Masteroppgåve

NTNU
Noregs teknisk-naturvitskaplege universitet
Fakultet for ingeniørvitenskap
Institutt for energi- og prosessteknikk

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Assessment of Operation of Biogas Production Plants in regards to Yield Factor, Energy Efficiency and Environmental Benefit

Masteroppgåve i Energi og miljø
Veileder: Sigrun Jahren
Juni 2019

NTNU
Kunnskap for en bedre verden

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Preface

This master thesis is written at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

Several challenges regarding data collection were met during the course of this thesis. The process of establishing contact with the right people has been time consuming. Difficulties obtaining relevant and sufficient data have led to challenges regarding the assessment of the yield factor, energy efficiency and environmental benefit of the evaluated biogas facilities. A cost-benefit analysis of the evaluated biogas facilities was originally planned to be executed as part of the thesis. However, due to difficulties obtaining sufficient and relevant economic data from the biogas plants in question, it was decided to exclude the analysis from the thesis.

I would like to thank my supervisor Sigrun Jahren (NTNU) for guidance and feedback throughout the project. Helge Brattebø (NTNU) was very helpful in the development of the model and gave valuable inputs regarding the project scope. Furthermore, I would like to thank everyone who provided relevant data and information regarding the evaluated biogas facilities: Chitra S. Raju (BBR), David Fritz (BA), Mariann Hegg (DMF), Johnny Stuen (RBA), Espen Govasmark (RBA) and René Steinmair (BW). Additional gratitude goes towards Johnny Stuen (RBA), Espen Govasmark (RBA) and Nicola Gabriela Herrmann (BW) for allowing me to visit their respective biogas facilities in order to further develop my understanding of the biogas production process.

Trondheim, 2019

Abstract

A constantly growing energy demand and an increased focus on environmental friendly energy sources calls for development and utilization of alternative energy solutions. Waste generation is a natural consequence of a modern lifestyle, and utilizing waste for biogas production offers a green energy source, as well as an efficient way to manage waste. The by-product from biogas production is rich in nutrients and can be used as a valuable resource in agriculture.

This project has studied the biogas production from organic waste. Several biogas production plants were analyzed in order to evaluate the production yield and energy efficiency of the facilities. Models representing the biogas value chain were developed based on principles from material flow analysis. The environmental benefit of each biogas plant was evaluated by calculating the avoided CO_2-emission due to biogas utilization.

Yield factors calculated based on incoming VS exceeded yield factors calculated based on incoming DM and incoming wet weight. The calculated energy efficiency ranged from 26% to 80%. Biogas plants producing upgraded biogas were found to have the highest energy efficiency, likely due to upgraded biogas having a higher energy content. The calculated environmental benefit was positive for each evaluated biogas plant, regardless of how the biogas was utilized.

A sensitivity analysis was performed in order to evaluate the impact of specific parameters on energy efficiency and environmental benefit. Parameters related to transport distances and DM share of incoming waste were analyzed due to a high degree of uncertainty. Transport distance of food waste and DM share of food waste proved to have a considerable impact on the energy efficiency and

environmental benefit for every evaluated biogas facility.

The calculated values were compared with relevant literature in order to assess the validity. The results generally corresponded well with values obtained from literature. Discrepancies may be due to differing system boundaries utilized, inaccurate assumptions made and inadequate data provided.

Detailed information regarding the operation of the evaluated biogas plants is needed in order to improve the validity of the calculated results. Due to several sources of error, none of the values obtained in this study are believed to hold for actual operations. Nonetheless, they might provide indications regarding possible focus areas for improved operation.

Samandrag

Ei kontinuerleg aukande energietterspurnad og eit auka fokus på miljøvenlege energikjelder krev stadig utvikling og bruk av alternative energikjelder. Avfallsproduksjon er ein naturleg konsekvens av ein moderne livsstil. Ved å utnytte avfallet til biogassproduksjon genererast grøn energi, samstundes som avfallet handterast på ei forsvarleg måte. Biproduktet frå biogassproduksjon er rikt på næringsstoff og vert dermed sett på som ein verdifull ressurs i landbruket.

Denne masteroppgåva omhandlar produksjon av biogass frå organisk avfall. Fleire biogassproduksjonsanlegg vart analysert i eit forsøk på å evaluere produksjonsutbyttet og energieffektiviteten til anlegga. Modellar vart utvikla basert på prinsipp frå materialstrømanalyse for å representere verdikjeda for biogassproduksjon. Miljøfordelen ved biogassbruk vart vurdert for kvart anlegg ved å berekne mengda unngått CO_2-utslipp.

Utbyttefaktorar berekna basert på innkomande mengde VS var høgare enn utbyttefaktorar berekna basert på innkomande mengde DM og våtvekt. Den berekna energieffektiviteten varierte frå om lag 26% til rundt 80%. Energieffektiviteten var høgare for anlegg som produserer oppgradert biogass, truleg grunna det auka energiinnhaldet i den oppgraderte gassen. Den berekna miljøfordelen ved biogassbruk var positiv for alle dei studerte anlegga, uavhengig av korleis biogassen vart nytta.

Ei sensitivitetsanalyse vart gjennomført for å evaluere påverknadskrafta til bestemte parametrar på energieffektivitet og miljøfordel. Parametrar knytt til transportavstandar og DM mengde av innkomande avfall vart analysert grunna høg grad av usikkerhet. Transportavstand for matavfall og DM mengde av matavfall

viste seg å ha betydeleg innverknad energieffektiviteten og miljøfordelen for alle dei evaluerte anlegga.

Dei berekna verdiane vart samanlikna med relevant litteratur for å vurdere gyldigheita av resultata. Resultata samsvarte i hovudsak godt med tall henta frå litteratur. Avvik kan skuldast ulike systemgrenser, urimeleg anteke verdiar og eit utilstrekkeleg datagrunnlag.

Meir detaljert informasjon med omsyn til drifta ved dei evaluerte biogassanlegga er naudsynt for å forbetre validiteten av dei berekna verdiane. Fleire feilkjelder er til stades og resultata kan derfor ikkje sjåast på som representative for den faktiske drifta ved dei evaluerte biogassanlegga. Like fullt kan dei gje indikasjonar på moglege fokusområde for forbetra drift.

Nomenclature

AD Anaerobic digestion

BA Bellersheim Abfallwirtschaft

BBR Billund BioRefinery

BOD Biochemical oxygen demand

BW Biogas Wien

CBG Compressed biogas

CH_4 Methane

CHP Combined heat and power

CO_2 Carbon dioxide

DM Dry matter

DMF Den Magiske Fabrikken

GWh Gigawatt hours

H_2S Hydrogen sulfide

kWh Kilowatt hour

LBG Liquid biogas

LHV Lower heating value

LNG Liquid natural gas

MFA Material flow analysis

MJ Megajoule

Nm^3 Normal cubic meter, gas volume at 273, 15 K (0 °C) and 1,01325 bar

NOx Nitrogen oxides

ppm Parts per million

PSA Pressure Swing Adsorption

RBA Romerike Biogassanlegg

SOx Sulphur oxides

THP Thermal hydrolysis process

TWh Terawatt hours

VFA Volatile fatty acids

VS Volatile solids

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1 Introduction

1.1 Background

Increased waste generation is a consequence of an ever-growing population, in combination with a throw-away mentality. Although waste prevention and minimization is top priority in the waste hierarchy, approximately 425 kg household waste per capita was produced Norway in 2017. It is therefore of utmost importance to develop efficient waste management strategies.

Society is dependent on a decoupling of increased welfare and economic growth from increased resource consumption to ensure sustainable development. The purpose of a circular economy is to create a looped value chain in order to optimize resource utilization, while simultaneously reducing waste generation to a minimum. Waste is considered raw material for production, thereby drastically reducing the need for virgin resources. In a circular economical perspective, no waste is generated as all resources are circulating. Waste handling and management will therefore play a key role in the implementation of circular economy.

The Paris agreement urges the member states to stabilize green house gas emissions and achieve a state of climate neutrality by 2050. Implementing a more circular economy has the potential to reduce emissions significantly. The European Union developed a plan of action in order to implement circular economy in 2015, where concrete measures and ambitious climate goals are presented for member states. The plan encourages the waste management sector to develop environmental friendly yet profitable solutions.

Biogas production is an example of a working circular economy, where waste is collected and refined into a profitable resource. The gas can be directly utilized for heat production and electricity generation, or upgraded and utilized as a fuel source. The by-product of biogas production can be utilized as fertilizer and thereby create a nutrient cycle, thus preserving scarce resources. Hence, biogas production reduces the need for petroleum-based energy sources, in addition to being a valuable resource in agriculture.

Biogas is utilized differently depending on available technology, plant location and government incentives. Evaluating the operation of various biogas production facilities could therefore help identify the advantage of the differing utilization methods in regards to the yield factor, energy efficiency and environmental benefit. The analysis may suggest focus areas for further improvement in order to optimize the production process. Efficient and profitable biogas production could lead to increased investment interest and further technological development, thus increasing the circularity of the economy.

1.2 Problem description

The object of this thesis is to evaluate the operation of the following biogas production plants: Billund BioRefinery (BBR), Bellersheim Abfallwirtschaft (BA), Den Magiske Fabrikken (DMF), Romerike Biogassanlegg (RBA) and Biogas Wien (BW). The yield factor, energy efficiency and environmental benefit in regards to CO_2-emission savings for the evaluated facilities are to be analyzed. The following tasks are to be considered:

- Carry out a literature study regarding topics of relevance to this project, with focus on relevant processes, technologies and methods utilized for biogas production.
- Develop general MFA-based models as a base for further analyzes. The models will include the total production chain, from waste entry to product delivery, and should be able to handle different types of input and a varying output distribution.
- Collect necessary information and data in order to calculate the yield factor, energy efficiency and environmental benefit of the evaluated biogas plants.
- Perform a sensitivity analysis in order to evaluate the impact of specific parameters on the energy efficiency and environmental benefit.
- Compare the calculated results with values obtained from literature in order to evaluate the validity of the calculations.
- Present the main results and discuss strengths and weaknesses of the work and methods applied.

1.3 Problem scope

The problem description states that data should be collected in order to develop models used for assessing the operation of the evaluated biogas facilities. However, due to difficulties acquiring data and inadequacies in the data received, developing precise models and calculating realistic values proved challenging. The calculated results should therefore not be considered representative for the actual operation of the biogas production plants. Hence, caution should be exercised when utilizing the specific values found in this project.

It was initially intended to perform a cost-benefit analysis of the biogas plants evaluated. However, an unwillingness to share economic data due to competitive reasons led to a severely lacking and inaccurate database, thus making reasonable calculations impossible. It was therefore decided, in agreement with the responsible supervisor, to exclude this part from the thesis.

1.4 Relation to specialization project

Segments of the literature study and methodology were obtained from a previous specialization project written by the author of this master thesis. The project had course code TEP4570 and was a specialization project at NTNU within the field of energy planning and environmental analysis. The project assessed the energy balance of biogas production at RBA. The specialization project was graded, but not published.

2 Literature study

This section presents the literature study regarding topics of relevance to this project. Emphasis has been put on relevant processes, technologies and methods. Information is gathered from existing literature and research found in reports, books, scientific journals and articles.

2.1 Biogas and bio-fertilizer

Biogas is a mixture consisting mainly of methane and carbon dioxide, which is produced through a biologic process where organic material is broken down in the absence of oxygen. This process is known as anaerobic digestion. Biogas can be produced using various organic matters, such as food waste, manure, plant material and sewage. Mixing and varying the share of the different substrates can improve the biogas yield.

Biogas is a flexible energy carrier that can be used for heating, electricity generation and fuel. When used as fuel, 1 Nm^3 of biogas corresponds to 1 L of gasoline or diesel [2]. The main emissions when burned are steam and carbon dioxide. Biogas produced from waste products and renewable resources is part of the natural cycle, and the net addition of carbon dioxide to the environment will therefore amount to zero. Other emissions, such as NOx, SOx, and particles, are considerably reduced when comparing biogas fuel to fossil fuel. Biogas is therefore considered an environmental friendly fuel.

The residual product, digestate, has a high nutrient content, which can be utilized as fertilizer in agriculture and therefore kept inside the agricultural cycle. Producing artificial fertilizer is energy demanding, and utilizing digestate as bio-fertilizer would thus have an energetic benefit as well.

According to Miljødirektoratet, biogas production has realistic potential to reach 2,3 TWh in 2025 if the right measures are utilized. The current production is approximately 0,5 TWh, and the remaining realistic potential comes from wet organic waste (ca. 1 TWh) and manure (ca. 0,7 TWh). Utilizing sources like wood, algae and fish sludge could further increase the future potential [69].

Buses are currently the most important fuel-market for biogas, with over Norwegian 700 buses running on bio-fuel. Long distance transport is a growing market for biogas, due to gas tanks weighing less than batteries per energy unit. Other potential markets are construction and shipping industry. Biogas could be used as fuel to stationary machines on construction sites, or added to the LNG-mix and used as ship fuel [77].

An increased focus on sustainability and circular economy will lead to new demands from consumers and producers, as well as new regulations from the government. This might result in increased amounts of sorted waste and improved waste handling, which in turn could boost biogas production.

2.2 Substrates

The main components in biogas are methane and carbon dioxide. The share of methane and carbon dioxide varies depending primarily on the composition of fat, carbohydrates and protein in the substrate mixture.

Table 1 shows the gas yield and the biogas composition for fat, proteins and carbohydrates for a complete anaerobe decomposition of 1 kg organic substrate.

The values are obtained from *Substrathandbok för biogasproduktion*. The degradation rate is lower in reality, but the values give an indication of the yield from the various substrates. Fat gives both a high gas yield and a high methane share, while carbohydrates produce low gas quality (low methane share in the gas) and have a low methane yield [16].

Table 1: Biogas and methane yield from various substrates [16]

Substrate	**Biogas**	**Methane**	**Methane share**
	Nm3/kg VS	Nm3/kg VS	%
Fat	1,37	0,96	70
Protein	0,64	0,51	80
Carbohydrate	0,84	0,42	50

Even though it is desirable to add fat to the substrate mixture to increase the gas yield, precautions need to be taken. Adding too much fat can result in the fat hardening and sticking to containers and pipes. Excessive amounts of fat might also inhibit the biological digestion of other substances [34].

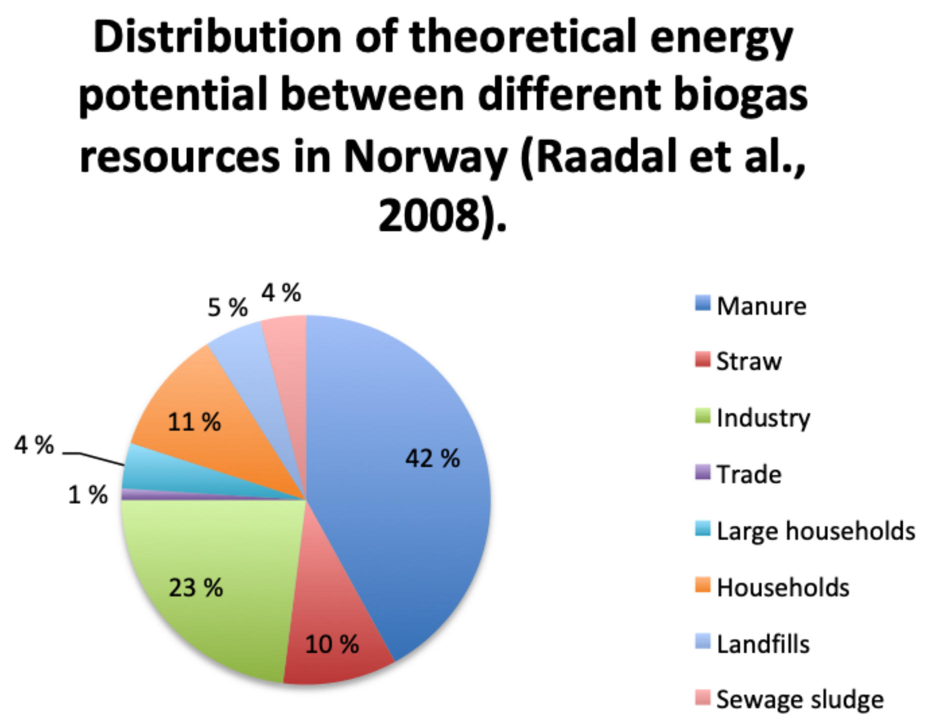
Table 2 shows important properties of some of the most relevant substrates in biogas production. The data is obtained from [44]. Food waste has a high biogas potential due to the large share of VS and a high content of protein and fat. However, the feedstock is diverse and the biogas potential will vary with the food waste composition. Straw and grass also have significant energy potentials, but the substrates need elaborate pretreatment before utilization. Even though the biogas potential of cattle manure is not particularly high, the substrate contains the necessary bacteria to act as an anaerobe reactor, which helps initiate the degradation process. It is therefore desirable to combine manure with different substrates.

Table 2: Important properties of relevant substrates [44]

Substrate	DM	VS	Specific methane potential	Methane share	Methane produced
	%	%	m3/kg VS	%	m3/m3 manure
Cattle manure, liquid	7-10	80	0,15-0,2	60	8,4-16
Cattle manure, solid	20-30	80	0,15-0,2	60	24-48
Pig manure, liquid	5-7	80	0,25-0,3	62	10-16,8
Pig manure, solid	20-30	80	0,3	62	40-72
Poultry manure, liquid	5-10	80	0,3	65	12-24
Poultry manure, solid20-30	20-30	80	0,3	65	48-72
Straw	70-90	80-90	0,15-0,30	0,5	-
Grass	20-25	88	0,3-0,55	56	-
Food waste, municipal	20-30	85-90	0,45-0,55	65	-
Food waste, industry	25-30	87	0,5-0,6	63	-
Horse manure	30	80	0,17-0,25	-	-

Østfoldforskning and UMB found the Norwegian theoretical energy potential from biogas resources from waste and by-products to be approximately 6 TWh/year in 2008. Figure 1 shows the distribution of theoretical energy potential between different biogas resources in Norway. The numbers are obtained from [56]. Manure represents the biggest potential (42%), followed by industry waste (23%) and household waste (11%).

Figure 1: Distribution of theoretical energy potential between different biogas resources in Norway [56]



Degradability, DM content and process temperature also affects the biogas composition [53]. The more time the substrate spends in the reactor, the more degraded the substrate will become, resulting in a higher methane share. A low DM content will result in a higher methane share, as the amount of carbon dioxide that can be dissociated in water increases with an increasing water concentration. A reactor temperature of 35-42 °C (mesophile process) will result in a biogas with higher methane content, than biogas produced with a reactor temperature of 50-60 °C (thermophile process). This is due to the amount of soluble carbon dioxide decreasing with increasing temperature [56].

The DM content in a material indicates the amount of other compounds remaining after the water content is evaporated at 105 °C [16]. It is often necessary to dilute a substance with a high DM content (>10-15%) for it to be able to operate in the reception systems, pumps and stirring processes. However, some substances can have a high DM content and still be pumpable. Substances with a low DM content (<10%) can be used to water out thicker substances, and thus improve the mechanical processes [16].

Volatile solids (VS) indicates the amount of combustible materials at 550 °C in a material. It is used to calculate the amount of organic material in a substance [16]. Some materials with a high VS content, such as plastic and lignin, cannot be broken down in the biogas production. The VS content is therefore not equal to the share of biological degradable material. A BOD analysis could be performed in order to better quantify the share of degradable organic material. The analysis measures the amount of oxygen required to aerobically degrade an organic material [4].

2.2.1 Food waste

The DM content in sorted food waste varies after the removal of reject. A base value of 33% DM for sorted food waste was used by [43]. Norgaard & Sørheim (2004) preformed several studies on Norwegian treatment facilities, and found the DM content to vary between 34,1% to 41% with a mean value of 37% [47]. The biogas yield of sorted food waste also varies. According to Carlsson & Uldal (2009), a biogas yield of 461 m^3 methane/ton VS and 204 m^3 biogas/ton wet weight is expected [16]. However, *Mikrobiologi för biogasanläggningar* states that the potential yield spans from 400 to 600 ^{3}/ton VS [29].

Sorted food waste from households often requires some sort of pretreatment before further entering the biogas production process. A thorough separation, dewatering and removal of plastics and metal are often necessary. Food waste is a well-suited substrate in the biogas process due to its high biogas yield. However, the yield may vary depending on the sorting quality and pretreatment method, as well as waste composition. It is therefore important that the food waste is varied to ensure a good balance of carbohydrates, proteins and fat [34].

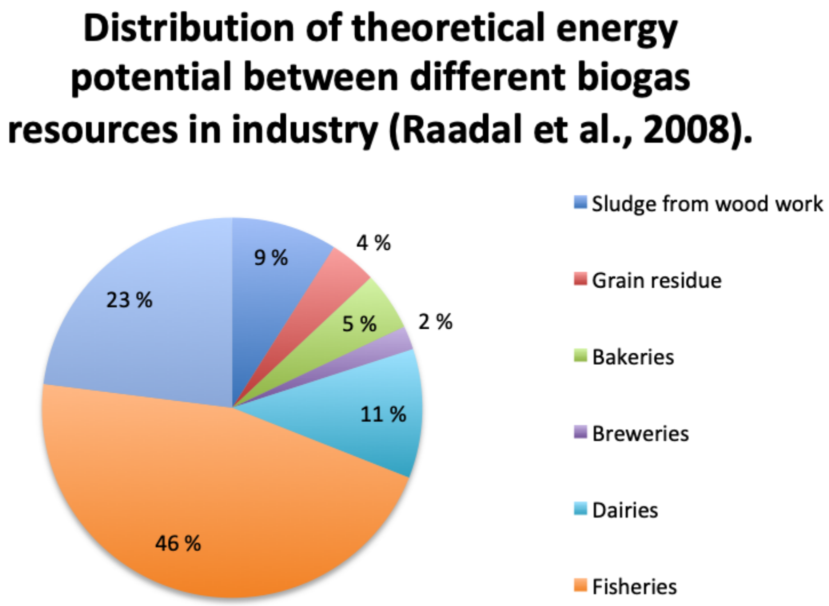
Sorted food waste contains a large proportion biodegradable organic fractions, which may cause a risk of decreasing pH as well as accumulation of VFA in the reactor. This is due to the rapid acidification that occurs during the decomposition of this type of waste [15].

2.2.2 Industry waste

Some of the waste and by-products produced in industry may represent biogas resources. This is especially true for industries such as meat production, dairies, fish farms, breweries, bakeries and wood processing. Food waste from industry is relatively similar in composition to food waste from households, but it might be better sorted and contain more fat [16].

A study conducted by Østfoldforskning and UMB, found the total theoretical biogas potential for Norwegian industry waste to be approximately 1,4 TWh. However, the survey is not complete as not all industries are included and because data gathering was complicated [56]. Figure 2 shows the theoretical energy potential of different industries. The numbers are obtained from [56]. Fisheries are the industry with the biggest energy potential. However, 70% of the potential in fisheries is already utilized as raw materials in feed [56]. Meat production and dairies also have great energy potential, 322 GWh and 154 GWh respectively.

Figure 2: Distribution of theoretical energy potential between different biogas resources in industry [56]

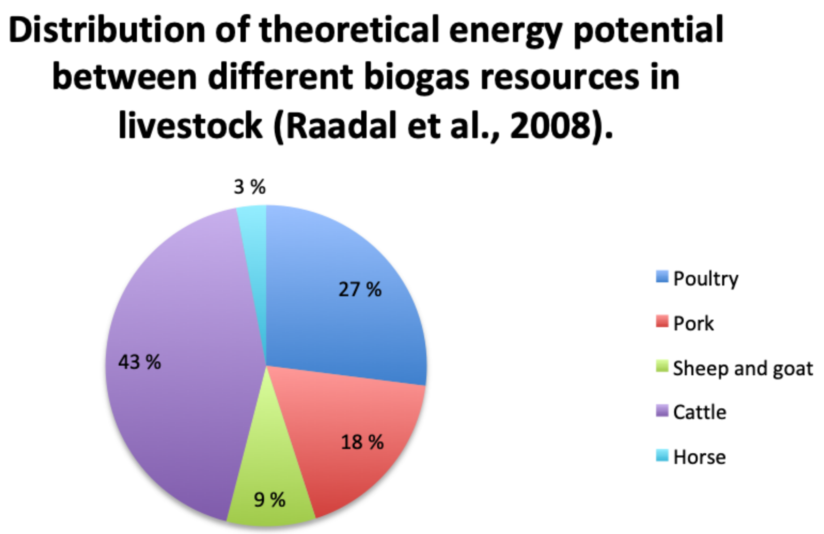


2.2.3 Manure

The Norwegian government has decided that 30% of the livestock manure should be utilized in biogas production by 2020. This will reduce the green house gas emissions by approximately 0,5 million ton CO_2-eq [40].

According to research done by Østfoldforskning and UMB, Norwegian manure has a theoretical energy potential of ca. 2.480 GWh/year. Different manure types have different methane yields. Decomposition of cattle manure will normally result in methane content of 60%, while pig- and poultry manure will give a methane content of about 65-70%, due to a higher protein content. The theoretical biogas yield of the various manure types studied can be found in figure 3, and the numbers are obtained from [56].

Figure 3: Distribution of theoretical energy potential between different biogas resources in livestock [56]



The energy potential also depends on how the manure is pretreated. The amount of DM varies with the type of manure, where a high DM content gives a higher biogas yield. It is advantageous to dewater the manure before it enters the biogas production process, if it has a low DM content. This will reduce the volume that needs to be treated [56].

Some of the potential energy in manure is lost due to the anaerobe digestion happening in the animal's stomach. However, manure is still a valuable substrate, as it contains various nutrients and organisms that stabilizes the decomposing process. Biogas production happens within a pH range of 6,5-8,5. Food waste has a quite low pH, and the buffer capacity of manure is therefore very important for the gas production [42]. In addition, microorganisms in cattle manure help speed up the start of the process [16].

Using manure as a substrate can be problematic. Some manure types have a high mineral content, which might lead to sedimentation and formation of bottom sludge [56]. In addition, manure can contain traces of heavy metals [69]. These substances may stem from heavy metals in the feed or pollutants in the drinking water [68]. Approximately half of the DM is removed in the form of biogas during a production process. The remaining digestate might therefore have a higher heavy metal content than the input. Even though the fertilizer value (i.e. the concentration of nitrogen, phosphorus, potassium, etc.) does not change considerably during a biogas production, the share of heavy metals might increase [38]. This may lead to problems when livestock manure accounts for a significant part of the incoming substrates [43].

2.2.4 Fish sludge and silage

The interest in fish sludge and silage is increasing, both for use in biogas production to increase energy potential, and for use in fertilizer to preserve nutrients. The yearly emission of fish sludge from Norwegian fisheries corresponds to sewage sludge from 12 million people [34].

Fish sludge and silage generally has a great biogas potential due to its high energy content. The potential will however vary with the amount of food wastage in the sludge. Utilizing the full energy potential is difficult due to high concentrations of both protein and fat. Excessive amounts of these nutrients inhibit the biogas production by preventing the production of ammonium and long-chain fatty acids needed in the degrading processes [34]. According to Gebauer et al. (2016), it is possible to increase the methane yield by adding fish sludge and silage to manure substrate [25].

2.2.5 Sewage sludge

Research done by Østfoldforskning and UMB found the theoretical yearly energy potential of sewage sludge to be approximately 266 GWh/year [56].

Sewage sludge from wastewater treatment plants consists of organic material, nutrients and pollutants that are extracted from the wastewater at purification. Producing biogas of sewage sludge is quite common in Norway, as this is a way of handling the waste. However, biogas has normally been considered a by-product of the waste handling process. The lack of focus on the energy production has therefore resulted in a low degree of utilization of these facilities [56].

2.2.6 Co-digestion

Co-digestion is mixing a base-substrate with various substrates to create an optimal substrate mixture, which is used in the biogas process. Co-digestion usually results in a more stable and effective process, due to the optimal nutrient combination and material structure in the mixture. Thus, the capacity of the facilities can be better utilized, resulting in a higher gas yield [16].

Co-digestion has several ecological, technical and economical advantages compared to single-substrate usage. It is possible to attain a more optimal nutrient, mineral and trace combination by combining substrates that complement each other. The anaerobe digestion depends on the substrate composition in order to reach its full potential. A well-combined substrate mixture is therefore important for a high gas yield [16].

An example of co-digestion, is adding manure to food waste substrate. Livestock manure has a higher pH-value than food waste, and will therefore act as a buffer when added to the substrate mixture. This prevents the pH to decrease below the operational range of 6,5-8,5 [43], which would result in the gas production being brought to a halt.

Table 3 shows specific methane production by co-digestion of different substrates. The values are obtained from [15]. The methane yield increases with a larger share of food waste in the mixture.

Table 3: Specific methane production by co-digestion of different substrates [15]

Substrate mixture [%]				Process	Specific methane production [m3/ton]
Food waste	**Cattle manure**	**Industrial sludge DM**	**Biological sludge DM**		
25	25	50		Wet	87
25	50	25		Wet	116
75	12,5	12,5		Wet	250
90	5	5		Wet	245
82	12		6	Dry	750
90	10*			Dry	630

* wet weight

2.3 Pretreatment

Pretreatment includes the treatment processes waste undergoes, from reception at the production plant to entering the biogas reactor as a substrate. The purpose of the pretreatment is to produce a clean and manageable substrate, with little loss of organic material, while minimizing the consumption of energy and other input factors [37]. The digestibility of the substrates is improved, by making the nutrients easily available to the microorganisms in the biogas production process [64].

Pretreatment could increase the biogas yield and improve the process efficiency. Another important aspect of pretreatment is the removal of foreign objects [37]. These impurities must be removed in order to protect the plant from mechanical failure and produce an output that can be used in agriculture [27].

According to Bochmann and Montgomery (2013), pretreatment technologies can be divided into three main categories: physical (including mechanical shear, heat, pressure and electric fields), chemical (acids, bases and solvents) and biological (microbial and enzymatic). It is also possible to combine different pretreatment methods in order to increase the efficiency, as different technologies perform better with different substrates [13].

High equipment costs, vast energy requirements and consumption of large volumes of chemicals are often associated with the current pretreatment technologies [13]. An ideal pretreatment technology should prepare the substrate for biogas production, without generating toxic by-products. It should have a low energy demand and be cost-efficient [51].

2.3.1 Physical

Rodriguez et al. (2016) defines physical pretreatment as methods that do not require external compounds such as chemicals, water or microorganisms during the pretreatment process. Examples of physical pretreatment methods are mechanical, thermal, ultrasound and microwave methods [60].

Mechanical

Mechanical pretreatment reduces the particle size, in order to reduce the constraints on heat and mass transfer caused by size [60]. The method makes the substrate more accessible for microorganisms, improving the speed and efficiency of the hydrolysis [45]. Common types of mechanical pretreatment are cutting, milling, shredding, chipping and grinding. The different treatment techniques have different effects on the biogas yield, depending on the type of substrate used [65].

Mechanical pretreatment can significantly improve the biogas production. However, the high energy requirement is a challenge [45]. The energy consumption depends on particle size reductions, as well as the structure and moisture content of the substrate used. Different treatment methods have different energy requirements [65].

Thermal

Thermal pretreatment improves the efficiency of the anaerobe digestion, by applying heat to solubilize the substrate [45]. The method reduces the viscosity of sewage sludge and increases the solid content in the dewatered cake [61]. Another benefit of thermal pretreatment is the elimination of pathogens. This sanitation of the substrates is advantageous when the biomass is stored and not used immediately following the pretreatment process [60].

Examples of thermal pretreatment methods are steam explosion and liquid hot water. Steam explosion has several beneficial features, including low environmental impacts and significant improvements of the hydrolysis process. However, the process requires large amounts of energy. Liquid hot water treatment produces less inhibitory by-products compared to steam explosion. The costs are manageable and no chemicals are required. The method is currently not developed at a commercial scale, due to high water and energy demand [39].

Ultrasound and microwave

Ultrasound technology is a pretreatment method used to disintegrate the substrate, by utilizing force generated by cavitation bubbles during high intensity ultrasonic waves [18]. Microwave technology can change the structure of the substrate by irradiation. It has a short reaction time and heats the substrate homogenously [39]. Both technologies require large amounts of energy, and might produce inhibiting components. The methods are relatively complex and require constant monitoring of equipment [65].

2.3.2 Chemical

Chemical pretreatment methods are initiated by chemical reactions for disruption of the biomass structure [65]. The methods disintegrate substrates through the actions of acids, alkali and oxidants [64]. The main disadvantage related to chemical pretreatment is the excessive energy requirement needed to reach high operational temperatures. In addition, formation of inhibiting by-products is possible, and the presence of acids at high temperature could be corrosive [39]. Chemical pretreatment is highly expensive, and usually used for substrates that otherwise could not be digested [60].

2.3.3 Biological

Biological pretreatment is based on bacteria and microorganisms degrading the substrates. Various fungi and bacteria are used in different pretreatment techniques, including brown-, white- and soft-rot fungi [60]. The method has several benefits compared to other pretreatment technologies, including low energy requirements and mild environmental conditions. It does not require chemicals and the operational costs are low [39]. Nevertheless, the treatment efficiency is too low for most industrial purposes. According to Agbor et al (2011), a residence time of 10-14 days is required, in addition to large amounts of space [3]. Another drawback of biological pretreatment is odour generation [64].

2.3.4 Combined pretreatment

Combined pretreatment is when various pretreatment methods are combined in order to optimize the process to obtain a higher biogas yield. Physical and chemicals methods are commonly combined in order to increase sludge solubilisation [64]. Treating the substrate thermally prior to mechanical treatment might decrease the amount of energy required for size reducing processes [65].

An effective pretreatment method should, among other things, increase the biogas yield, while minimizing energy demand and operational costs. The method should not produce inhibiting by-products and large amounts of residues, and the consumption of chemicals should be minimized [45]. Further research is necessary in order to establish the application range and efficiency of potential pretreatment combinations. Energy requirements and costs should also be evaluated.

2.4 Thermal hydrolysis

Thermal hydrolysis improves the performance of the biogas production by increasing the degradability of the substrate and the digestion loading rate. The method also enhances the dewaterability [6]. By applying pressure-cooking followed by rapid decompression, the substrate mixture is sterilized and made easier degradable [79]. This results in an increased biogas yield and a high quality digestate.

The technology requires energy in order to maintain an operational temperature. It is therefore crucial to optimize the temperature and the quantity of the substrate being processed. The increased energy yield combined with a higher energy demand results in a net energy balance similar to only using anaerobic digestion, when only concentration on anaerobic digestion and co-generation. However, the energy benefits become clear when studying processes further downstream, where the enhanced dewaterability reduces the need for energy related to transport and processing requirements [6].

2.5 Biogas production

Biogas production or anaerobic digestion is the process of breaking down microorganisms without access to air. The process occurs naturally in nature, when dead plants and animals are broken down in swamps and wetlands. It is also possible to control the process in facilities in order to produce biogas. The method is a way of handling waste, while simultaneously generating biogas and producing a nutritious bio-fertilizer.

The decomposing process happens anaerobic in closed biogas reactors, which are fed with pumpable or grounded material [22]. The interaction between the various microorganisms that carry out the decomposition has a major impact on the stability and efficiency of the biogas process [30]. The decomposition of a substrate can last 14-30 days, depending on the type of substrate and the type of biogas facility (industrial or farm facility) [11]. The operational temperature is also important in order to obtain a high quality digestate [34]. Operational conditions should ideally be held stable, as sudden changes could reduce the degradation efficiency and result in lesser quality products [35].

Biogas production processes can be classified according to various criteria, including DM content, temperature and number of stages.

2.5.1 DM content

Christensen (2011) states that the moisture content in the biological reactor determines the division into wet or dry processes. The moisture content in the substrate determines the moisture content in the processes. Processes with moisture content below 75% are classified as dry processes. Wet processes usually have moisture content above 90% and the substrate is liquid [17].

2.5.2 Temperature

Three main temperature zones are found in anaerobic digestion [56].

- Psychotropic. The temperature is below 20 °C and the decomposition rate is low.
- Mesophilic. The temperature can vary between 32-42 °C, with an optimal temperature of 35 °C. The decomposition time is approximately 20 days.
- Thermophilic. The temperature varies between 48-55 °C. Decomposition usually happens within 8 days under optimal conditions.

The division of temperature zones is due to microorganisms having different optimal temperatures for operation. Even though a thermophile process has the highest efficiency, the substrate mixture could become unstable as the microorganisms become more sensitive to hydrogen sulfide and ammonia. A thermophile process also has additional costs related to extra heating and insulation required. A mesophile process is therefore preferable [48].

2.5.3 Number of stages

Separating the biogas production into several stages can increase the efficiency and improve the stability of the process. The separation allows for different operation conditions, which may increase the biogas yield. However, the technology is complex and costs are high [1].

2.6 Outputs from anaerobe digestion

The anaerobic digestion process produces biogas and digestate. According to Christensen (2011), usually around 70% of the energy content in the substrate is converted to biogas. Once the gas has been removed, the remaining substance is known as digestate or bio-fertilizer [17].

Biogas consists of methane and carbon dioxide as well as water vapour, nitrogen, hydrogen sulphide, ammonia and other gases. A methane content of 45-70% and a carbon dioxide content of 25-45% is commonly assumed [7]. The composition and properties of the biogas depends on the substrate mixture and the treatment methods utilized [50].

There are various types of bio-fertilizer. Liquid bio-fertilizer has a DM content of approximately 3-8% and a high nutrient content. The liquid bio-fertilizer is produced in the reactor. Dewatered bio-fertilizer has a DM content of approximately 15-25% and a high share of phosphorus. It is possible to further increase the DM content by drying and pelleting. Reject water is the residual water derived from the dewatering process [22]. Usually around 80% of the nitrogen in the substrate ends up in reject water [26].

2.7 Utilization

2.7.1 Heat production

Biogas can be utilized for heat production by incinerating it directly in a boiler. The heat can be used internally or in local district heating networks. This utilization technology is considered simple, and is mostly used in small plants where additional technology is considered too expensive to be beneficial [17].

2.7.2 Electricity production

Electricity is generated by utilizing biogas in a gas turbine or in an internal combustion engine that is connected to a generator [63]. It is necessary to eliminate CO_2, H_2S, water vapor and other undesired particles from the gas, in order to ensure optimal operation of the electricity generation process. The produced electricity can be utilized internally by the production plant or sold to the grid [72]. Recovered waste heat from the engines can provide heating or hot water for internal use.

2.7.3 CHP production

Utilizing biogas for CHP production is common. The gas can be used in standard gas engines by removing water and hydrogen sulphide. The process results in electricity and heat, which can be fed into the national grid and used in district heating networks. It is also possible to utilize some of the heat in AD process control and for sterilizing the feedstock. Research done by Pöschl et al. (2010) found that small-scale biogas plants usually have a higher thermal efficiency that large-scale biogas plants. The same can however not be said about the electrical efficiency, where large-scale biogas plants were found to have an efficiency of approximately 11,25%, while the efficiency of the small-scale plants was ca. 9,09%

[54].

2.7.4 Upgrading

Purification of biogas is done in order to reduce the amount of contaminants that can cause damage, disadvantages or adverse environmental effects. In addition, it is a way to increase the calorific value of the gas. The degree of upgrading necessary depends on the composition of the gas and its field of application [50].

The most common contaminants that are removed are particles, water vapour and hydrogen sulphide. It is also possible to remove nitrogen, however, the necessary technology is expensive [50]. The gas utilization and treatment technologies vary across Europe, depending on the country's priorities and economic subsidies [17].

Østfoldforskning og UMB studied several Norwegian biogas facilities and found that on average 53% of the produced biogas was utilized in heat production. Approximately 19% was commonly flared, while 18% was used to produce electricity. Only 2% of the produced biogas was upgraded [56].

Fuel production

Biogas must be cleaned and upgraded to at least 95% methane, in order to be used as fuel for vehicles. The gas is upgraded in a facility where CO_2 is removed. Through advanced compressor and washing systems, a purity of up to 99% methane can be achieved. The gas is then pressurized or liquefied for transport to the costumer [22]. Using biogas as fuel can reduce the green house gas emissions by 100% compared to fossil energy sources. Additionally, emissions of harmful particles like NOx and SOx are reduced [58].

Natural gas substitute

It is possible to use upgraded biogas as a substitute for natural gas by injecting it into the gas grid [54]. However, the biogas needs an even higher degree of purity than for vehicle fuel. The necessary technology is under development, and the process is highly subsidized due to high operational costs [17].

2.8 Upgrading technologies

Several upgrading technologies currently exist. A few of the most common technologies are presented below.

2.8.1 Water washing/absorption with water

The technique is based on carbon dioxide dissolving easier in water than methane. Pressurized crude gas is led into the bottom of an absorption tower while water is led into the top of the tower. Methane and carbon dioxide separate when the steams of gas and water meet. Carbon dioxide dissolves in water, while methane remains as gas [48]. The water is then transferred to a flash tank where the pressure is reduced and carbon dioxide is released from the water. If desired, the water can be vented and used again. An advantage of water washing is the removal of particles and hydrogen sulphide. However, the gas will be saturated with water vapour, which may be necessary to remove [50].

2.8.2 Absorption with chemicals

The technique is similar to absorption with water, but chemicals are used instead of water. It is not necessary to pressurize the gas due to the chemicals. The technique can experience methane losses less than 0,1% when optimized [56]. However, large amounts of energy are required in order to release carbon dioxide from the chemicals [48]. The effect will vary depending on the chemicals, pressure and temperature used.

2.8.3 Cryo technique

Carbon dioxide is separated from the methane by pressurizing and cooling the biogas down to a temperature of -85 °C, where the carbon dioxide condensates. Reducing the temperature to -161 °C will result in LBG. The methane is now liquid, and 600 times more biogas can be accommodated in a tank than at atmospheric pressure [48]. The main drawbacks of this technique are the high energy requirements and operational costs [56].

2.8.4 Membrane separation

The technique is based on molecules in carbon dioxide and methane having different shapes and sizes. The biogas is led through a membrane by applied pressure, which retains carbon dioxide while the methane passes through. It is however difficult to achieve a high methane share using this technique [50]. Another drawback is methane and nitrogen having similar properties for membrane penetration, making it challenging to remove nitrogen [56].

2.8.5 Pressure Swing Adsorption (PSA)

The technique utilizes a molecular sieve, which retains molecules over a certain size while smaller molecules are pushed through. The size of the molecules retained depends on the chosen adsorbent material. In the adsorption step, carbon dioxide, oxygen and nitrogen will adsorb on the surface of the adsorbent. Purified gas typically contains > 97% methane [50]. According to Raadal et al. (2008), PSA techniques usually experience a methane loss of around 2% [56].

2.9 Post-treatment

Digestate is further treated after the anaerobe digestion in order to obtain proper conditions for final utilization or disposal. Dewatering, wastewater treatment, composting, and storage facilities for digestate are examples of post-treatment techniques [17]. If the digestate cannot be used on land, it is possible to subject it to wastewater treatment in order to remove organic matter and nitrogen. Depending on available technology, this can either be done within the facility or at local wastewater treatment plants [17].

Separating the digestate into liquid and solid fractions, along with loading, transport and spreading of the final fertilizer products, accounts for the primary energy input in the post-treatment processes [54].

2.9.1 Fertilizer

The nutrient content of the digest is highly dependent on the substrates involved in the production process. It is normally very nutritious, and can be used as a high quality fertilizer with similar properties as conventional fertilizer. Utilizing bio-fertilizer can therefore reduce greenhouse gas emissions and the consumption of energy and materials resources related to the production of artificial fertilizers [34]. Additionally, important nutrients, such as phosphorus and nitrogen, are preserved.

2.10 Distribution of biogas product

Produced electricity can easily be transported over long distances and is used throughout the year. Produced heat must however be utilized locally, and the demand normally fluctuates strongly throughout the year [26].

Biogas used as fuel can be transported either in a compressed or liquid form. The gas is filled on isolated tanks, which is then transported to filing stations. Compression and liquefaction of biogas is advantageous both regarding transportation and storage. Liquid gas occupies approximately 2,5 times less space than compressed gas, thus increasing the geographical range of the fuel. However, the necessary liquefaction technology is complex and costly, and the demand for energy is high. Production of LBG is therefore only applicable for larger biogas plants [33]. Another option is to distribute the biogas through gas grids.

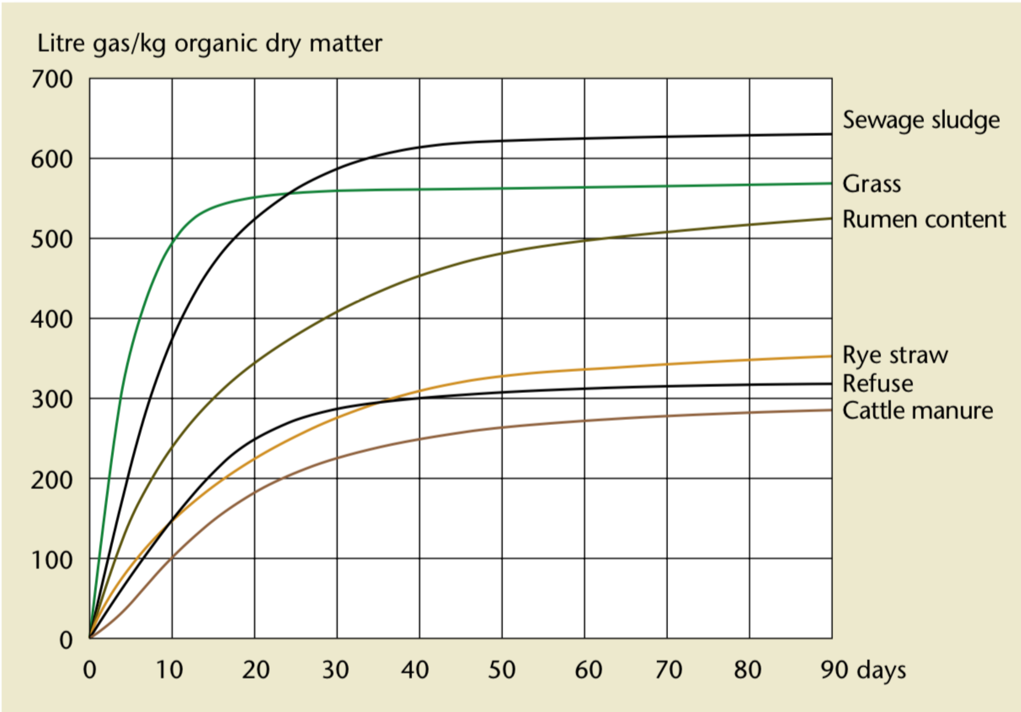
2.11 Performance of biogas production facilities

2.11.1 Yield factor

The yield factor is dependent on various factors, such as substrate composition, pretreatment techniques and the efficiency of the production processes. It is therefore crucial to optimize these variables in order to obtain a maximized yield factor.

Yngvesson and Tamm (2017) define the yield factor as the amount of methane obtained per ton substrate treated. The study provides a general biogas yield factor of 470 Nm^3 CH_4/ton DM [80]. Jørgensen (2009) emphasize that variations in substrate composition will affect the gas yield, with fatty substrates having a higher methane yield than substrates based on proteins and carbohydrates [31]. Figure 4 is obtained from [31] and presents an overview of how the biogas yield varies with the digestion of various organic materials at 30 °C. Sewage sludge, grass and rumen content were found to have a higher yield factor than rye straw, refuse and cattle manure.

Figure 4: Variation of biogas yield based on various organic matter treated at 30 °C [31]



Lind et al. (2019) analyzed the potential of a hypothetical biogas facility located in Helgeland, and found yield factors of 461 Nm^3 CH_4/ton incoming VS and 204 Nm^3 CH_4/ton incoming wet weight for biogas containing 63% methane. The yield factors are calculated based on incoming household waste [34]. Svenskt Gastekniskt Center (2012) presents a yield factor of 389,34 Nm^3 CH_4/ton incoming DM for biogas with a methane content of 63% [62].

2.11.2 Energy efficiency

The heat losses and the internal electricity consumption should be minimized in order to increase the energy efficiency of a biogas plant. The main internal sources of energy consumption are usually substrate heating, electricity needed for pumps, stirrers etc., and energy consumed during upgrading of the biogas, while fuel demand for transport accounts for a large share of the total energy demand.

Controlling the substrate temperature before it enters the heating process might reduce the electricity demand related to substrate heating. The heat demand of a biogas facility is relatively constant throughout the year. However, compensation for heat loss during winter increases the demand. Isolating reactors, pipes, tanks, hygiene tanks and other components is therefore important [44]. Increasing the efficiency of pretreatment processes will reduce the internal electricity demand.

Berglund and Börjesson (2006) analyzed Swedish biogas plants and found that the energy input corresponds to 20-40% of the energy content of the produced biogas, and concluded that the energy demand for operation of the biogas plant equals 40-80% of the total energy demand. Increasing the transport distance will eventually result in a negative energy balance. Furthermore, the research presents an average heat demand as 6-17% of the biogas energy produced, while an average electricity demand is given as 8-24% of the biogas energy produced. The study concludes that large deviations exist in regards to the energy efficiency of biogas plants, depending on the substrate composition, system boundaries and system design [8].

An electricity demand of 0,083 kWh/MJ of biogas produced was given in [55].

The study clarifies that assumption made regarding LHV and biogas yield would greatly affect the results. Yngvesson and Tamm (2017) evaluated several biogas facilities in order to identify improvement potential of the production line. The study presents a general energy efficiency of 35% for electricity production. The study defines the energy requirement of a biogas facility as the utilized primary energy divided by the received amount of substrate [80].

2.11.3 Environmental benefit

The environmental benefit of biogas and bio-fertilizer production varies depending on the substrate composition and the biogas utilization. It is important to evaluate which energy source is being replaced, as well as emissions stemming from alternative waste handling methods, in order to find the total environmental benefit linked to biogas production.

Raadal and Modahl (2009) compared the CO_2-emissions of biogas production with the emissions of composting, waste incineration and landfilling. Biogas production was found to have the lowest emission factor at 0,006 kg CO_2-eq/kg wet weight incoming waste, followed by composting and incineration, which had an emission of approximately 0,03 kg CO_2-eq/kg wet weight incoming waste. All waste management methods evaluated, except landfilling, resulted in saved GHG emissions. This is due to all the assessed methods producing goods that replace fossil energy carriers and possibly also artificial fertilizer. The magnitude of the avoided emission depends on which energy carrier is being replaced and how the digestate and compost is utilized [55].

According to Magnus (2014), the CO_2-emission per MJ biogas produced in Norway is approximately 0,032 kg CO_2-eq. The study evaluates the reduction of

CO_2-emissions due to biogas being utilized for heat production compared to an alternative fuel, and evaluates both Norway and Sweden. Swedish alternative fuel was found to contain a larger share of renewables and the degree of energy exploitation in Sweden was higher than in Norway. Thus, Norwegian biogas plants were found to have a greater potential for emission savings [36].

Pederstad (2017) evaluated the standard emission values related to transport and distribution in a biogas production process. This includes emissions related to the transport of raw materials, semi-manufactured and processed products, such as transport of incoming waste and transport of biogas products to filling stations. A standard value of 3 g CO_2-eq/MJ CBG produced was found based on organic municipal waste. The study assumes that biogas does not emit any CO_2-eq while utilized as fuel [52].

Fiksen (2016) calculated the avoided emissions when utilizing biogas as an alternative to fossil based energy sources. A reduction of 412 kg CO_2-eq/ton incoming DM was found based on food waste. Utilizing biogas based on food waste for electricity production resulted in a reduction of 374 kg CO_2-eq/ton incoming DM, while transport emissions were reduced by 799 kg CO_2-eq/ton incoming DM. Assumptions made regarding the fossil energy sources were a Nordic electricity mix, diesel fuel for transport and heat generated by a combination of waste, bio-energy, heat pumps, electricity and oil [22].

Replacing mineral fertilizer with bio-fertilizer could save approximately 13 kg CO_2-eq/ton treated organic waste, according to the European Biogas Association [19]. Additionally, bio-fertilizer is a by-product of biogas production, and could therefore provide economical benefits compared to artificial fertilizer, which requires separate production.

3 Methodology

A case study of the evaluated biogas facilities is performed in this chapter. The general MFA concept is presented, as well as the system definition and the models created. Data and assumptions are presented, along with the procedures conducted in order to calculate the desired indicators.

3.1 Case study

The case study provides an overview of the operation of the various biogas facilities evaluated, from the waste reception to the biogas utilization and post-treatment. The level of detail concerning the description of each biogas production facility varies with the information provided by the facilities themselves and the publicly accessible information.

3.1.1 Billund BioRefinery (BBR)

Billund BioRefinery (BBR) is located in Billund municipality in Denmark. Appendix H provides a process diagram of the operation at BRR. The biogas plant receives waste from Billund municipality. The residents of the municipality sort out the organic waste at home, which is collected and sent through a sorting and pulping unit located at the facility [57]. The facility has a capacity of 250 ton per day [32], and consists of a reception area for food waste, a reception area for liquid industrial waste and a hygienization facility. Two digesters are available, in addition to a gas storage tank, two gas engines and a storage location for bio-fertilizer [10]. The facility has the possibility of adding magnesium to the reject water stream, however, as of 2019, this feasibility is not being utilized [57].

Pretreatment

Waste is transported by trucks to the biogas facility. Sorted household waste is delivered to a closed reception bunker, while sludge and liquid organic waste is pumped into underground storage tanks. Wastewater is pumped into pipelines and mixed with the organic waste [32].

Solid household waste is passed through two shredders and a magnet separator in order to remove unwanted substances and reduce the particle size of the substrate. The household waste is homogenized together with wastewater, before the mixture is degassed in a digester as part of the pretreatment [32].

Thermal hydrolysis

The thermal hydrolysis process at BBR is based on the Danish EXELYS technology, which is meant to enable optimal biogas production from the biomass, while simultaneously reducing the production of sludge. The EXELYS technology increases the biogas production by 50% and reduces the sludge production by 30% [9]. The thermal hydrolysis process is part of a digestion–lysis–digestion configuration, where the substrate is pre-digested and dewatered prior to entering the EXELYS THP. Due to the pre-digestion, the energy demand of the processes decreases drastically [73]. Following the thermal hydrolysis, the substrate is mixed with the liquid organic industrial waste [32].

Anaerobic digestion

A second degassing is performed in order to ensure maximum exploitation of the gas potential in the substrate. The microorganisms in the digester convert the organic material into methane and carbon dioxide under oxygen-free conditions. The substrate is heated in order to create optimal operational conditions for the working bacteria. The retention time is 20-25 days, and approximately half of the incoming DM is converted into biogas [32].

Upgrading and utilization

The biogas is utilized in a biogas driven engine to produce electricity, which is sold to the public grid. The heat produced by the electricity generation is utilized as district heating in the Danish city Grindsted. [32].

Post-treatment

The remaining digestate from the anaerobic digestion is dewatered through a precipitation process, where magnesium could replace the current precipitation with iron. The digestate has a DM content of approximately 25% and is utilized as biofertilizer on agricultural land. Nitrogen is removed from the drained wastewater before it is discharged to a wastewater treatment facility [32].

3.1.2 Bellersheim Abfallwirtschaft (BA)

Bellersheim Abfallwirtschaft (BA) is located in Boden, west in Germany, and receives waste from the inhabitants of Westerwaldkreis and Altenkirchen [49]. The facility is run by the private company Bellersheim. The plant started its operation in 1999 and has, according to Ohr (2003), a maximum capacity of 43.000 tons incoming waste/year, mainly consisting of bio-waste from private households [49]. Fritz (2019) states that BA has an average yearly input of 30.000 tons incoming waste and produce approximately 3.500.000 kWh electricity per year. Additionally, 10.000 tons of compost is produced per year for agriculture [23]. A diagram presenting the various processes at BA is given in appendix H.

The biogas plant utilizes anaerobic mesophile methanogenesis in order to treat biological waste and produce energy and compost. By German law, the plant is allowed to treat municipal and industrial waste, such as sorted household waste and food waste from restaurants. In order to receive subventions for ecological energy production, the treated waste mixture at BA must have a composition of approximately 90% municipal waste and 10% industrial biological waste [23].

Pretreatment

BA has separate reception systems for solid and liquid waste. The solid bio-waste is discharged by trucks into the reception hall and then transported by a wheedled loader into a storage facility that feeds the pretreatment system with waste via a conveyor belt. The liquid waste is delivered to a separate reception facility and directly transferred to a buffer tank [49].

A magnetic separator removes iron and other magnetic material from the solid waste, before it is passed through a sieve in order to remove particles larger than 150 mm. The amount of debris produced from this sieving process amounts to approximately 10% of the incoming waste. However, the amount varies with the seasons. The debris mostly consists of twigs and branches [49].

The remaining substrate is grinded in order to further reduce the particle size, before the substrate is fed into two separate suspensers. Each suspenser has a volume of 10 Nm^3. Water with a temperature of 70 °C is added to the substrate in order to achieve a DM share of 10-12%. A rotor stirs the substrate for approximately one hour in order to remove inorganic material, such as sand, glass and ceramics. The substrate is then transferred to two separate hygienization tanks, each with a volume of 20 Nm^3. The substrate matter is continually stirred with a temperature of 70-80 °C for one hour in order to disinfect the treated material [49].

A sieve with 15 mm gaps removes plastics, twitches and other undesired substances. The substrate is then passed through an aired sand trap in order to remove sand and other heavy grit. This part of the pretreatment process is crucial for the reduction of abrasion on pumps and pipes, as well as for preventing a build-up of sand in the digester. The removed sand constitutes to approximately 5-10% of the incoming waste [49]. The remaining substrate undergoes a final shedding process in order to remove particles larger than 8 mm. The substrate is cooled down to approximately 35-40 °C through a pipe heat exchanger and transferred to a buffer tank [23].

Anaerobic digestion

Substrate is continually transferred from the buffer tank to the digester, which has a volume of 3.500 Nm^3. The operating temperature is mesophile and the retention time is 16-24 days. The microbiological community converts the organic matter into methane, carbon dioxide, water and other gases [23]. The biogas is compressed to 3 Bar [49].

The biogas production varies with the waste composition. Approximately 80 Nm^3 biogas/ton waste is produced during the summer months, while approximately 110 Nm^3 biogas/ton waste is produced during the winter months. The produced biogas has a methane content between 60-65%, with an average share of 62% [49].

Biogas utilization

The biogas produced at BA is used to produce electricity onsite with a 1.000 kW gas engine. The additional heat production from the engine is utilized internally, while the electricity is fed into the communal electricity system [23].

Post-treatment

Polymers are added to the digested substrate and dewatered by two separate centrifuges until a DM share of 30% is achieved. Each centrifuge has a capacity of 20 Nm^3 per hour [49]. The separated water is further cleaned in a wastewaster treatment facility, while the solid digestate is stored and used as fertilizer for agriculture [23].

3.1.3 Den Magiske Fabrikken (DMF)

Den magiske fabrikken (DMF) is located in Rygg, Norway, and receives waste from the inhabitants in Vestfold and Grenland, as well as industrial waste and manure from 34 surrounding farms. The incoming waste is used to produce environmental friendly bio-fuel for vehicles, bio-fertilizer used in agriculture and green, renewable CO_2 used in greenhouses [28]. DMF first full operation year was 2016 [76].

DMF is a collaboration project between Greve Biogass, Vesar and Lindum. Tønsberg municipality owns and finances the facility. Greve Biogass has been responsible for designing and building the facility on behalf of the municipality, and will also be responsible for further extensions. Lindum currently operates the biogas plant. The facility contributes to a significant reduction in climate emissions, and promotes green growth and value creation in the region. DMF was initiated by the municipalities, county authority and the agricultural industry in Vestfold [34].

Pretreatment

The facility consists of two separate production lines. One is used for food waste, while the other one is used for wastewater, sludge and manure [71].

Sludge is delivered by truck to reception tanks, before it is homogenized and sanitized as part of the pretreatment. The DM share is adjusted in order to make the substrate pumpable [24]. Plastics and other impurities are separated from the food waste before it is mixed with manure. The substrate is heated in order to remove unwanted bacteria [28].

Anaerobic digestion

The substrate in transferred through pipes to a digester with a volume of 9.000 Nm^3. The substrate is continually stirred and treated under mesophile conditions. The retention time in the digester is approximately 30 to 40 days [24]. The bacteria in the digester breaks down the substrate without oxygen access and creates biogas consisting of approximately 65% methane in the process [70].

Upgrading and utilization

The upgrading process is performed using a water scrubber technique, which removes carbon dioxide, hydrogen sulphide and nitrogen dioxide from the gas. This is done in order to enable gas distribution and compression [24]. The upgraded biogas produced at DMF is sold to Air Liquide Skagerak. The product is distributed directly from the biogas plant to tanking stations and industrial clients through a gas grid. Some of the CBG is transported via truck to the surrounding areas Horten, Moss and Grenland. Refuse trucks and buses in Vestfold, Grenland and the Moss region utilize the bio-fuel [28].

Post-treatment

The remaining digestate is dewatered and utilized as bio-fertilizer by local agriculture in Vestfold.

3.1.4 Romerike Biogassanlegg (RBA)

Romerike Biogassanlegg (RBA) is located in Nes, outside Oslo. It opened in 2012 and was the first biogas plant in Oslo designed to handle food waste. RBA receives solid food waste from households in Oslo and surrounding municipalities, as well as solid and liquid food waste from industries and commercial activities. The food waste is not supposed to contain antibiotics, pesticides, heavy metals, organic pollutants or other environmentally harmful substances. Additionally, glass, metal and styrofoam boxes should be separated from the waste prior to further processing. The food waste received from Oslo has been sorted in optical sorting systems.

RBA has capacity to handle 50.000 tons of food waste per year and produce around 45 GWh of bio-methane [52]. Production at this scale could supply 135 buses with biogas and 100 medium sized farms with bio-fertilizer. The facility received 7.300 tons of food waste in 2013. This resulted in approximately 1.164.000 Nm^3 biogas produced and 24.800 Nm^3 upgraded biogas. A total of 1.200 tons bio-fertilizer and 1.550 Nm^3 bio-fertilizer-concentrate was generated [21]. A report by Remøy et al. (2017) states that RBA delivered 1,1 million Nm^3 biogas in 2016, while 0,6 million Nm^3 biogas was used as heat internally. The plant delivered 43.000 tons liquid bio-fertilizer and 2.000 tons solid bio-fertilizer. The same report found that 30% of the biogas produced at RBA in 2016 was flared, and approximately 25% of the gas was used internally as process energy due to difficulties regarding planned gas delivery [59].

Pretreatment

RBA has separate pretreatment systems for solid and liquid waste. Liquid waste undergoes a simple pretreatment with cutting grinders (Rotacut), and is then pumped directly into the buffer tanks. Cambi's THP technology operates with a temperature above 133 °C, which allows for a particle size <50 mm [5]. The solid packaged waste requires a more thorough pretreatment, which happens in two parallel lines. The separate lines ensure high flexibility and redundancy in the system. Each line contains a grinder, a conveyor belt with a metal separator, two bio-separators, a pump tank and a strainpress. The capacity of each line is 8 ton per hour [5].

A crane brings the solid waste from the reception bunker to a bag opener (Acta-grinder). The waste is then passed through a magnetic separator in order to remove iron and other magnetic material, which is moved to a container and considered metal reject. The remaining waste is transported onto two separate, parallel lines by a spiral conveyor. Treatment in the bio separators removes plastic particles over 25 mm by adding water. The result is a pumpable substrate, which is transferred to a homogenization tank (pump tank). A strainpress is utilized in order to remove particles over 10 mm. The removed particles are considered fiber reject, and the remaining substrate is transferred to storage tanks (buffer tanks). RBA utilizes three buffer tanks in order to ensure a smooth distribution of waste, independent of quality of supply and irregularities in the previous pretreatment steps [20]. Each tank has a capacity of 100 Nm^3 [5].

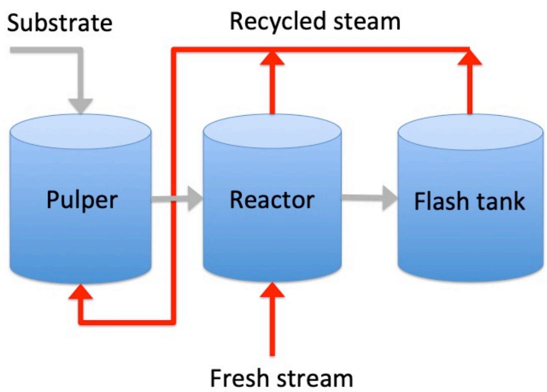
The main objective of the pretreatment process is to produce a substrate with a high DM content, which is suitable for thermal hydrolysis and anaerobe digestion. A high DM concentration in the substrate would increase the DM content in liquid bio-fertilizer, and reduce the energy consumption in the facility. Pretreatment is also done in order to remove potential rejects and plastic fractions [5].

Research done by Marthinsen (2017) found that RBA has had several operational disruptions due to foreign objects in the substrate mixture. This includes abrasion on facilities and equipment and accumulation of particles, which has required substantial maintenance and high operational costs. This has reduced the capacity of the biogas facility. Replacing the components and remodelling the pretreatment processes have solved some of the challenges related to foreign objects in the substrate mixture [37].

Thermal hydrolysis

RBA utilizes thermal hydrolysis technology developed by Cambi. A schematic of Cambi's thermal hydrolysis process is shown in figure 5. The process dissolves, disintegrates and sterilizes the substrate using pressure and temperature.

Figure 5: A schematic of Cambi's thermal hydrolysis process (F. H. Revheim)



The substrate at RBA initially enters a pre-heating tank, called a pulper. It is heated to approximately 97 °C by applying recycled steam from the flash tank and reactor. This reduces the viscosity of the substrate, leading to increased degradability and reduced retention time. Treatment in the pulper tank also helps reduce the odour. The DM content of substrate in the pulper is normally between 12-16% [5]. Homogenized substrate is then transferred to the reactor, where steam is applied in order to reach optimal operational temperature (165-170 °C) and pressure (6 bar). The substrate undergoes hygienisation and hydrolysation in the reactor [66].

The hydrolyzed substrate then enters a flash tank, where cells and fibers are broken down. After a retention time of 20-30 minutes, the pressure suddenly drops [35]. The technique is known as steam explosion, and further increases the degradability by tearing cells and fibers apart. Benefits of steam explosion include increased energy generation, increased digestion speed, a high DM content in the remaining sludge, and a reduced carbon footprint. Cambi reuses steam energy from the reactor and the flash tank, in order to make the process more energy efficient [41].

Anaerobic digestion

The biogas facility has two bioreactors, which both have a maximum capacity of 3.200 Nm^3. Each tank is able to treat 70% of the incoming waste, assuming 50.000 ton per year [5].

The substrate is transferred from the THP to the bioreactors, where it is broken down in an anaerobe process. The operational temperature in the bioreactors is 38 °C and the retention time is around 24 days. The process results in biogas consisting of approximately 60% methane and 40% other gases, mainly carbon dioxide. The residual product is called digestate and can be further utilized as fertilizer [20].

Biogas upgrading and utilization

The biogas is upgraded in order to maximize the methane content. The gas produced in the bioreactor contains approximately 40% CO_2 and has a H_2S content between 5-2.500 ppm. Upgrading reduces the CO_2 content to less than 2% and the H_2S to around 1 ppm [5].

The biogas produced in anaerobic digestion is pressurized before upgrading. RBA upgrades the gas by leading it through a compressor, in order to acquire optimal temperature and pressure. The gas is then led through a water scrubber filled with plastic beads, which causes the carbon dioxide to absorb to the water. The resulting biogas has a purity of 97-98% methane [20].

Liquid biogas accounts for one sixth of the volume compared to compressed biogas. Liquidation of biogas is therefore done in order to reduce costs related to transport and logistics. The process compresses the gas to 30 bar and absorbs the remaining CO_2 using molecular filters. The resulting biogas has a purity of over 99,9% and is cooled down to -166 °C. The gas is stored at approximately -159 °C at 2 bar, and can be filled on tanker trucks. The liquid biogas produced at RBA is sold to AGA [20].

Post-treatment

RBA produces three types of bio-fertilizers: liquid bio-fertilizer, solid bio-fertilizer and bio-fertilizer-concentrate. The digestate at RBA is moved through a strainpress in order to remove particles larger than 0,2 mm. The remaining substrate is pumped to a storage tank. The liquid bio-fertilizer produced as RBA has a DM content of ca. 4,5% [20].

Dewatering the remaining substrate results in solid bio-fertilizer. Polymers are added to the substrate, which is then centrifuged. This process binds the majority of the phosphor, improving the quality of the solid bio-fertilizer. The solid bio-fertilizer has a DM content of approximately 25%. RBA acidifies the extracted water prior to evaporation. This is done in order to further concentrate the nutrient value. The final product is a liquid called bio-fertilizer-concentrate, which is high on nitrogen and potassium. It has a DM share of around 15% [20].

3.1.5 Biogas Wien (BW)

The biogas production plant in Vienna opened in 2007 and is part of the Waste Treatment Department of the Municipality of the City of Vienna („MA 48"). The annual waste input is approximately 22.000 tons, which consists of biological waste collected from residential areas, as well as food scraps from restaurants and market waste. The produced heat supplies approximately 1.100 households with district heating. The facility is located within the city of Vienna and is therefore equipped with an air-cleaning system to prevent spreading odors [75].

Pretreatment

Solid incoming waste is delivered into two deep bunkers, while liquid waste is delivered by tank vehicles and discharged directly into a leak-proof storage container. The waste is grinded separately in order to achieve a maximum particle size of 200 mm for the solid waste and 40 mm for the liquid waste. Conveyor belts transports the solid waste to further processing, while the liquid waste is pumped directly into the turbo mixer using high consistency pumps [12].

The substrate based on solid waste is further processed by a magnetic separator, which removes ferrous metals from the waste. A disc separator, applied in a flower screen form, cleans the substrate further by removing impurities such as wood parts and plastics. The debris is collected in a container, while the cleaned substrate is transported to a turbo mixer [12].

BW has two turbo mixers used for liquefaction and homogenization of substrate. Water is added until the DM share reaches 8-12% in order to enable pumping and disintegration of the substrate. The substrate is stirred thoroughly in the turbo mixers for about 5-15 minutes, in order to achieve a mash consistency and ensure a well-blended substrate and waster mixture, before it is transported to a rake-riffler-facility [12].

The substrate is passed through a cylindrical rake cage in order to remove particles larger than 15 mm. Sand, grit, glass, nonferrous metals and other heavy materials are disposed of downstream from the rake cage. The substrate undergoes a final grinding and homogenization process before it transported to a storage bunker. Hygienization is necessary in order to disinfect the substrate. The process lasts minimum one hour and the operation temperature is 70 °C [12].

Anaerobic digestion

The pretreated substrate undergoes a single-stage, mesophile wet process in the digester. The operation temperature is approximately 37 °C and the average retention time is 20 days. The bacteria culture in the digester produces around 2 million Nm^3 of gas, which consists of 40-70% methane [78].

The hydrogen sulphide in the produced biogas is removed by biological desulphurization via microorganisms. The method consists of adding air to the biogas, which enables oxidization of hydrogen sulphide. The biogas is then transferred into a low-pressure biogas storage tank. A security torch is placed between the digester tank and the biogas storage tank as a safety measure [12].

Upgrading and utilization

Biogas is incinerated in a boiler to produce hot water, which is fed into the district-heating network, in addition to being used to cover the internal heat demand [78].

Post-treatment

Centrifuges dewater the substrate in order to separate the matter into a solid and a liquid phase. Structured material is added to the solid phase of the digestate, which is then transported to the Lobau composting facility for further treatment. The liquid phase is utilized in the turbo mixers as wastewater [12].

3.2 MFA concept

Brunner & Rechberger (2004) defines material flow analysis (MFA) as "systematic assessment of the flows and stocks of materials within a system defined in space and time" [14]. The method analyzes the flows and stocks of a particular material within given system boundaries using a mass balance principle. It is possible to couple MFA with an analysis of energy, in order to study energy flows and sinks within a system. An MFA gives a better understanding of the analyzed system, and can work as a basis for sound decision-making. Interpretation of the results can lead to better resource management, both environmentally and economically.

3.3 System definition

A good system definition is crucial when performing a material flow analysis. The system is the object of the investigation, and should contain all relevant flows, stocks and processes. The system boundaries determine the scope of the investigation, and are defined in time and space. They should include all relevant processes and flows, while still maintaining an understandable system [14].

Models were developed based on MFA methodology and literature regarding the biogas facilities evaluated. The mass layer models provide a simplified overview of the mass flows related to biogas and digestate production, and the energy layer model provides a simplified overview of the energy flows.

The system boundaries were set to include the most relevant processes regarding an energy and environmental assessment of the system. Transport of waste, biogas and bio-fertilizer is included within the system boundaries, while external waste sorting and treatment of reject and centrate are omitted. Some of the processes have been merged in order to create a general model that holds for all evaluated production facilities. Flows labelled "I" symbolize inflows and flows labelled "E" symbolize outflows. The period of the analysis was assumed to be one year and all values are assumed annual.

3.3.1 Mass layer model

An overall mass layer model was developed and further divided into three sub-models, thus providing a distinct overview of necessary flows and processes for the various biogas production facility types.

The sub-model labelled "General mass layer model – BGP" represents biogas production facilities that produce non-upgraded biogas. This model consists of a single process, one incoming flow and four outgoing flows. "General mass layer model – BGU" represents biogas production facilities that produce upgraded biogas. This sub-model was created by expanding "General mass layer model – BGP" by adding an additional process for biogas upgrading and necessary flows. The sub-model labelled "General mass layer model – liq" provides a simplified overview of LBG producing biogas facilities. A liquefaction process and necessary flows were added to "General mass layer model – BGU" in order to create this sub-model. The sub-models are displayed below, where figure 6 shows the "General mass layer model – BGP", figure 7 shows the "General mass layer model – BGU" and figure 8 shows the "General mass layer model – liq".

Figure 6: General mass layer model – BGP

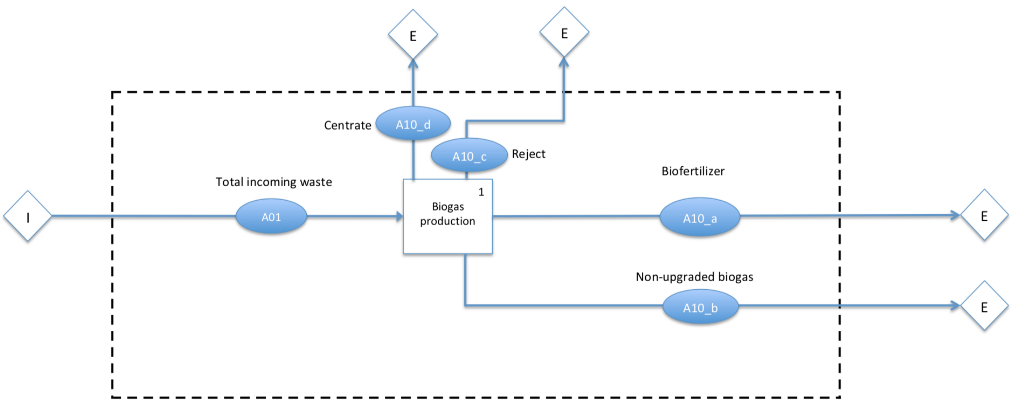


Figure 7: General mass layer model – BGU

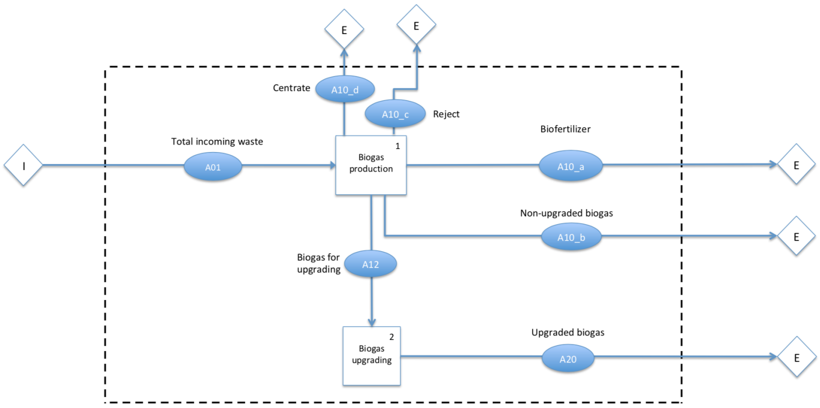
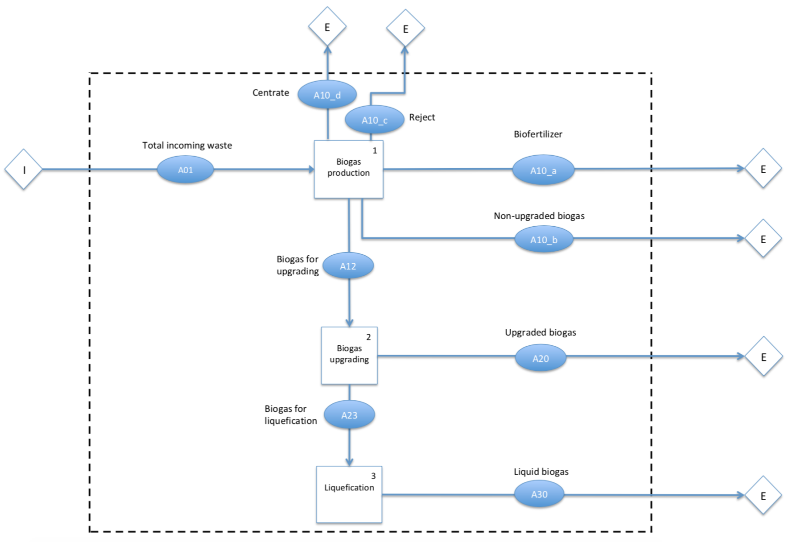


Figure 8: General mass layer model – liq

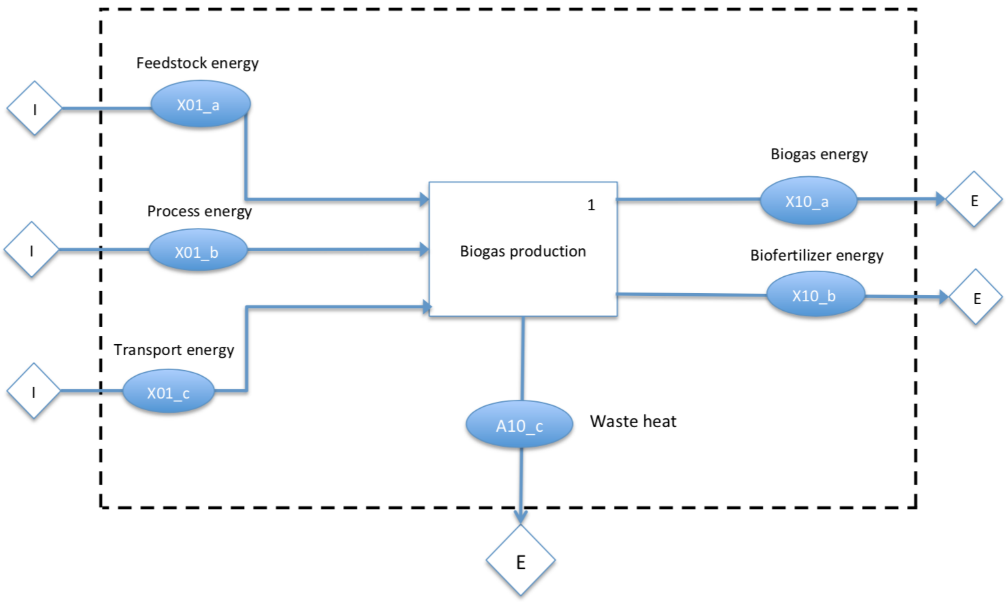


DM flows and VS flows were calculated when possible, based on information received from the biogas production plants evaluated. Wet weight was used as a basis for further calculations when data regarding the DM share and VS share of flows were lacking.

3.3.2 Energy layer model

The energy layer model provides an overview of the energy flows entering and exiting a biogas production plant. The model is greatly simplified and only includes one general biogas production process. Three incoming flows represent the feedstock energy, transport energy and process energy required in a biogas production facility. Three outgoing flows represent the biogas energy, biofertilizer energy and waste heat energy produced in the process. Figure 9 presents the energy layer model.

Figure 9: General energy layer model



The energy content of the incoming feedstock flow was calculated using received data and information concerning LHV found in literature. The amount of process energy needed for the various biogas plants were provided by the biogas plants themselves, except for RBA 2012 where no information concerning the internal energy demand was given. Seldal (2014) provides data regarding the internal electricity demand for the various processes at RBA 2012 at 100% capacity, for a specific time period between October 2013 and May 2014 [67]. This process energy data has been used for further calculations regarding RBA 2012.

The transport energy flow for each biogas plant was found by adding the energy content of the fuel used to carry out the necessary feedstock transport, biofertilizer transport and biogas product transport, and accounting for the diesel consumption and truck load. Biogas energy was calculated by multiplying the produced amount of biogas product with the associated LHV. The energy in biofertilizer was set equal to zero, due to the product being used as fertilizer and therefore not exploiting the energy within the product. Waste heat energy was provided by one of the biogas plants evaluated, however, this value was omitted from further calculations, as the energy is not utilized.

3.4 Data and assumptions

Several biogas production plants were contacted in order to obtain a sufficient database for the analysis. Due to industrial competition and difficulties getting in touch with the right people, obtaining satisfactory and relevant data proved challenging. However, five different biogas plants (BA, BBR, RBA, DMF and BW) provided data regarding energy flows and mass flows. BA, RBA and DMF supplied data for two different years, which were treated as separate cases in the analysis. Additionally, visits were made to RBA in September 2018 and BW in March 2019 in an attempt to obtain relevant data and to gain a better understanding of the biogas production facilities.

Assumptions made when the received data was insufficient or uncertain are a major source of error throughout the thesis. When calculating mass flows, only information regarding the sold amount of upgraded biogas were provided by RBA and DMF. The sold amount of upgraded biogas was therefore assumed to equal the produced amount of upgraded biogas.

Feedstock energy was calculated based on treated amount of incoming waste. However, when no information was given regarding treated amount or reject, the feedstock energy was calculated based on total amount of incoming waste. A uniform LHV for food waste was assumed when calculating the feedstock energy, although this parameter might vary with the variations in the feedstock composition. Similarly, it was assumed that the LHV of fuel oil used to cover energy requirements within the biogas plants was equal to the LHV of diesel.

Several assumptions were made in connections with transport energy calculations. Route distances for both feedstock transport and transport of biogas product and bio-fertilizer were assumed based on literature or estimated from online map providers. Additionally, the parameters representing average truckload and average diesel consumption for trucks were derived from literature, despite the fact that the parameters are likely to vary depending on type of truck used, amount of product transported and local regulations.

Biogas energy was calculated based on the energy in the biogas product delivered from each specific biogas plant. The energy content in bio-fertilizer was, as previously mentioned, set equal to zero due to the internal energy not being further utilized.

Ratios regarding produced biogas to incoming waste and sold biogas product to produced biogas were calculated based on received data. These ratios were found necessary in order to enable sensitivity analysis.

3.5 Yield factor

The yield factor provides a ratio of the quantity of outgoing product to the amount of incoming matter, while accounting for residuals and other production process losses. A yield factor was calculated in order to evaluate the relationship between treated waste and outgoing biogas. The amount of produced biogas was multiplied with the corresponding CH_4 content in order to find the methane content in the gas produced.

The amount of treated waste was assumed to equal the amount of incoming waste when no information concerning treated waste or reject was obtained. The most accurate yield factor is found when calculations are based on the amount of VS in the incoming waste. However, when information regarding VS was not provided, the amount of DM or wet weight was used for yield factor calculations. The equation used to calculate yield factor is given in equation 1.

$$YF = \frac{X_{producedbiogas} * C_{CH4}}{X_{treatedwaste}} \tag{1}$$

where

- YF - yield factor [Nm^3 CH_4/ton]
- $X_{producedbiogas}$ - amount of produced biogas [Nm^3]

- C_{CH4} - CH_4 concentration in produced biogas [%]
- $X_{treatedwaste}$ - amount of treated waste [ton]

3.6 Energy efficiency

An energy indicator was developed based on the energy layer model, in order to evaluate the energy balance of the system. The equation used to calculate the efficiency indicator is presented in equation 2. The total amount of produced energy is given in the numerator, and the total energy demand of the system is given in the denominator. The system definition determines which energy flows should be included in the efficiency calculation. Changing the input or the output of the model would result in a different energy indicator value, thus enabling for optimization of the energy efficiency in the biogas facility.

$$EE = \frac{Q_{out}}{Q_{in}} = \frac{Q_{biogas} + Q_{biofertilizer}}{Q_{feedstock} + Q_{process} + Q_{transport}} \tag{2}$$

where

- EE - energy efficiency [%]
- Q_{out} - total outgoing energy [MJ]
- Q_{in} - total incomming energy [MJ]
- Q_{biogas} - biogas energy [MJ]
- $Q_{biofertilizer}$ - biofertilizer energy [MJ]
- $Q_{feedstock}$ - feedstock energy [MJ]
- $Q_{process}$ - process energy [MJ]
- $Q_{transport}$ - transport energy [MJ]

3.7 Environmental benefit

The environmental benefit of biogas was evaluated by calculating the amount of CO_2-eq emission avoided by utilizing biogas in lieu of fossil energy sources. Due to the scope of this thesis, only the effects on CO_2-emission were evaluated.

The amount of electricity, heat or fuel sold by each biogas plant was calculated, together with the amount of CO_2-eq emitted if the equivalent amount of energy was produced by fossil based sources. Additionally, the amount of CO_2-eq emitted from artificial fertilizer production was found based on the amount of bio-fertilizer produced. The CO_2-eq emitted from the biogas production process was calculated based on received process data and emission factors found in literature. According to SSB (2017), biogas does not emit any CO_2-eq during the use-phase [74]. In order to estimate the amount of avoided CO_2-eq emission, the emissions connected to biogas production was subtracted from the amount of CO_2-eq emitted when utilizing fossil resources to produce an equivalent energy amount. The equation is presented below in equation 3.

$$EB = E_{fossilsource} - E_{biogasproduction} \tag{3}$$

where

- EB - environmental benefit [kg CO_2-eq]
- $E_{fossilsource}$ - CO_2 emission related to fossil energy production [kg CO_2-eq]
- $E_{biogasproduction}$ - CO_2 emission related to biogas production [kg CO_2-eq]

3.8 Cost-benefit analysis

The intended formula for the cost-benefit analysis is given in equation 4. The total yearly income is given in the nominator, while the amount of treated mass is given in the denominator. The total yearly income is found by subtracting the yearly expenses from the yearly profit. A biogas production facility profits from sale of products, gate fees, other earnings and potential subsidies, while the expenses include variable cost such as cost related to transport and wages and fixed costs such as lease and interest payments.

$$CB = \frac{I_{annual}}{X_{treatedwaste}} \tag{4}$$

where

- CB - cost benefit [NOK/ton]
- I_{annual} - annual income [NOK]
- $X_{treatedwaste}$ - amount of treated waste [ton]

3.9 Sensitivity analysis

A sensitivity analysis evaluates how sensitive variables and flows are to changes in parameters. The analysis can, according to Müller, identify key parameters, help validate models and improve system understanding [46]. Absolute sensitivity calculates the change in an output flow or value due to an alteration of an input parameter. The method is used to find when a parameter has its greatest effect. Relative sensitivity analysis can be used to compare the impact of parameters and analyze which parameter has greatest effect on a specific flow or value. The formula for absolute sensitivity is given in equation 5 and the formula for relative sensitivity is given in equation 6. Both 5 and 6 were obtained from [46].

$$S(x_i, p_j) = \frac{\delta X_i}{\delta p_j} \tag{5}$$

$$\bar{S}(x_i, p_j) = \frac{\delta X_i}{\delta p_j} * \frac{p_j}{X_i} \tag{6}$$

where

- S(x_i, p_j) - absolute sensitivity
- $\bar{S}$(x_i, p_j) - relative sensitivity
- X_i - evaluated flow
- p_j - evaluated parameter

Both the absolute sensitivity and the relative sensitivity were calculated. The absolute sensitivity calculates the change of a value due to unitary changes in a parameter. However, some parameters must have values that lie in the range of 0 and 1, and can therefore not be altered by a whole unit. An example is the DM share of incoming waste, which cannot exceed 100%. Additionally, absolute sensitivity cannot be used to compare the impacts of parameters, as a one-unit increase will vary in magnitude depending on the analyzed parameter.

Relative sensitivity is normalized with respect to the altered parameter and can therefore be used to compare the impacts of the evaluated parameters. The sign of the sensitivity indicates whether the output value increases or decreases as a result of the unitary parameter change. The higher the relative sensitivity, the more impact a parameter has on the calculated value. Equal relative sensitivities indicate that the evaluated parameters have equal impact on a specific output value.

The energy efficiency and environmental benefit of each biogas facility was further analyzed by performing a sensitivity analysis. Both the absolute and relative sensitivity were calculated. Some parameters were assumed fixed, such as LHV, emission factors and CH_4 content, thus no sensitivity analysis was performed with respect to these parameters. Parameters related to transport distances and DM shares were evaluated due to a high level of uncertainty tied to the parameter values. Due to restrictions on the DM share values, relative sensitivity was used to analyze the parameter impact.

No analysis was performed without an original parameter provided. Nor were parameters altered when the altering did not make sense, such as when the biogas product was delivered from the facility itself without additional transport required.

4 Results

This chapter presents the results obtain during the course of the analysis. Yield factor, energy efficiency and environmental benefit are presented, as well as results from the sensitivity analysis. The results are calculated based on the data provided by BA, BBR, RBA, DMF and BW. Mass flows and energy flows are given in appendix B, while parameters and preliminary calculations are given in appendix A.

4.1 Yield factor

The yield factor was calculated based on information regarding treated waste and produced biogas. No information was given regarding the incoming waste at RBA 2018, and the corresponding yield factor could therefore not be calculated. The yield factors based on VS were higher than the yield factors based on DM, which again were higher than the yield factors found when the calculations were based on wet weight.

Two separate yield factors were calculated in order to separate upgraded and non-upgraded biogas. Figure 10 presents the yield factors found when analyzing non-upgraded biogas. The yield factors based on upgraded biogas were in general higher than the yield factors based on non-upgraded biogas. RBA 2018 is avoided from figure 10 due it not being possible to calculate a yield factor for this facility. Figure 11 presents the yield factors found when analyzing upgraded biogas.

The highest yield factor based on wet weight for non-upgraded biogas was found to be approximately 98,74 Nm^3 CH_4/ton for RBA 2012. The remaining yield factors based on wet weight for non-upgraded biogas were found to lay within the range of approximately 30 Nm^3 CH_4/ton to approximately 54 Nm^3 CH_4/ton. Yield factors based on DM were not calculated for BA 2015, BA 2018 and BW due to lacking information regarding the DM content of the incoming waste. The yield factor values range from approximately 290 Nm^3 CH_4/ton DM to 400 Nm^3 CH_4/ton DM. Only DMF 2016 and DMF 2017 provided information regarding the VS content in the incoming waste. Their respective yield factors were calculated to 344,68 Nm^3 CH_4/ton VS and 438,25 Nm^3 CH_4/ton VS.

The yield factor based on wet weight for upgraded biogas for RBA 2012 was significantly higher than the yield factors found for DMF 2016 and DMF 2017. The yield factors for upgraded biogas based on DM ranged from approximately 280 Nm^3 CH_4/ton DM to 355 Nm^3 CH_4/ton DM. The yield factors calculated based on VS were found to be 337,68 Nm^3 CH_4/ton VS for DMF 2016 and 420,48 Nm^3 CH_4/ton VS for DMF 2017.

Figure 10: Yield factor for non-upgraded biogas

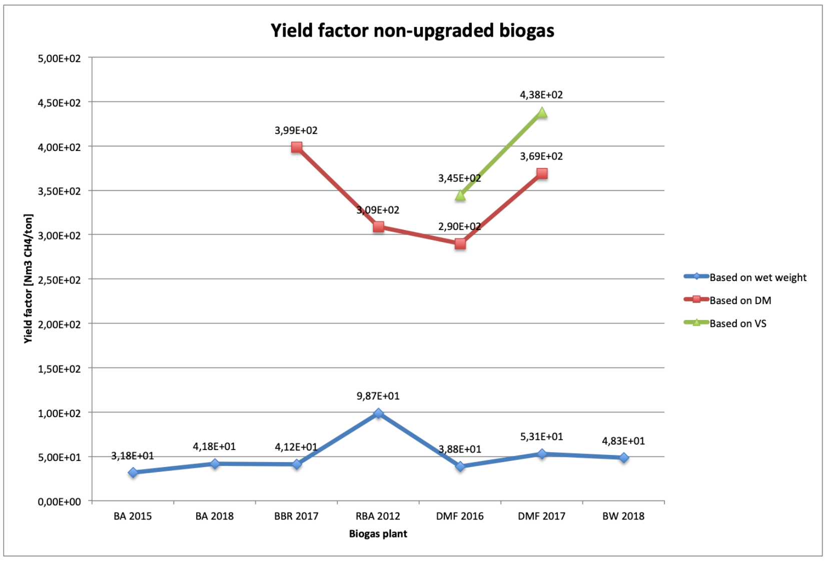
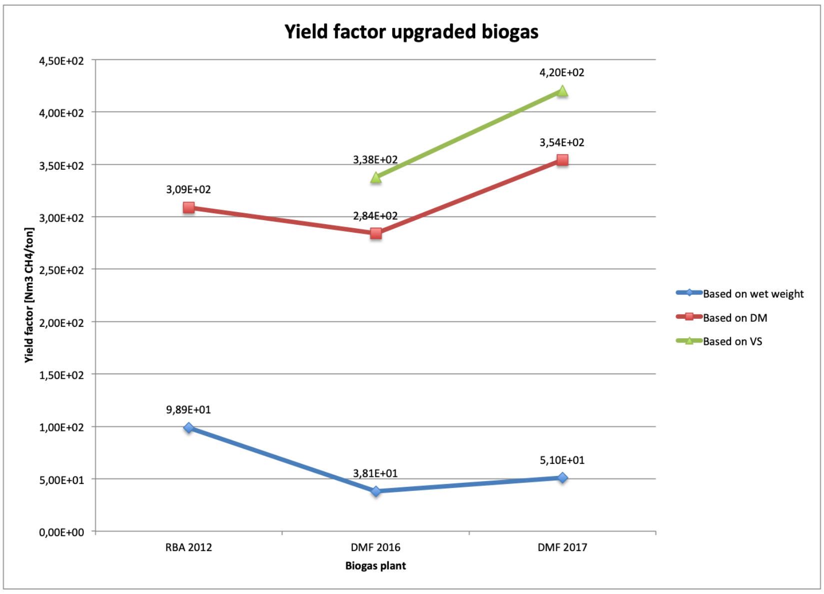


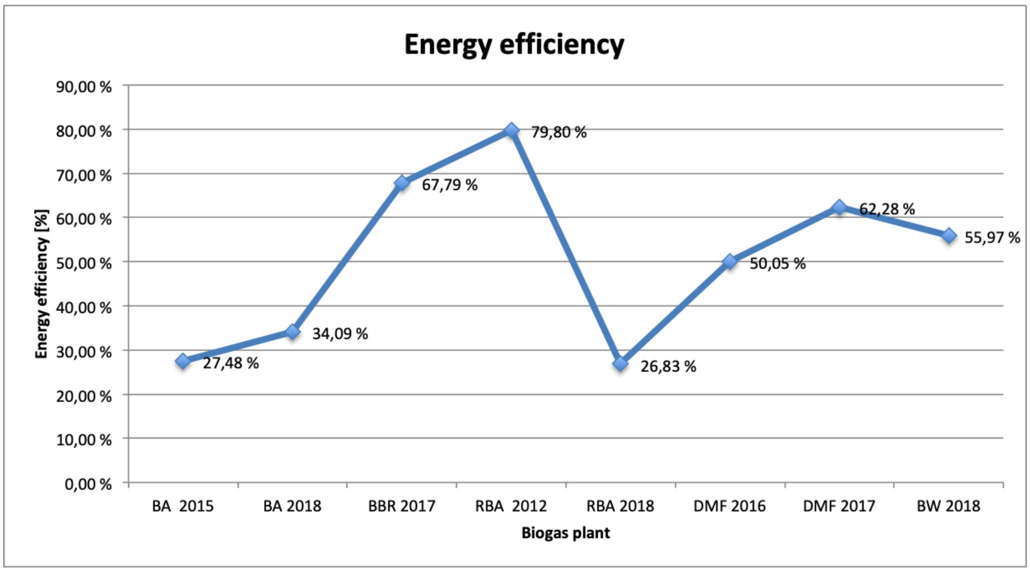
Figure 11: Yield factor for upgraded biogas



4.2 Energy efficiency

Energy efficiency indicators were calculated in order to assess the energy balance of the evaluated biogas plants. Total energy input and total energy output were found based on information given about the energy flows of each facility. This information was further utilized in combination with equation 2, in order to calculate the energy efficiency indicators. The calculated indicators are presented in figure 12.

Figure 12: Energy efficiency



The largest energy efficiency indicator was found to be 79,80% for RBA 2012, followed by an indicator value of 67,79% for BBR and 62,28% for DMF 2017. The lowest efficiency indicators were found for BA 2015 and RBA 2018, respectively 27,48% and 26,83%.

4.3 Environmental benefit

The environmental benefit of each facility was evaluated by studying the avoided CO_2-emission as a consequence of biogas utilization. The avoided emissions are given in kg CO_2-eq and are presented in figure 13. Due to the massive difference in CO_2-eq avoided at BBR compared to the remaining facilities, a graph excluding BBR was created in order to create a better basis of comparison. The graph is presented in figure 14.

The greatest avoided emission was found for BBR, at 1.069.039.542,18 kg CO_2-eq. The remaining biogas plants resulted in less CO_2-emission avoided, with 87.795.563,69 kg CO_2-eq for DMF 2017 and 67.342.216,34 kg CO_2-eq for DMF 2016. The lowest emission savings belongs to BA 2015 and BW, with respectively 5.425.869,91 kg CO_2-eq and 1.644.193,23 kg CO_2-eq saved.

Figure 13: Environmental benefit

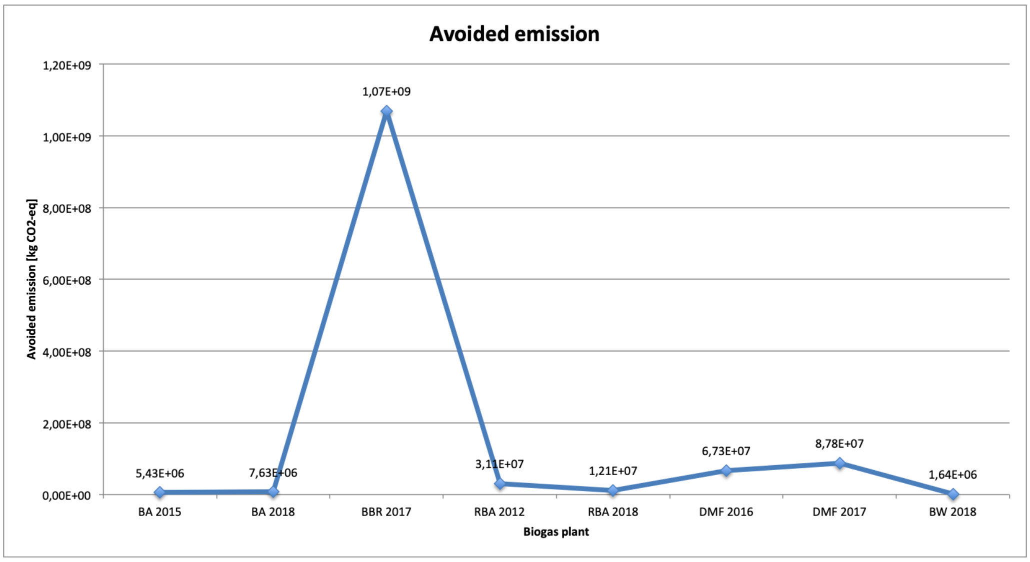
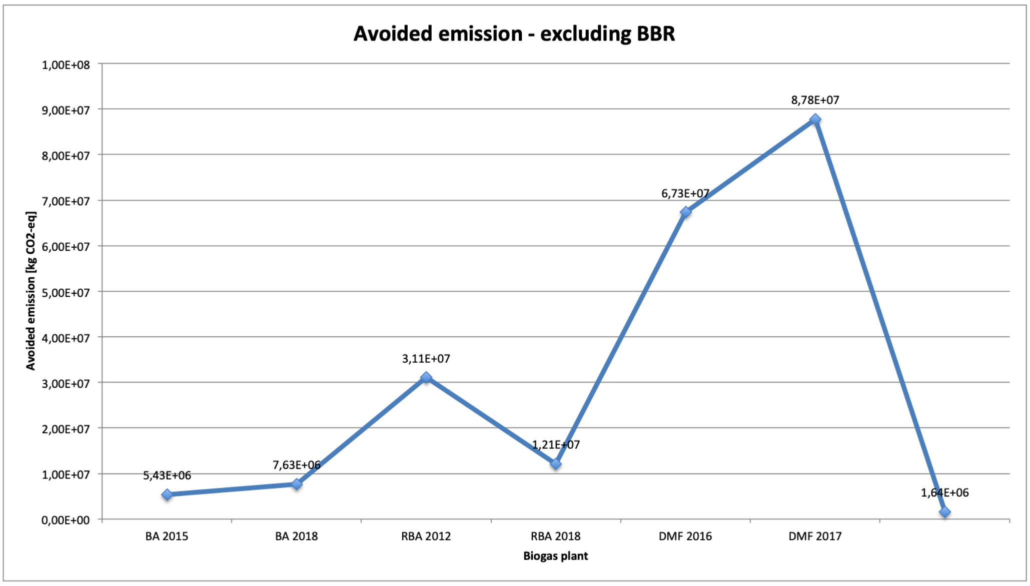


Figure 14: Environmental benefit - excluding BBR



4.4 Sensitivity analysis

A sensitivity analysis was performed in order to examine the impact of parameters on the energy efficiency and the environmental benefit. Both the absolute sensitivity and the relative sensitivity were calculated and the results are shown in table 4. A.S. is short for absolute sensitivity and R.S. is short for relative sensitivity. The evaluated parameters were DM share of incoming waste and transportation distance of various goods. No analysis was performed when original parameters were lacking or alterations of a parameter were senseless, e.g. the route distance related to transport of biogas product was not changed when the biogas product is delivered from the facility location and therefore not dependent on transport.

Table 4: Results from sensitivity analysis

	Energy efficiency		**Environmental benefit**	
Bellersheim Abfallwirtschaft 2015				
	A.S.	R.S	A.S.	R.S.
Distance food waste BA 2015	-8,62E-05	-1,25E-02	-3,44E+03	-2,54E-02
Distance biogas product BA 2015				
Distance biofertilizer product BA 2015				
Bellersheim Abfallwirtschaft 2018				
	A.S.	R.S.	A.S.	R.S.
Distance food waste BA 2018	-6,22E-05	-7,30E-03	-1,98E+03	-1,04E-02
Distance biogas product BA 2018				
Distance biofertilizer product BA 2018				
Billund BioRefinery				
	A.S.	R.S.	A.S.	R.S.
DM in organic household waste BBR	4,63E-01	2,19E-01	1,09E+07	3,28E-03
DM in liquid biowaste BRR	1,88E+00	1,38E-01	4,44E+07	2,08E-03
Distance food waste BRR	-2,42E-04	-1,79E-02	-3,23E+03	-1,51E-04
Distance biogas product BRR				
Distance biofertilizer product BRR				
Romerike Biogassanlegg 2012				
	A.S.	R.S.	A.S.	R.S.
DM in liquid food waste RBA 2012	1,04E-02	1,96E-03	4,91E+06	2,37E-02
DM in solid food waste RBA 2012	3,88E-01	1,46E-01	4,42E+07	4,26E-01
Distance food waste RBA 2012	-1,55E-04	-1,17E-02	-2,72E+03	-5,26E-03
Distance biogas product RBA 2012	-1,01E-05	-7,62E-04	-2,22E+02	-4,30E-04
Distance biofertilizer product RBA 2012	-8,65E-05	-3,79E-03	-1,90E+03	-2,14E-03
Romerike Biogassanlegg 2018				
	A.S.	R.S.	A.S.	R.S.
DM in liquid food waste RBA 2018				
DM in solid food waste RBA 2018				
Distance food waste RBA 2018				
Distance biogas product RBA 2018	-3,83E-03	-8,57E-01	-2,23E+05	-1,10E+00
Distance biofertilizer product RBA 2018	-1,15E-05	-1,49E-03	-2,30E+03	-6,63E-03

Den Magiske Fabrikken 2016				
	A.S.	R.S.	A.S.	R.S.
DM incoming waste DMF 2016	3,74E+00	1,00E+00	8,01E+07	1,59E-01
Distance food waste DMF 2016	-1,43E-04	-2,01E-02	-6,24E+03	-6,49E-03
Distance biogas product DMF 2016				
Distance biofertilizer product DMF 2016	-1,41E-04	-8,43E-03	-6,12E+03	-2,73E-03
Den Magiske Fabrikken 2017				
	A.S.	R.S.	A.S.	R.S.
DM incoming waste DMF 2017	4,32E+00	1,00E+00	1,24E+08	2,03E-01
Distance food waste DMF 2017	-1,66E-04	-1,86E-02	-7,72E+03	-6,16E-03
Distance biogas product DMF 2017				
Distance biofertilizer product DMF 2017	-1,62E-04	-7,82E-03	-7,57E+03	-2,59E-03
Biogas Wien				
	A.S.	R.S.	A.S.	R.S.
Distance food waste BW	-1,40E-04	-2,50E-03	-1,50E+03	-9,11E-03
Distance biogas product BW				
Distance biofertilizer product BW				

The distance related to food waste transportation was the only parameter evaluated for BA 2015 and BA 2018. No information was provided regarding the transportation of bio-fertilizer product and the generated electricity was produced on-site. Hence, the parameters related to transport of bio-fertilizer and transport of biogas product were not evaluated. Increasing the distance of food waste transport for BA 2015 by one unit resulted in an absolute sensitivity of -8,62E-05 for the energy efficiency and an absolute sensitivity of -3,44E+03 for the environmental benefit. A unitary increase of the same parameter in regards to BA 2018 led to an absolute sensitivity of -6,22E-05 for the energy efficiency and an absolute sensitivity of -1,98E+03 for the environmental benefit.

The parameters DM share of organic household waste, DM share of liquid biowaste and distance for food waste transportation were analyzed for BBR. The DM share of organic household waste was found to have the largest positive impact on both the energy efficiency and the environmental benefit, with relative sensitivities of 2,19E-01 and 3,28E-03 respectively. Increasing the parameter related to transport of food waste had a negative impact on both the energy efficiency and the environmental benefit of the biogas facility.

Five parameters were evaluated for RBA 2012, namely the DM share of liquid food waste, the DM share of food waste, the transportation distance for food waste, the transportation distance for biogas product and the transportation distance for bio-fertilizer. The DM share of food waste had the largest positive impact on the energy efficiency with a relative sensitivity of 1,46E-01, while the transport distance of food waste to the biogas facility had the largest negative impact with a relative sensitivity of -1,55E-04. The environmental benefit was mostly affected by the DM share of the incoming food waste, which had a relative sensitivity of 4,26E-01. The parameter with the greatest negative impact on the environmental benefit was the distance of bio-fertilizer transport, which had a relative sensitivity of -2,14E-03.

Parameters related to incoming waste at RBA 2018 were not evaluated due to deficient data. Transport of the biogas product had the biggest negative impact on both the energy efficiency and the environmental benefit, with relative sensitivities of -8,57E-01 and -1,10E+00 respectively.

The DM share of incoming food waste was found to have a relative sensitivity of 1, in regards to the energy efficiency, both for DMF 2016 and DMF 2017. The parameter also greatly affected the environmental benefit, with a relative sensitivity of 1,59E-01 for DMF 2016 and a relative sensitivity of 2,03E-01 for DMF 2017. The parameter with the greatest negative impact on the environmental benefit was the transport distance of food waste to DMF, with a relative sensitivity of -6,49E-03 for DMF 2016 and a relative sensitivity of -6,16E-03 for DMF 2017. The parameter related to transport of CBG from DMF was not evaluated due to the CBG being transported in pipes from the production plant.

The distance of food waste to BW biogas facility had an absolute sensitivity of -1,40E-04 on the energy efficiency and an absolute sensitivity of -1,50E+03 on the environmental benefit. The relative sensitivities were found to be -2,50E-03 and -9,11E-03 for the energy efficiency and the environmental benefit respectively. No information was provided regarding the production of bio-fertilizer and the generated heat was produced on-site. Hence, the parameters related to transport of bio-fertilizer and transport of biogas product were not evaluated.

5 Discussion

This chapter presents the main findings and evaluates the validity of the results. Strengths and weaknesses related to assumptions made, data received and the models utilized are assessed. A comparison of the results found for yield factor, energy efficiency and environmental benefit is made in regards to relevant literature. The chapter is finalized by presenting possible recommendations for further work.

5.1 Main findings

5.1.1 Yield factor

Separate yield factors were calculated in order to distinguish yield factors based on non-upgraded biogas and upgraded biogas. For each of the factors, wet weight, DM and VS were evaluated. Due to deficiencies in the received data, information regarding the DM share and the VS share of the incoming waste were missing for several of the biogas plants. Combined with uncertainties related to the amount of treated waste and the amount of biogas produced, the assessment of the biogas facilities was found to be defective.

The yield factor based on VS is higher than the yield factors based on both DM and wet weight. This is due to the VS share indicating the amount of organic material in a substance. Hence, weight based on VS will not significantly change during treatments such as dewatering and reject-removal, as no considerable amounts of organic material is removed during these processes. Yield factors based on VS are therefore considered the most accurate. Basing yield factors on DM will result in lower indicator values, as potential inorganic matter will be included in the calculations. Yield factors based on wet weight are regarded the most inaccurate, due to both water and inorganic substances being included in further calculations.

All but two biogas facilities provided sufficient information in order to calculate the yield factor for non-upgraded biogas based on wet weight. The yield factors were found to lie within the range of 31,78 Nm^3 CH_4/ton to 53,14 Nm^3 CH_4/ton, except for RBA 2012, which had a yield factor of 98,74 Nm^3 CH_4/ton. The high yield factor is likely a result of various assumptions made in regards to the operations of RBA 2012. Additionally, contrary to several of the biogas facilities evaluated, RBA 2012 provided data regarding the amount of treated waste, thus enabling for more accurate calculations. Furthermore, the data received for RBA 2012 is based on ideal operation and 100% capacity, and it is therefore likely that unscheduled downtime is excluded from the provided data.

Yield factors calculated based on DM for non-upgraded biogas were fairly similar in value, with BBR having the highest yield factor of 398,57 Nm^3 CH_4/ton DM. This might be due to BBR having a relatively low amount of incoming DM compared to the other facilities. Information regarding the amount of incoming VS was only provided by DMF 2016 and DMF 2017. Both yield factors based on VS were found to be approximately 19% higher than their respective DM yield factor values. This is due to the VS share of the incoming DM being equal for both 2016 and 2017 at DMF.

Yield factors based on wet weight, DM and VS for upgraded biogas were calculated for RBA 2012, DMF 2016 and DMF 2017. Yield factors based on DM and VS were significantly higher than those based on wet weight, due to water and inorganic substances being included in the calculations. The highest yield factor based on wet weight was found for RBA 2012. That is likely a result of RBA 2012 having considerably lower incoming amount of wet weight compared to DMF 2016 and DMF 2017. DMF 2017 had the highest biogas yield factor when calculations were based on DM and VS. values.

In order to create a better basis for comparison, the amount of biogas produced was multiplied with its respective methane content. The methane content of the biogas was provided by the evaluated biogas facilities. Although RBA 2012 produced more non-upgraded biogas than upgraded biogas, the yield factor based on upgraded biogas was higher due to the increased methane content in the gas. On the contrary, yield factors based on non-upgraded biogas were higher than yield factors based on upgraded biogas for DMF 2016 and DMF 2017, even though the increased CH_4-content was accounted for. Data regarding the amount of upgraded biogas for DMF 2016 and DMF 2017 were given for the amount of sold biogas. It could therefore be assumed that the respective yield factors would be higher if the data was based on the produced amount.

The significant variations found for the calculated yield factors could have several reasons. Variations in the incoming feedstock composition would greatly affect the result, as a high fat content in the waste would increase the methane share of the biogas produced. Additionally, variations in pretreatment technologies and digestion methods utilized would influence the outcome of anaerobic digestion. Furthermore, false assumptions, inaccurate data and calculation errors could also have affected the yield factor calculations.

5.1.2 Energy efficiency

An energy efficiency indicator was calculated for each biogas plant in order to evaluate the energy balance of each facility. The results indicate that biogas plants producing upgraded biogas have higher energy efficiency than plants producing non-upgraded biogas. This is probably due to upgraded biogas having a higher energy content, thus resulting in a larger energy outflow. Exceptions are BBR and BW, which have high energy efficiency indicator values although they produce non-upgraded biogas. This is likely related to BW having a low demand for transport energy and BBR producing a relatively high amount of non-upgraded biogas.

RBA 2018 had an energy efficiency indicator of 26,83%, which was the lowest indicator value found. As no information regarding the incoming feedstock was provided, the energy content in the feedstock and the energy demand related to feedstock transport were excluded from the calculations. Additionally, the energy content of the produced biogas was based on the amount of CBG and LBG sold by the facility. The calculated energy efficiency indicator can therefore not be assumed representative of the energy balance at RBA 2018.

RBA 2012 is found to have the highest energy efficiency, with an indicator value of 79,80%. This may be due to the provided data being based on an ideal scenario with 100% capacity, thus generating higher energy outputs than under normal operation conditions. Additionally, no information was provided regarding the amount of CBG produced by the facility. Therefore, all upgraded biogas was treated as LBG.

The biogas production at DMF was more energy efficient in 2017 than in 2016.

This is likely due to the facility experiencing various run-in problems, as a consequence of 2016 being the first full year of operation, which led to high amounts of produced biogas being flared. It should also be noted that the energy efficiency of DMF depends on the amount of biogas sold, as the outgoing energy flow was calculated based on the energy in the sold product.

The energy efficiency of BA was higher in 2018 than in 2015. This could be a result of BA 2015 receiving significantly more waste than BA 2018, thus requiring more transport energy. Other factors, such as feedstock composition and technology upgrades, may also have influenced the result.

5.1.3 Environmental benefit

The environmental benefit of each biogas plant depends on the alternative energy source being substituted. The alternative fuel was assumed to be diesel for all biogas facilities and all transport distances, therefore, the biogas plants producing bio-fuel were found to have significant amounts of saved CO_2-emissions. Biogas plants producing electricity in Europa would have a greater environmental benefit than biogas plants producing electricity in Scandinavia, due to the emission factor associated with each electricity mix. It was assumed that every biogas plant evaluated, except DMF 2016 and DMF 2017 which use natural gas as an energy source, utilizes light fuel oil in order to cover the heat demand for biogas production. The environmental benefit of each facility could therefore have been further increased had internally produced biogas been used to cover parts of the heat demand.

The avoided CO_2-eq emissions at BBR were found to be massively higher than that of any other biogas plant evaluated. The biogas facility produces both heat and electricity in contrast to the other plants, which only provided data for one output product. The dual production resulted large reductions of the CO_2-emissions when comparing with emissions stemming from fossil based production. However, such a great deviation in the results implies that calculation errors and falsely made assumptions have been made or that inaccurate data has been utilized.

5.1.4 Sensitivity analysis

A sensitivity analysis was performed in order to evaluate the results and analyze the impact of specific parameters. Both the absolute and relative sensitivity of parameters were calculated. The absolute sensitivity determines expected change in a variable due to a change in parameter, while the relative sensitivity evaluates which parameter has the greatest effect on a particular outflow or value. It is important that parameters with a high relative sensitivity are as accurate as possible, due to their significant impact on the evaluated outflow or value. Parameters with lower relative sensitivities can to a greater extent be based on estimates.

The energy efficiency and environmental benefit were analyzed due to uncertainties in assumptions and data utilized in their calculations. The evaluated parameters were chosen based on their degree of uncertainty, combined with their anticipated impact on the energy efficiency and environmental benefit of the evaluated biogas plants. The transport distances were mainly estimated based on information provided by online mapping services and were therefore considered highly uncertain. Furthermore, the energy demand and CO_2-emission from additional fuel requirements were expected to have a significant impact on both the energy efficiency and the environmental benefit. The DM share of incoming waste was provided as estimates by the various facilities and therefore considered uncertain. Additionally, altering the waste composition and thereby the DM share of the incoming waste could greatly impact the energy efficiency and environmental benefit of a biogas production facility.

Neither the distance related to transport of biogas product nor the distance related to transport of bio-fertilizer were evaluated for BA 2015 and BA 2018. This was due to the facility producing electricity that is sold on-site and lacking information regarding the usage of bio-fertilizer. Increasing the transport of food waste by one unit led to a decrease of both energy efficiency and environmental benefit for BA 2015 and BA 2018. An increase of transport would require more fuel, thus increasing the energy demand of the biogas plant. Additionally, CO_2-emissions would rise as a result of the increased transportation distance. The transport of food waste is found to have a greater impact on both the energy efficiency and environmental benefit for BA 2015 than for BA 2018, when comparing the relative sensitivities. This could be because BA 2015 has a greater amount of incoming waste than BA 2018.

The DM share of organic household waste had the biggest positive impact on both the energy efficiency and the environmental benefit of BBR. This is due to the facility receiving more organic household waste than liquid bio-waste. Increasing the DM share of organic household waste would therefore result in a higher energy content of the total incoming waste, which in turn would enhance the biogas production. Increasing the distance of food waste transport had a negative impact on both the energy efficiency and the environmental benefit of the facility.

The incoming solid food waste constitutes the greatest mass inflow at RBA

2012. Thus, altering the DM share of the flow resulted in significant impacts on both the energy efficiency and environmental benefit. Increasing transport distances reduces the energy efficiency and environmental benefit, as the demand for additional fuel is raised. As the amount of incoming food waste exceeds the amount of LBG and bio-fertilizer produced, altering the distance of food waste transport resulted in the biggest negative relative sensitivity. No information was provided regarding the incoming food waste at RBA 2018, therefore, no parameters related to the food waste could be evaluated for the facility. Transport of biogas product was found to have a greater impact on the energy efficiency and environmental benefit for RBA 2018 than 2012. This is likely due to RBA 2018 producing more biogas product, as well as the energy demands and emissions related to incoming feedstock being excluded from the RBA 2018 calculations.

Increasing the DM share of the incoming waste impacted the energy efficiency of DMF 2016 and DMF 2017 equally. The environmental benefit of DMF 2017 was found more sensitive to alterations of the DM share of the incoming waste, which is likely due to DMF 2017 receiving larger amounts of waste and producing more bio-fertilizer. Furthermore, the energy efficiency and environmental benefit of DMF 2016 were more responsive to alterations of the transport of food waste and the transport of bio-fertilizer than DMF 2017. This might be a result of DMF 2016 producing less CBG than DMF 2017. Altering transport distances would therefore have a greater impact on the calculated energy efficiency and environmental benefit. The CBG produced at DMF is transported through a gas grid located on-site and additional transport is therefore not necessary. Hence, the parameter related to transport of biogas product was not further analyzed.

Increasing the transport distance of food waste decreased the energy efficiency and environmental benefit of BW. The relative sensitivities imply that the increased transport has a stronger impact on the environmental benefit, as the additional fuel increases CO_2-emissions. The parameters related to transport of bio-fertilizer and transport of biogas product were not analyzed due to the biogas facility producing heat on-site and no information regarding amount of produced bio-fertilizer being provided.

5.2 Strengths and weaknesses

Several potential sources of error are present in this study. The most critical weakness is the lack of relevant data available. The data used in calculations were insufficient and the results will therefore not be accurate or representative for the actual operation of the biogas plants. Furthermore, the data does not account for variations throughout the year nor the occurrence of unpredicted incidents. Hence, an incomplete database and data uncertainties are significant sources of error in this thesis.

The models have been greatly simplified in order to create generic models that were sufficient for the desired scope of the analysis. This could have resulted in erroneous flows and unbalanced processes, which would impact the calculated values used in the analysis. Both spatial and temporal boundaries were perhaps set to narrow to give relevant results for the operation of evaluated biogas plants. Widening the system boundaries could have provided a more holistic and realistic view of the operation.

Information regarding treated waste was lacking for several of the biogas plants evaluated. The treated feedstock was therefore assumed equal to the incoming feedstock. This resulted in erroneously high amounts of treated waste compared to the actual production values, which is likely to have had ripple effects on the further calculations. Similarly, the produced amount of upgraded biogas was assumed equal to the sold amount of upgraded biogas when adequate data was lacking. As the produced amount in reality exceeds the sold amount, this assumption impacts further calculations and results.

Little information was provided regarding the feedstock composition, and a general LHV was therefore assumed for incoming food waste. Thus, the specific waste composition at each biogas plant, in addition to seasonal variations, were not accounted for. Additionally, variations of the methane content of the biogas could also have influenced the accuracy of the results. More information regarding the composition of the incoming waste and accurate data concerning the methane content of produced biogas would have been necessary in order to compute more realistic results.

The calculations for several of the evaluated biogas plants were based on wet weight, due to lacking information regarding the DM share of incoming waste. This led to inaccurate results, as wet weight is considered an imprecise base for further calculations. Furthermore, several of the biogas plants reported that the provided DM share value was an estimate, as the DM share greatly varies throughout the year. A complete database containing information regarding the DM share for each evaluated biogas facility would have been necessary to ensure a fair comparison of results. In order to further improve the accuracy of the results, information regarding the VS share of the incoming waste is needed, preferably provided for shorter time spans.

The share of nitrogen in artificial fertilizer, used to calculate the CO_2-emissions stemming from fertilizer production, was estimated based on information regarding the nitrogen share in various artificial fertilizers. The environmental benefit of utilizing bio-fertilizer, which was found by comparing the CO_2-emissions of biogas production with the emissions from artificial fertilizer production, should therefore be considered uncertain.

The majority of the transportation distances were estimated based on information provided by online mapping services and can therefore not be considered accurate. This is a significant source of error, which has the potential to greatly influence both the energy efficiency and the environmental benefit of a facility. Additionally, some biogas facilities did not provide information regarding transport of incoming waste and bio-fertilizer. Hence, these facilities have an artificially low value of emitted CO_2 and transport energy demand. The accuracy of the results would therefore increase if precise information regarding transportation distances were provided.

The assumption that all transport is carried out by diesel fuel driven vehicles has a major impact on the energy efficiency and the environmental benefit calculated. It is however reasonable to assume that some of the vehicles used for transporting feedstock, upgraded biogas or bio-fertilizer is run on biofuel, electricity or other alternative fuels. Additional assumptions related average truckload and average diesel consumption for trucks are other potential sources of error. The actual truckload is likely to vary with each biogas plant, as the size of the biogas plant and the amount of incoming waste and outgoing product varies. Likewise, the actual diesel consumption varies with the type of vehicle utilized.

Ratios regarding the amount of biogas produced per treated incoming matter and the amount of sold biogas product per amount of biogas produced were calculated based on information received from the biogas plants. The ratios were necessary in order to enable sensitivity analysis. Inaccuracies in the provided data could have resulted in imprecise ratios, which do not correctly represent the actual operation at each biogas plant. Inaccurate ratios would also impact the results of the sensitivity analysis. The calculated sensitivities should therefore not be considered definite, but rather a measure to provide general insight concerning the impact force of specific parameters.

Wrongfully made assumptions, miscalculations and inaccurate data are likely to be present in the study. Acquiring a more complete database with realistic and accurate information would improve the validity of the results. Even though the models might have significant weaknesses, the general MFA-based models can be used as a base for further studies. By updating and adjusting input and output flows, the results can be used as a reliable basis for an even more specific analysis. It should also be mentioned that the model is quite intuitive and therefore suitable for educational purposes. Even though the results might not be completely correct, the values may give indications concerning the yield factor, energy efficiency and environmental benefit of the evaluated biogas plants, as well as implications regarding focus areas for improved operation.

5.3 Comparison with literature

5.3.1 Yield factor

Svenskt Gastekniskt Center (2012) presents a yield factor of 389,34 Nm^3 CH_4/ton DM for biogas with a methane content of 63% [62]. Comparing this yield factor with the yield factors based on DM found for non-upgraded biogas, it is clear that the value is in sync with the calculated yield factors. Research performed by Jørgensen (2009) resulted in a yield factor of 279,5 Nm^3 CH_4/ton DM for biogas consisting of 65% methane [31]. This is slightly lower than the yield factors calculated based on the received data, yet still within an acceptable range when considering the uncertainty of the calculated yield factors. Additionally, possible technical improvements and increased process efficiencies could have increased production yield factors.

Yngvesson and Tamm (2017) found a median yield factor value of 470 Nm^3 CH_4/ton DM, which is significantly higher than the calculated values [80]. No information was provided regarding the incoming feedstock or the methane content of the gas analyzed by Yngvesson and Tamm (2017), thereby making it hard to evaluate potential reasons for discrepancy. Lind et al. (2019) performed a feasibility study of a biogas facility located in Helgeland in Norway and concluded with yield factors of 461 Nm^3 CH_4/ton VS and 204 Nm^3 CH_4/ton wet weight for a biogas containing 63% methane [34]. Both yield factors presented by Lind et al. (2019) exceeds the calculated values. This is likely due to Lind et al. (2019) basing the yield factor calculations purely on household food waste, which usually have a high fat content, resulting in biogas with a high methane share.

The calculated yield factors are found to correspond fairly well with yield factors found in relevant literature. Disparities may be due to variations in feedstock composition, different pretreatment methods utilized and local process efficiency improvements, in addition to erroneous assumptions and inaccurate data utilized when calculating.

5.3.2 Energy efficiency

The energy input into a biogas system is 20-40% of the energy content in the biogas produced and the energy demand for operation is 40-80% of the energy input, according to Berglund and Börjesson (2006) [8]. The input energy found for the evaluated biogas plants are higher than 40% of the energy content in the biogas, when assuming that input energy corresponds to feedstock energy. The process energy demand of the evaluated biogas facilities corresponds fairly well with the statement made regarding energy demand for operation. The deviations are likely due to the energy content of the biogas being based on sold and not produced amount, in addition to inaccuracies in received data concerning feedstock mixture, DM content and rejected amount. Furthermore, the spatial system boundaries of the thesis may not coincide with the boundaries chosen by Berglund and Börjesson (2006).

An average heat demand of 6-17% of the biogas energy produced and an average electricity demand of 8-24% of the biogas energy produced were presented by Berglund and Börjesson (2006) [8]. The heat demand is found to correspond nicely with the heat demand of the evaluated biogas facilities, while the electricity demand is lower than the electricity demand found through calculations. The discrepancy might be a result of inaccuracies concerning the amount of produced biogas, combined with imprecise data regarding the electricity demand of each biogas plant.

Raadal and Modahl (2009) state that 0,083 kWh of electricity is needed per MJ of biogas produced [55]. The value corresponds well with the calculated electricity demand. However, inaccurate data regarding electricity demand, differences in treatment technologies utilized and differing feedstock compositions are could possibly have influenced the results.

According to Yngvesson and Tamm (2017), electricity production has an efficiency of 35% [80]. This is significantly higher than the electricity production efficiencies found for the evaluated facilities. Yngvesson and Tamm (2017) state that the efficiency holds for biogas production, it is thus unclear if the energy demand of pretreatment and post-treatment processes are included in the calculations. An additional reason for discrepancy is uncertainty in regards to the correspondence of system boundaries.

5.3.3 Environmental benefit

Pederstad (2017) presents a standard emission value for transport of 3 g CO_2-eq/MJ CBG produced, based on organic municipal waste [52]. The value coincides with the calculated emissions stemming from transport for the evaluated biogas facilities that produce CBG. An exception is RBA 2018, which has a significantly higher transport emission. This is likely due to missing information regarding the incoming waste at RBA 2018. Hence, emissions stemming from transportation of feedstock are avoided from further calculations. The calculated emission can therefore not be assumed to accurately represent the actual transport related emissions for RBA 2018.

Approximately 0,032 kg CO_2-eq is emitted per MJ biogas produced by Norwegian biogas facilities, according to Magnus (2014) [36]. The value corresponds with the calculated emissions from the evaluated biogas facilities. It should be mentioned that some of the calculations were based on the energy content in the sold biogas, hence the magnitude of emission might not be completely correct for all facilities.

Raadal and Modahl (2009) state that an average of 6 kg CO_2-eq is emitted from the treatment phase per ton incoming waste [55]. Emissions from the treatment phase are assumed to include the emissions stemming from electricity and heat demand of the biogas production process, excluding transport emissions. The Norwegian biogas plants evaluated have a similar degree of emission per ton incoming waste, when disregarding the transport emissions. The European biogas plants are however emitting more CO_2-eq than what is stated in Raadal and Modahl (2009). This may be a result of the differing emission intensity of the electricity-mixes utilized.

Fiksen (2016) found an emission reduction of 412 kg CO_2-eq/ton incoming DM when biogas was utilized for heat production compared to heat generated by a combination of waste, bio-energy, heat pumps, electricity and oil [22]. Both BW and BBR produce heat, however, lacking data regarding the DM share of incoming waste at BW made further comparisons difficult. The heat production at BBR was found to have a smaller reduction of CO_2-emissions than the value provided by literature. An emission reduction of 374 kg CO_2-eq/ton incoming DM for electricity production is presented by Fiksen (2016) [22]. BBR was the only biogas plant producing electricity, which provided information regarding the DM share of the incoming waste. Emissions related to the demand for Nordic electricity are lower than emissions stemming from biogas production at BBR. Hence, negative emission savings were found for BBR in regards to electricity production. Furthermore, Fiksen (2016) provided an estimate of emission reductions when utilizing biogas as an alternative to diesel fuel. The expected reduction is 799 kg CO_2-eq/ton incoming DM [22]. The value corresponds to the saved transport emissions calculated for the fuel-producing biogas plants evaluated.

The main reason for the dissimilarities between the calculated emission savings for BBR and the values presented by Fiksen (2016) might be due to Fiksen (2016) excluding transport related emissions from the analysis. Additionally, differing assumptions made regarding utilized fuel alternatives and inaccurate emission data could have influenced the result.

A reduction of 13 kg CO_2-eq/ton treated organic waste is possible when utilizing bio-fertilizer instead of artificially produced fertilizer. The value is presented by EBA (2015) [19]. Information regarding bio-fertilizer production was given for all biogas facilities except BW. The calculated reductions were generally higher than the ones given by EBA (2015), which could be a result of erroneous assumptions made regarding the emission factor of artificial fertilizer and the share of nitrogen in artificial fertilizer. Additionally, variations in substrate mixture affecting the amount and quality of bio-fertilizer being produced, as well as uncertanity regarding how EBA (2015) defined the system boundaries also affects the results.

5.4 Recommendations for further work

In order to obtain more reliable results, further work should include an update and validation of the received data to make sure that they correspond to the actual state of the systems evaluated. Accurate data regarding internal energy demand, transportation distances, feedstock composition and lower heating values, together with additional flows, should be added if needed, to ensure a realistic yield factor, energy efficiency indicator and environmental benefit.

A more comprehensive environmental analysis could have evaluated the reduced emissions of NOx and particulate matter for biogas utilized as fuel. Additionally, the environmental benefit of utilizing bio-fertilizer in regards to nitrogen and phosphorus preservation could be assessed.

Preforming a cost-benefit analysis would further strengthen the thesis. Studying biogas plants from an economical viewpoint would provide a more holistic perspective of the operations and create a basis for comparing the profitability of biogas to other energy sources. Additionally, a cost-benefit analysis could provide a broader understanding of political resolutions and investment decisions made in regards to biogas.

Expanding the sensitivity analysis to including additional parameters would enhance the analysis. The sensitivity analysis provides information concerning the impact of parameters on specific flows, and could therefore provide valuable information regarding which parameters to adjust in order to optimize the operation. If more information regarding the substrate mixture was provided, a sensitivity analysis could be performed in order to evaluate which waste composition results in an optimal energy balance. Parameters with a high relative sensitivity has a significant impact on the evaluated value and should therefore be as accurate as possible, while parameter with very little impact on the evaluated value could be based on estimates to a greater degree.

6 Conclusion

The object of this thesis was to evaluate the yield factor, energy efficiency and environmental benefit of several biogas production facilities. MFA-based models were developed in order to quantify the mass and energy flows in the systems. Comparisons of the results were made with relevant literature and a sensitivity analysis was performed in order to evaluate the impact of specific parameters.

General MFA-models were developed in order to evaluate the mass and energy flows of biogas systems. Spatial system boundaries were chosen to include transport of incoming feedstock, biogas production processes and transport of finalized biogas product and bio-fertilizer, while temporal system boundaries were chosen on an annual basis. Processes in both the mass layer models and the energy layer model have been merged in order to create a simplified overview of flows related to biogas production.

Yield factors were calculated in order to evaluate the relationship between treated waste and produced biogas. Separate yield factors were calculated based on non-upgraded and upgraded biogas. The yield factors based on upgraded biogas were higher than the yield factors based on non-upgraded biogas, due to the increased methane content in the upgraded gas. However, calculations found that DMF had a higher yield factor when producing non-upgraded biogas. This could be a consequence of assuming that produced amount of upgraded biogas equals the sold amount of upgraded biogas. Yield factors based on VS had a higher value than the yield factors based on DM, which again exceeded the yield factors found when the calculations were based on wet weight. As VS indicates the amount of organic material in a substance, weight based on VS will not significantly change during treatments processes such as dewatering and reject-removal. Hence, yield factor calculations based on VS generate higher output values.

The energy balance of the systems was assessed using available data. Energy efficiency indicators were calculated for each biogas facility and found to range from approximately 26% to around 80%. The results imply that biogas plants producing upgraded biogas have higher energy efficiency than plants producing non-upgraded biogas, which is likely due to upgraded biogas having a higher energy content. Transport energy demand and feedstock composition are found to significantly influence the energy balance of biogas plants.

The environmental benefit of biogas utilization was evaluated by calculating the amount of CO_2-eq emission avoided by utilizing biogas in lieu of fossil energy sources. The magnitude of the avoided emissions depends on the alternative energy source being substituted. BBR was found to have the highest emission savings of all the evaluated biogas plants, with an avoided emission of 1.069.039.542,18 kg CO_2-eq. This could be due to the dual production at BBR resulting in a vast reduction of CO_2-emissions. However, the diverging value may indicate erroneous calculation or incorrectly made assumptions. The avoided emissions found for the remaining biogas production plants ranged from 1.644.193,23 kg CO_2-eq to 87.795.563,69 kg CO_2-eq.

The results were compared with relevant literature in an attempt to evaluate the validity. The calculated yield factors corresponded fairly well with yield factors found in literature. The total process energy demand for biogas production was found to correspond with the calculated energy demand for operation for the evaluated biogas facilities. Values regarding internal heat demand coincided with the calculated heat demand, however, the internal electricity demand was found to exceed the electricity demand factor obtained from literature. The evaluated biogas facilities had an electricity production efficiency that was lower than efficiencies found in literature. Disparities may be a result of variations in feedstock composition, different pretreatment methods utilized and local process efficiency improvements, in addition to erroneous assumptions and inaccurate data utilized when calculating.

Emission values obtained from literature regarding the environmental benefits of biogas and bio-fertilizer utilization was compared with calculated values. Emissions intensities per MJ biogas produced are generally found to correspond with the calculated emissions. Norwegian biogas facilities had a better correspondence with a few of the obtained emission values, which could be due to the different electricity mixes utilized in calculations. The avoided CO_2-emission due to biogas-based heat production and biogas-based electricity production were lower for the evaluated facilities than what was presented in literature, while calculated emission savings due to bio-fertilizer utilization exceeded literary values. The avoided emissions from bio-fuel usage corresponded with the values obtained from literature. It should be mentioned that some of the calculations were based on the energy content in the sold biogas, hence the magnitude of emission might not be completely correct for all facilities. Additionally, differing spatial system boundaries could have influenced the emission calculations.

The energy efficiency and environmental benefit of each biogas facility was further analyzed by performing a sensitivity analysis. Transport distances and DM share of incoming waste was evaluated due to significant uncertainties tied to these parameters. Both absolute and relative sensitivity were calculated in order to enable comparison of impacts. Parameters related to incoming waste, such as transport of food waste and DM share of incoming waste, had a significant impact on both the energy efficiency and environmental benefit of the evaluated biogas facilities. This is likely a consequence of incoming feedstock constituting the largest inflow into the biogas systems.

Limited and imprecise data made it challenging to produce valid results, and the calculated values should therefore not be considered accurate or representative for the actual operation of the biogas plants. Amplified databases, precise models and reasonable assumptions are needed in order to improve the validity of the calculated results. Nevertheless, the results may provide valuable indications and suggest focus areas for improved operation.

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Appendices

Appendix A - Parameters and preliminary calculations

Appendix B - Mass flows and energy flows

Appendix C - Calculation of yield factor

Appendix D - Calculation of energy efficiency

Appendix E - Calculation of environmental benefit

Appendix F - Sensitivity analysis calculations

Appendix G - Results used for comparison with literature

Appendix H - Process diagrams

Appendix A - Parameters and preliminary calculations

Parameters

Parameter	Symbol	Value	Unit	
Absolute pressure	P	1,01E+05	Pa	
Absolute temperature	T	2,73E+02	K	
Molar mass CH4	M_CH4	1,60E+01	g/mol	
Molar mass CO2	M_CO2	4,40E+01	g/mol	
Ideal gas constant	R	8,31E+00	J/(K*mol)	
Share of CH4 in liquid bigogas at RBA	p_CH4	99,70 %		[5]
Share of CO2 in liquid biogas at RBA	p_CO2	0,30 %		[5]
DM in liquid food waste at RBA	dm_lfw_rba	15,00 %		[4]
DM in solid food waste at RBA	dm_cfw_rba	30,00 %		[4]
DM in solid biofertilizer at RBA	dm_sbf_rba	25,00 %		[4]
DM in centrate at RBA	dm_cen_rba	0,80 %		[4]
DM in organic household waste at BBR	dm_ohhw_bill	32,00 %		[3]
DM in liquid biowaste at BBR	dm_lbw_bill	5,00 %		[3]
DM in biofertilizer at BBR	dm_biof_bill	24,00 %		[3]
DM in incoming waste DMF 2016	dm_iw16_dmf	13,40 %		[6]
DM in incoming waste DMF 2017	dm_iw17_dmf	14,40 %		[6]
VS of DM incoming waste DMF 2016	vs_iw16_dmf	84,10 %		[6]
VS of DM incoming waste DMF 2017	vs_iw17_dmf	84,20 %		[6]
Lower heating value food waste (wet weight)	lhv_fw_ww	2,69E+03	MJ/ton	[7]
Lower heating value food waste (DM)	lhv_fw_dm	1,38E+04	MJ/ton DM	[5]
Lower heating value liquid food waste (DM)	lhv_lfw	1,38E+04	MJ/ton DM	[5]
Lower heating value non-upgraded biogas	lhv_nubg	2,30E+01	MJ/Nm3	[1]
Lower heating value upgraded biogas	lhv_ubg	3,59E+01	MJ/Nm3	[2]
Lower heating value diesel	lhv_d	3,53E+01	MJ/l	[2]
Lower heating value natural gas	lhv_ng	3,90E+01	MJ/Nm3	[2]
Distance food waste to BBR	d_fw_bill	5,00E+01	km/load	[8]
Distance food waste to BA	d_fw_bod	4,00E+01	km/load	[9]
Distance food waste to DMF	d_fw_dmf	7,00E+01	km/load	[10]
Distance food waste to RBA	d_fw_rba	6,00E+01	km/load	[5]
Distance food waste to BW	d_fw_wie	1,00E+01	km/load	[11]
Distance biogas product from BBR	d_bg_bill	0,00E+00	km/load	[3]
Distance biogas product from BA	d_bg_bod	0,00E+00	km/load	[22]
Distance biogas product from DMF	d_bg_dmf	0,00E+00	km/load	[23]
Distance biogas product from RBA	d_bg_rba	6,00E+01	km/load	[5]
Distance biogas product from BW	d_bg_wie	0,00E+00	km/load	[17]
Distance biofertilizer product from BBR	d_bf_bill	-	km/load	
Distance biofertilizer product from BA	d_bf_bod	-	km/load	
Distance biofertilizer product from DMF	d_bf_dmf	3,00E+01	km/load	[12]
Distance biofertilizer product from RBA	d_bf_rba	3,50E+01	km/load	[5]
Distance biofertilizer product from BW	d_bf_wie	1,50E+01	km/load	[13]
Average truckload	tl	2,00E+01	ton/load	[14]
Average diesel consumption for trucks	dc	4,50E-01	l/km	[15]
Conversion factor 1 ton to Nm3	cf_ton	4,16E-01	Nm3	
Conversion factor 1 kWh to MJ	cf_kwh	3,60E+00	MJ	
CH4 content non-upgraded biogas BBR	CH4_nubg_bil	63,00 %		[2]
CH4 content non-upgraded biogas BA	CH4_nubg_bod	62,00 %		[16]
CH4 content non-upgraded biogas DMF	CH4_nubg_dmf	63,50 %		[6]
CH4 content non-upgraded biogas RBA	CH4_nubg_rba	60,00 %		[4]
CH4 content non-upgraded biogas BW	CH4_nubg_wie	62,50 %		[17]
CH4 content upgraded biogas DMF	CH4_ubg_dmf	98,50 %		[6]
CH4 content upgraded biogas RBA	CH4_ubg_rba	97,00 %		[4]
CH4 content liquid biogas RBA	CH4_lbg_rba	99,90 %		[4]
Emission factor natural gas	em_ng	5,10E-02	kg CO2-eq/MJ	[18]
Emission factor heat (light fuel oil, at boiler 100 kW)	em_h	9,39E-02	kg CO2-eq/MJ	[19]
Emission factor diesel	em_d	8,58E-02	kg CO2-eq/MJ	[19]
Emission factor artificial fertilizer production	em_f	3,20E+03	kg CO2-eq/ton N	[19]
Emission factor Norwegian el-mix (NO, low voltage, at gri	em_el_no	1,79E-02	kg CO2-eq/kWh	[20]
Emission factor Nordic el-mix (NORDEL, low voltage, at gr	em_el_nordel	1,91E-01	kg CO2-eq/kWh	[20]
Emission factor European el-mix (UCTE, low voltage, at gr	em_el_eur	5,94E-01	kg CO2-eq/kWh	[20]
Share of nitrogen in artificial fertilizer	n_af	20,00 %		[21]
Ratio non-upgraded biogas/treated dry matter BA 2015	r_nu_bo15	51,26437968	Nm3/ton	
Ratio non-upgraded biogas/treated dry matter BA 2018	r_nu_bo18	67,35282514	Nm3/ton	
Ratio non-upgraded biogas/treated dry matter BBR 2017	r_nu_bil	6,33E+02	Nm3/ton DM	
Ratio non-upgraded biogas/treated dry matter RBA 2012	r_nu_rba12	5,1439E+02	Nm3/ton DM	
Ratio upgraded biogas/treated dry matter RBA 2012	r_u_rba12	318,5964912	Nm3/ton DM	
Ratio non-upgraded biogas/treated dry matter RBA 2018	r_nu_rba18	-		
Ratio upgraded biogas/treated dry matter RBA 2018	r_u_rba18	-		
Ratio non-upgraded biogas/treated volatile solid DMF 20	r_nu_dmf16	542,8010228	Nm3/ton VS	
Ratio upgraded biogas/treated volatile solid DMF 2016	r_u_dmf16	342,8266163	Nm3/ton VS	
Ratio non-upgraded biogas/treated volatile solid DMF 20	r_nu_dmf17	690,1557285	Nm3/ton VS	
Ratio upgraded biogas/treated volatile solid DMF 2017	r_u_dmf17	426,8862508	Nm3/ton VS	
Ratio non-upgraded biogas/treated dry matter BW 2018	r_nu_wie	77,27272727	Nm3/ton	
Ratio sold electricity/produced biogas BA 2015	r_bg_bo15	0,079575435	kWh/MJ	
Ratio sold electricity/produced biogas BA 2018	r_bg_bo18	0,075452742	kWh/MJ	
Ratio sold electricity/produced biogas BBR	r_bg_bil_el	0,086065198	kWh/MJ	
Ratio sold heat/produced biogas BBR	r_bg_bil_heat	0,679786607	MJ/MJ	
Ratio sold fuel/produced biogas RBA 2012	r_bg_rba12	1	MJ/MJ	
Ratio sold fuel/produced biogas RBA 2018	r_bg_rba18	1	MJ/MJ	
Ratio sold fuel/produced biogas DMF 2016	r_bg_dmf16	0,983909892	MJ/MJ	
Ratio sold fuel/produced biogas DMF 2017	r_bg_dmf17	0,983902586	MJ/MJ	
Ratio sold heat/produced biogas BW	r_bg_wie	0,791815857	MJ/MJ	

Parameter sources

Parameter sources

[1] Value based on (Hung & Solli, 2011)
[2] Value based on (Swedish Gas Technology Centre Ltd , 2012)
[3] Value provided by Chitra S. Raju
[4] Value obtained from (Cambi, 2012)
[5] Value obtained from (Seldal, 2014)
[6] Value obtained from (Stensgård et al, 2017)
[7] Value obtained from (Lind et al, 2019)
[8] Value estimated from google maps, based on the size of BBR kommune
[9] Value estimated from google maps, based on the distance to Westerwaldkreis and Altenkirchen
[10] Value estimated from google maps, based on the distance to Bjorstaddalen optical sorting facility
[11] Value estimated from google maps, based on the distance to Vienna city center
[12] Value estimated from google maps, based on the distance to Vestfold
[13] Value estimated from google maps, based on the distance to Lobau compost facility
[14] Value derived from (Berglund & Börjesson, 2006)
[15] Value obtained from (Simonsen, 2012)
[16] Value obtained from (Ohr, 2003)
[17] Value estimated based on data recieved from Ing. René Steinmair
[18] Value obtained from (SSB, 2017)
[19] Value obtained from (Hauso, 2013)
[20] Value obtained from the Ecoinvent database
[21] Value estimated based on information regarding YaraMila FULLGJØDSEL (yara.no)
[22] Value estimated based on data provided by David Fritz
[23] Value estimated based on data provided by Mariann Hegg

Preliminary calculation values

Name	Symbol	Flow	Value	Unit
Liquid biogas RBA 2012	LBG	A30	3,27E+03	ton
Feedstock energy RBA 2012	Q_f	A01_a	1,74E+08	MJ
Transport energy BA 2015	Q_t_bo15	A01_c	1,61E+06	MJ
Transport energy BA 2018	Q_t_bo18	A01_c	9,22E+05	MJ
Transport energy BBR 2017	Q_t_bil	A01_c	1,88E+06	MJ
Transport energy RBA 2012	Q_t_rba12	A01_c	3,31E+06	MJ
Transport energy RBA 2018	Q_t_rba18	A01_c	1,57E+08	MJ
Transport energy DMF 2016	Q_t_dmf16	A01_c	7,23E+06	MJ
Transport energy DMF 2017	Q_t_dmf17	A01_c	8,95E+06	MJ
Transport energy BW 2018	Q_t_wie	A01_c	1,75E+05	MJ

Appendix B - Mass flows and energy flows

Mass flows

			BA 2015				BA 2018				BBR 2017				RBA 2012			
Name	**Symbol**	**Flow**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**
Total incoming waste	TW	A01	5,06E+04	ton			2,90E+04	ton				ton						
- Solid biowaste	SBW			ton				ton			9,38E+03	ton	3,00E+03		4,50E+04	ton	1,35E+04	
- Liquid biowaste	LBW			ton				ton			3,80E+04	ton	1,90E+03		5,00E+03	ton	7,50E+02	
Biofertilizer	BF	A10_a	8,37E+03	ton			1,09E+04	ton			1,67E+04	ton	4,00E+03		2,79E+04	ton	6,97E+03	
Non-upgraded biogas	Non_up_b	A10_b	1,53E+06	Nm3			1,87E+06	Nm3			3,10E+06	Nm3						
Reject	Reject	A10_c	2,07E+04	ton			1,26E+03	ton				ton			5,46E+03	ton		
Centrate	Centrate	A10_d		ton				ton				ton			8,67E+04	ton	6,94E+02	
Biogas for upgrading	BG_up	A12		Nm3				Nm3				Nm3			7,33E+06	Nm3		
Upgraded biogas	UBG	A20		Nm3				Nm3				Nm3						
Biogas for liquefication	BG_lq	A23		Nm3				Nm3				Nm3			4,54E+06	Nm3		
Liquid biogas	LBG	A30		ton				ton				ton			3,27E+03	ton		

			RBA 2018				DMF 2016				DMF 2017				BW 2018			
Name	**Symbol**	**Flow**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**	**Mass flow**	**Unit**	**DM flow (ton DM)**	**VS flow (ton VS)**
Total incoming waste	TW	A01					9,16E+04	ton	1,23E+04	1,03E+04	1,13E+05	ton	1,63E+04	1,38E+04	2,20E+04	ton		
- Solid biowaste	SBW															ton		
- Liquid biowaste	LBW															ton		
Biofertilizer	BF	A10_a	3,38E+04	ton	8,44E+03		8,99E+04	ton			1,11E+05	ton				ton		
Non-upgraded biogas	Non_up_b	A10_b													1,70E+06	Nm3		
Reject	Reject	A10_c					6,41E+03	ton								ton		
Centrate	Centrate	A10_d														ton		
Biogas for upgrading	BG_up	A12	2,71E+06	Nm3			5,61E+06	Nm3			9,49E+06	Nm3			0,00E+00	Nm3		
Upgraded biogas	UBG	A20	6,62E+05	Nm3			3,54E+06	Nm3			5,87E+06	Nm3			0,00E+00	Nm3		
Biogas for liquefication	BG_lq	A23													0,00E+00	Nm3		
Liquid biogas	LBG	A30	7,01E+05	Nm3											0,00E+00	ton		

Energy flows

Energy flows

			BA 2015	BA 2018	BBR 2017	RBA 2012	RBA 2018	DMF 2016	DMF 2017	BW 2018
Name	**Symbol**	**Flow**	**Energy flow [MJ]**	**Energy flow [MJ]**	**Energy flow [MJ]**	**Energy flow [MJ]**	**Energy flow [MJ]**	**Energy flow [MJ]**	**Energy flow [MJ]**	**Energy flow [MJ]**
Feedstock energy	Q_f	A01_a	8,03E+07	7,48E+07	6,76E+07	1,74E+08		2,30E+08	3,05E+08	5,92E+07
Process energy	Q_p	A01_b	4,61E+07	5,05E+07	3,57E+07	2,69E+07	2,52E+07	1,72E+07	2,41E+07	1,04E+07
Transport energy	Q_t	A01_c	1,61E+06	9,22E+05	1,88E+06	3,31E+06	1,57E+08	7,23E+06	8,95E+06	1,75E+05
Biogas energy	Q_bg	A10_a	3,52E+07	4,30E+07	7,13E+07	1,63E+08	4,89E+07	1,27E+08	2,11E+08	3,91E+07
Biofertilizer energy	Q_bf	A10_b	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Waste heat	Q_wh	A10_c	4,45E+06	4,63E+06						

Appendix C - Calculation of yield factor

Yield factor calculations

	BA **2015**	BA **2018**	BBR **2017**	RBA **2012**	RBA **2018**	DMF **2016**	DMF **2017**	BW **2018**
Non-upgraded biogas produced [Nm3 CH4]	9,48E+05	1,16E+06	1,95E+06	4,3980E+06	1,63E+06	3,56E+06	6,03E+06	1,06E+06
Upgraded biogas produced [Nm3 CH4]				4,4038E+06	1,34E+06	3,49E+06	5,78E+06	
Feedstock input [ton VS]						1,03E+04	1,38E+04	
Feedstock input [ton DM]			4,90E+03	1,43E+04		1,23E+04	1,63E+04	
Feedstock input [ton wet weight]	2,98E+04	2,78E+04	4,74E+04	4,45E+04		9,16E+04	1,13E+05	2,20E+04
Yield factor [Nm3 CH4/ton]								
Yield factor VS, non-upgraded biogas								
Yield factor biogas [Nm3 CH4/ton]						3,45E+02	4,38E+02	
Yield factor DM, non-upgraded biogas								
Yield factor biogas [Nm3 CH4/ton]			3,99E+02	3,0863E+02		2,90E+02	3,69E+02	
Yield factor wet weight, non-upgraded biogas								
Yield factor biogas [Nm3 CH4/ton]	3,18E+01	4,18E+01	4,12E+01	9,87E+01		3,88E+01	5,31E+01	4,83E+01
Yield factor VS, upgraded biogas								
Yield factor biogas [Nm3 CH4/ton]						3,38E+02	4,20E+02	
Yield factor DM, upgraded biogas								
Yield factor biogas [Nm3 CH4/ton]				3,0904E+02		2,84E+02	3,54E+02	
Yield factor wet weight, upgraded biogas								
Yield factor biogas [Nm3 CH4/ton]				9,89E+01		3,81E+01	5,10E+01	

Appendix D - Calculation of energy efficiency

Energy efficiency calculations

	BA **2015**	BA **2018**	BBR **2017**	RBA **2012**	RBA **2018**	DMF **2016**	DMF **2017**	BW **2018**
Total energy output [MJ]	3,52E+07	4,30E+07	7,13E+07	1,63E+08	4,89E+07	1,27E+08	2,11E+08	3,91E+07
Total energy input [MJ]	1,28E+08	1,26E+08	1,05E+08	2,04E+08	1,82E+08	2,54E+08	3,38E+08	6,99E+07
Energy efficiency indicator	27,48 %	34,09 %	67,79 %	79,80 %	26,83 %	50,05 %	62,28 %	55,97 %

Appendix E - Calculation of environmental benefit

Environmental benefit calculations

	BA 2015	BA 2018	BBR 2017	RBA 2012	RBA 2018	DMF 2016	DMF 2017	BW 2018
Amount electricity sold [kWh]	2,80E+06	3,25E+06	6,14E+06					
Amount heat sold [MJ]			4,85E+07					3,10E+07
Amount fuel sold [MJ]				1,63E+08	4,89E+07	1,25E+08	2,07E+08	
Amount biofertilizer sold [ton wet weigh	8,37E+03	1,09E+04	1,67E+06	2,79E+04	3,38E+04	8,99E+04	1,11E+05	
Electricity consumption biogas productio	1,69E+06	2,00E+06	1,11E+06	2,69E+07	6,81E+06	4,54E+06	6,04E+06	2,10E+06
Heat consumption biogas production [M.	4,80E+06	3,00E+05	3,17E+07		6,67E+05	2,17E+06	2,88E+06	
Diesel consumption transport [MJ]	1,61E+06	9,22E+05	1,88E+06	3,31E+06	1,57E+08	7,23E+06	8,95E+06	1,75E+05
CO2-eq biogas production [kg CO2-eq]	1,59E+06	1,29E+06	3,35E+06	7,64E+05	1,37E+07	9,05E+05	1,15E+06	1,26E+06
Fossil based								
Emission electricity [kg CO2-eq]	1,66E+06	1,93E+06	1,17E+06					
Emission district heating [kg CO2-eq]			4,55E+06					2,91E+06
Emission fuel [kg CO2-eq]				1,40E+07	4,20E+06	1,07E+07	1,78E+07	
Emission artificial fertilizer [kg CO2-eq]	5,35E+06	7,00E+06	1,07E+09	1,78E+07	2,16E+07	5,75E+07	7,12E+07	0,00E+00
Avoided emission [kg CO2-eq]	5,43E+06	7,63E+06	1,07E+09	3,11E+07	1,21E+07	6,73E+07	8,78E+07	1,64E+06

Appendix F - Sensitivity analysis calculations

- F - complete mathematical expression
- x - analyzed parameter
- f - nominator of F
- g - denominator of F
- df - derivative of f
- dg - derivative of g
- g^2 - value of g raised to the second power
- abs sens - absolute sensitivity
- rel sens - relative sensitivity

Sensitivity analysis calculations for BA 2015

BA 2015			
Energy efficiency		Environmental ben	
Distance food waste		Distance food waste to	
f	3,52E+07	F	5,43E+06
df	0,00E+00	x	4,00E+01
dg	4,01E+04		
g	1,28E+08		
g^2	1,64E+16		
F	2,75E-01		
x	4,00E+01		
abs sens	-8,62E-05	abs sens	-3,44E+03
rel sens	-1,25E-02	rel sens	-2,54E-02

Sensitivity analysis calculations for BA 2018

BA 2018			
Energy efficiency		Environmental benefit	
Distance food waste to BA		Distance food waste to BA	
f	4,30E+07	F	7,63E+06
df	0,00E+00	x	4,00E+01
dg	2,31E+04		
g	1,26E+08		
g^2	1,59E+16		
F	3,41E-01		
x	4,00E+01		
abs sens	-6,22E-05	abs sens	-1,98E+03
rel sens	-7,30E-03	rel sens	-1,04E-02

Sensitivity analysis calculations for BBR.

BBR											
Energy efficiency		Energy efficiency		Energy efficiency		Environmental benefit		Environmental benefit		Environmental benefit	
DM in organic household waste a		DM in liquid biowaste at BBR		Distance food waste to		DM in organic househ		DM in liquid biowaste		Distance food waste to	
f	7,13E+07	f	7,13E+07	f	7,13E+07	F	1,07E+09	F	1,07E+09	F	1,07E+09
df	1,36E+08	df	5,53E+08	df	0,00E+00	x	3,20E-01	x	5,00E-02	x	5,00E+01
dg	1,29E+08	dg	5,24E+08	dg	3,76E+04						
g	1,05E+08	g	1,05E+08	g	1,05E+08						
g^2	1,11E+16	g^2	1,11E+16	g^2	1,11E+16						
F	6,78E-01	F	6,78E-01	F	6,78E-01						
x	3,20E-01	x	5,00E-02	x	5,00E+01						
abs sens	4,63E-01	abs sens	1,88E+00	abs sens	-2,42E-04	abs sens	1,09E+07	abs sens	4,44E+07	abs sens	-3,23E+03
rel sens	2,19E-01	rel sens	1,38E-01	rel sens	-1,79E-02	rel sens	3,28E-03	rel sens	2,08E-03	rel sens	-1,51E-04

Sensitivity analysis calculations for RBA 2012

RBA 2012									
Energy efficiency		Energy efficiency		Energy efficiency		Energy efficiency		Energy efficiency	
DM in liquid food waste at RBA		DM in solid food waste at RBA		Distance food waste to		Distance biogas produ		Distance biofertilizer p	
f	1,63E+08	f	1,63E+08	f	1,63E+08	f	1,63E+08	f	1,63E+08
df	5,72E+07	df	5,15E+08	df	0,00E+00	df	0,00E+00	df	0,00E+00
dg	6,90E+07	dg	5,46E+08	dg	3,97E+04	dg	2,59E+03	dg	2,21E+04
g	2,04E+08	g	2,04E+08	g	2,04E+08	g	2,04E+08	g	2,04E+08
g^2	4,17E+16	g^2	4,17E+16	g^2	4,17E+16	g^2	4,17E+16	g^2	4,17E+16
F	7,98E-01	F	7,98E-01	F	7,98E-01	F	7,98E-01	F	7,98E-01
x	1,50E-01	x	3,00E-01	x	6,00E+01	x	6,00E+01	x	3,50E+01
abs sens	1,04E-02	abs sens	3,88E-01	abs sens	-1,55E-04	abs sens	-1,01E-05	abs sens	-8,65E-05
rel sens	1,96E-03	rel sens	1,46E-01	rel sens	-1,17E-02	rel sens	-7,62E-04	rel sens	-3,79E-03

Environmental benefit		Environmental benefit		Environmental benefit		Environmental benefit		Environmental benefit	
DM in liquid food wast		DM in solid food waste		Distance food waste to		Distance biogas produ		Distance biofertilizer p	
F	3,11E+07	F	3,11E+07	F	3,11E+07	F	3,11E+07	F	3,11E+07
x	1,50E-01	x	3,00E-01	x	6,00E+01	x	6,00E+01	x	3,50E+01
abs sens	4,91E+06	abs sens	4,42E+07	abs sens	-2,72E+03	abs sens	-2,22E+02	abs sens	-1,90E+03
rel sens	2,37E-02	rel sens	4,26E-01	rel sens	-5,26E-03	rel sens	-4,30E-04	rel sens	-2,14E-03

Sensitivity analysis calculations for RBA 2018

RBA 2018							
Energy efficiency		Energy efficiency		Environmental benefit		Environmental benefit	
Distance biogas product from RBA		Distance biofertilizer product f		Distance biogas produ		Distance biofertilizer p	
f	4,89E+07	f	4,89E+07	F	1,21E+07	F	1,21E+07
df	0,00E+00	df	0,00E+00	x	6,00E+01	x	3,50E+01
dg	2,60E+06	dg	2,68E+04				
g	1,82E+08	g	3,38E+08				
g^2	3,33E+16	g^2	1,15E+17				
F	2,68E-01	F	2,68E-01				
x	6,00E+01	x	3,50E+01				
abs sens	-3,83E-03	abs sens	-1,15E-05	abs sens	-2,23E+05	abs sens	-2,30E+03
rel sens	-8,57E-01	rel sens	-1,49E-03	rel sens	-1,10E+00	rel sens	-6,63E-03

Sensitivity analysis calculations for DMF 2016

DMF 2016											
Energy efficiency		Energy efficiency		Energy efficiency		Environmental benefit		Environmental benefit		Environmental benefit	
DM in incoming waste DMF 2016		Distance food waste to DMF		Distance biofertilizer p		DM in incoming waste		Distance food waste to		Distance biofertilizer p	
f	1,27E+08	f	1,27E+08	f	1,27E+08	F	6,73E+07	F	6,73E+07	F	6,73E+07
df	9,49E+08	df	0,00E+00	df	0,00E+00	x	1,34E-01	x	7,00E+01	x	3,00E+01
dg	0,00E+00	dg	7,27E+04	dg	7,13E+04						
g	2,54E+08	g	2,54E+08	g	2,54E+08						
g^2	6,45E+16	g^2	6,45E+16	g^2	6,45E+16						
F	5,01E-01	F	5,01E-01	F	5,01E-01						
x	1,34E-01	x	7,00E+01	x	3,00E+01						
abs sens	3,74E+00	abs sens	-1,43E-04	abs sens	-1,41E-04	abs sens	8,01E+07	abs sens	-6,24E+03	abs sens	-6,12E+03
rel sens	1,00E+00	rel sens	-2,01E-02	rel sens	-8,43E-03	rel sens	1,59E-01	rel sens	-6,49E-03	rel sens	-2,73E-03

Sensitivity analysis calculations for DMF 2017

DMF 2017											
Energy efficiency		Energy efficiency		Energy efficiency		Environmental benefit		Environmental benefit		Environmental benefit	
DM in incoming waste DMF 2017		Distance food waste to DMF		Distance biofertilizer p		DM in incoming waste		Distance food waste tc		Distance biofertilizer p	
f	2,11E+08	f	2,11E+08	f	2,11E+08	F	8,78E+07	F	8,78E+07	F	8,78E+07
df	1,46E+09	df	0,00E+00	df	0,00E+00	x	1,44E-01	x	7,00E+01	x	3,00E+01
dg	0,00E+00	dg	9,00E+04	dg	8,83E+04						
g	3,38E+08	g	3,38E+08	g	3,38E+08						
g^2	1,15E+17	g^2	1,15E+17	g^2	1,15E+17						
F	6,23E-01	F	6,23E-01	F	6,23E-01						
x	1,44E-01	x	7,00E+01	x	3,00E+01						
abs sens	4,32E+00	abs sens	-1,66E-04	abs sens	-1,62E-04	abs sens	1,24E+08	abs sens	-7,72E+03	abs sens	-7,57E+03
rel sens	1,00E+00	rel sens	-1,86E-02	rel sens	-7,82E-03	rel sens	2,03E-01	rel sens	-6,16E-03	rel sens	-2,59E-03

Sensitivity analysis calculations for BW

BW			
Energy efficiency		Environmental benefit	
Distance food waste to BW		Distance food waste to BW	
f	3,91E+07	F	1,64E+06
df	0,00E+00	x	1,00E+01
dg	1,75E+04		
g	6,99E+07		
g^2	4,88E+15		
F	5,60E-01		
x	1,00E+01		
abs sens	-1,40E-04	abs sens	-1,50E+03
rel sens	-2,50E-03	rel sens	-9,11E-03

Appendix G - Calculated values used for comparison with literature

Calculated yield factor related values used for comparison with literature

Comparison with literature - Yield factor	Value	Unit
Produced nonupgraded Nm3 CH4/ton DM for BA 2015	-	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for BA 2018	-	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for BBR	3,99E+02	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for RBA 2012	3,09E+02	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for RBA 2018	-	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for DMF 2016	2,90E+02	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for DMF 2017	3,49E+02	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton DM for BW	-	Nm3 CH4/ton DM
Produced nonupgraded Nm3 CH4/ton wet weight for BA 2015	1,87E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for BA 2018	3,99E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for BBR	2,49E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for RBA 2012	8,80E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for RBA 2018	-	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for DMF 2016	3,88E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for DMF 2017	5,31E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton wet weight for BW	4,83E+01	Nm3 CH4/ton wet weight
Produced nonupgraded Nm3 CH4/ton VS for BA 2015	-	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for BA 2018	-	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for BBR	-	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for RBA 2012	-	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for RBA 2018	-	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for DMF 2016	3,39E+02	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for DMF 2017	4,31E+02	Nm3 CH4/ton VS
Produced nonupgraded Nm3 CH4/ton VS for BW	-	Nm3 CH4/ton VS

Calculated energy efficiency related values used for comparison with literature

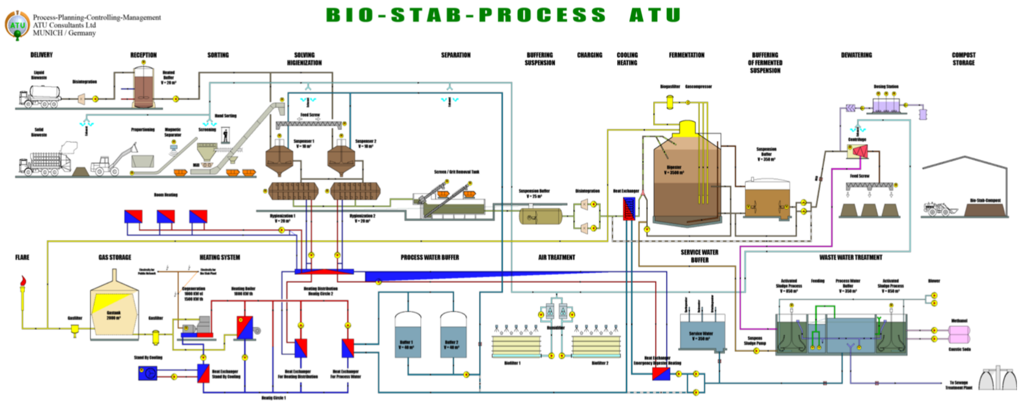
Comparison with literature - Energy efficiency	Value	Unit
Share of feedstock energy in energy content of biogas BA 2015	228,38 %	
Share of feedstock energy in energy content of biogas BA 2018	173,83 %	
Share of feedstock energy in energy content of biogas BBR	94,84 %	
Share of feedstock energy in energy content of biogas RBA 2012	106,79 %	
Share of feedstock energy in energy content of biogas RBA 2018	-	
Share of feedstock energy in energy content of biogas DMF 2016	180,56 %	
Share of feedstock energy in energy content of biogas DMF 2017	144,92 %	
Share of feedstock energy in energy content of biogas BW	151,51 %	
Share of process energy in feedstock energy BA 2015	57,33 %	
Share of process energy in feedstock energy BA 2018	67,54 %	
Share of process energy in feedstock energy BBR	52,76 %	
Share of process energy in feedstock energy RBA 2012	15,45 %	
Share of process energy in feedstock energy RBA 2018	-	
Share of process energy in feedstock energy DMF 2016	7,50 %	
Share of process energy in feedstock energy DMF 2017	7,88 %	
Share of process energy in feedstock energy BW	17,62 %	
Average heat demand of biogas energy BA 2015	13,64 %	
Average heat demand of biogas energy BA 2018	0,70 %	
Average heat demand of biogas energy BBR	44,43 %	
Average heat demand of biogas energy RBA 2012	-	
Average heat demand of biogas energy RBA 2018	1,36 %	
Average heat demand of biogas energy DMF 2016	1,70 %	
Average heat demand of biogas energy DMF 2017	1,37 %	
Average heat demand of biogas energy BW	-	
Average electricity demand of biogas energy BA 2015	4,80 %	
Average electricity demand of biogas energy BA 2018	4,64 %	
Average electricity demand of biogas energy BBR	1,56 %	
Average electricity demand of biogas energy RBA 2012	-	
Average electricity demand of biogas energy RBA 2018	13,92 %	
Average electricity demand og biogas energy DMF 2016	3,57 %	
Average electricity demand og biogas energy DMF 2017	2,87 %	
Average electricity demand of biogas energy BW	-	
Electricity demand per MJ biogas produced BA 2015	4,80E-02	kWh/MJ
Electricity demand per MJ biogas produced BA 2018	4,64E-02	kWh/MJ
Electricity demand per MJ biogas produced BBR	1,56E-02	kWh/MJ
Electricity demand per MJ biogas produced RBA 2012	1,65E-01	kWh/MJ
Electricity demand per MJ biogas produced RBA 2018	1,39E-01	kWh/MJ
Electricity demand per MJ biogas produced DMF 2016	3,57E-02	kWh/MJ
Electricity demand per MJ biogas produced DMF 2017	2,87E-02	kWh/MJ
Electricity demand per MJ biogas produced BW	5,37E-02	kWh/MJ
Electricity production efficiency BA 2015	7,87 %	
Electricity production efficiency BA 2018	9,26 %	
Electricity production efficiency BBR	21,00 %	
Electricity production efficiency RBA 2012	-	
Electricity production efficiency RBA 2018	-	
Electricity production efficiency DMF 2016	-	
Electricity production efficiency DMF 2017	-	
Electricity production efficiency BW	-	

Calculated environmental benefit related values used for comparison with literature

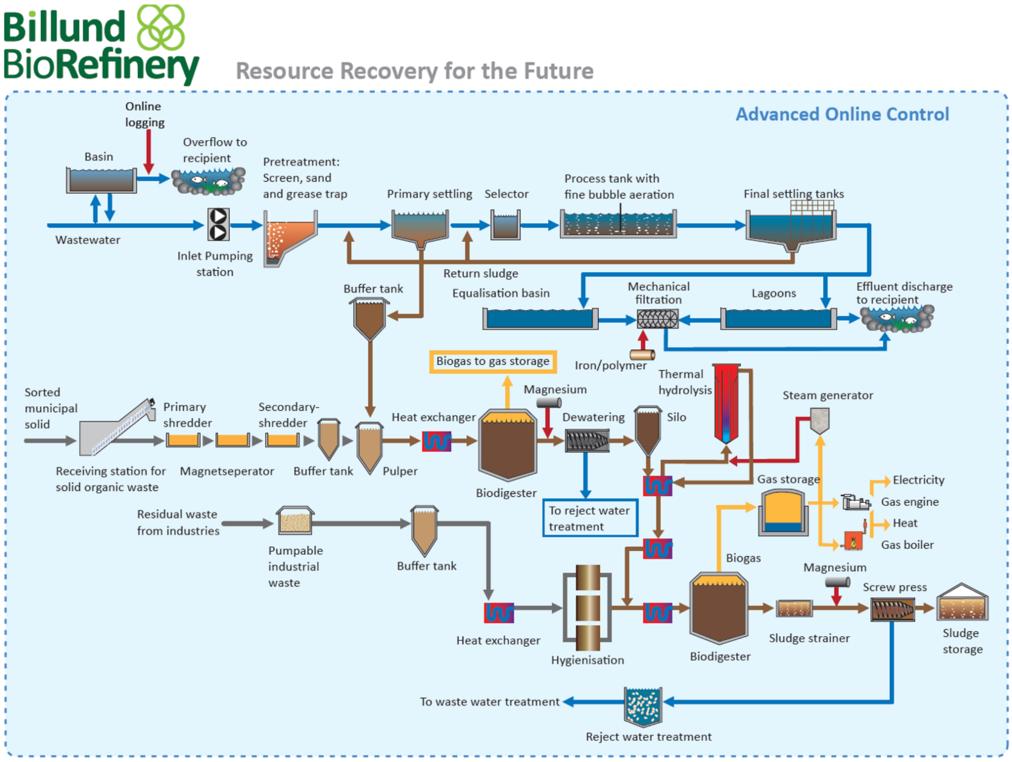
Comparison with literature - Environmental benefit	Value	Unit
Transport emissions upgraded biogas BA 2015	-	
Transport emissions upgraded biogas BA 2018	-	
Transport emissions upgraded biogas BBR	-	
Transport emissions upgraded biogas RBA 2012	-	
Transport emissions upgraded biogas RBA 2018	2,76E+02	g CO2-eq/MJ CBG
Transport emissions upgraded biogas DMF 2016	4,88E+00	g CO2-eq/MJ CBG
Transport emissions upgraded biogas DMF 2017	3,64E+00	g CO2-eq/MJ CBG
Transport emissions upgraded biogas BW	-	
Emission per MJ biogas produced BA 2015	4,53E-02	kg CO2-eq/MJ
Emission per MJ biogas produced BA 2018	3,01E-02	kg CO2-eq/MJ
Emission per MJ biogas produced BBR	4,70E-02	kg CO2-eq/MJ
Emission per MJ biogas produced RBA 2012	4,69E-03	kg CO2-eq/MJ
Emission per MJ biogas produced RBA 2018	2,79E-01	kg CO2-eq/MJ
Emission per MJ biogas produced DMF 2016	7,12E-03	kg CO2-eq/MJ
Emission per MJ biogas produced DMF 2017	5,44E-03	kg CO2-eq/MJ
Emission per MJ biogas produced BW	3,23E-02	kg CO2-eq/MJ
Emisison reduction heat production BA 2015	-	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production BA 2018	-	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production BBR	2,46E+02	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production RBA 2012	-	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production RBA 2018	-	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production DMF 2016	-	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production DMF 2017	-	kg CO2-eq/ton DM incoming waste
Emisison reduction heat production BW	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production BA 2015	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production BA 2018	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production BBR	-4,45E+02	kg CO2-eq/ton DM incoming waste
Emisison reduction el production RBA 2012	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production RBA 2018	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production DMF 2016	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production DMF 2017	-	kg CO2-eq/ton DM incoming waste
Emisison reduction el production BW	-	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production BA 2015	-	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production BA 2018	-	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production BBR	-	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production RBA 2012	9,28E+02	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production RBA 2018	-	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production DMF 2016	8,00E+02	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production DMF 2017	1,02E+03	kg CO2-eq/ton DM incoming waste
Emisison reduction fuel production BW	-	kg CO2-eq/ton DM incoming waste
Emisison reduction biofertilizer production BA 2015	1,26E+02	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production BA 2018	2,05E+02	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production BBR	2,24E+04	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production RBA 2012	3,84E+02	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production RBA 2018	-	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production DMF 2016	6,64E+02	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production DMF 2017	6,17E+02	kg CO2-eq/ton treated waste
Emisison reduction biofertilizer production BW	-	kg CO2-eq/ton treated waste

Appendix G - Process diagrams

Process diagram of BA. Received from [23].



Process diagram of BBR. Recevied from [57]



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