ; Calculated from Amon et al. 2006
Storage_Sepa_Wet_CH4	0.785	Numeric % methane (CH4) produced by storage of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006
Storage_Digested_CH4	1	Numeric % methane (CH4) produced by storage of digested organic waste substrates ; Calculated from Amon et al. 2006
App_Sepa_Dry_NH3	0.1654	Numeric % ammonia (NH3) produced by application of dewatered bioresidual ; Calculated from Amon et al. 2006
App_Sepa_Wet_NH3	0.02258	Numeric % ammonia (NH3) produced by application of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006
App_Sepa_Dry_N2O	0.1331	Numeric % dinitrogen monoxide (N2O) produced by application of dewatered bioresidual ; Calculated from Amon et al. 2006
App_Sepa_Wet_N2O	0.09	Numeric % dinitrogen monoxide (N2O) produced by application of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006
App_Sepa_Dry_CH4	0	Numeric % methane (CH4) produced by application of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006
App_Sepa_Wet_CH4	0	Numeric % methane (CH4) produced by storage of liquid fraction of dewatered bioresidual ; Calculated from Amon et al. 2006
CH4_Undig	3.01	Numeric % methane (CH4) produced from undigested manure relative to digested bioresidual ; Calculated from Amon et al. 2006
CH4_Wet	1	Numeric % methane (CH4) produced from digested bioresidual relative to digested bioresidual ; Calculated from Amon et al. 2006
CH4_Sepa	0.58	Numeric % methane (CH4) produced from separated manure relative to digested bioresidual ; Calculated from Amon et al. 2006
N_Runoff_SW	0	Nitrogen (N) runoff to surface water ; Bernstad & Jansen 2011
N_Runoff_GW	0.22	Nitrogen (N) runoff to ground water ; Bernstad & Jansen 2011
P_Runoff_SW	0.107	Phosophorus (P) runoff to surfase waters; Hamilton et al. 2015