Quantitative Characterization of Biogas Quality

A Study of Biogas Quality at Stormossen Oy

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BACHELOR'S THESIS

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Abstract

This Bachelor's thesis describes biogas as a sustainable biofuel and a realistic alternative to fossil fuels, such as gasoline and diesel. In this work the quality of biogas, produced at Stormossen Oy waste treatment plant, is analyzed to evaluate its feasibility as a fuel for combustion engines manufactured by Wärtsilä Finland Oy. The analysis is based on the determination of the biogas quality fluctuations during its production process using collected organic waste. The quality of the biogas was characterized as the variation of methane, carbon dioxide and contamination components compositions measured online, using an optical gas analyzer. The results of the analysis showed that the biogas quality does not meet the Wärtsilä requirements for combustible engine fuel, by not reaching the required minimum of methane content. The results also showed that the variation of the biogas composition is stable, although the biogas methane composition was observed to oscillate during the production process and periodically fluctuate during a time period of a week.

Language: English Key words: biogas quality, biofuel, optical gas analyzer

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Abstrakt

Detta ingenjjörsarbete beskriver biogas som ett hållbart och realistiskt alternativ till fossila bränslen, såsom bensin och diesel. I detta arbete analyseras och evalueras potentialen för biogas producerad vid Ab Stormossen avfallshanteringsanläggning, för användning i förbränningsmotorer tillverkade av Wärtsilä, Finland. Analysen är baserad på fastställande av biogasens kvalitetsfluktuationer under produktionsprocessen från insamlat organiskt avfall. Biogasens kvalitet karakteriserades som variationer i metan, koldioxid och sammansättningar av förorenande komponenter, vilka mättes online med en optisk gasanalysator. Resultaten från analysen visar att biogasen inte uppnår Wärtsiläs krav för förbränningsmotorbränslen, eftersom minimikravet för metanhalt inte uppnås. Resultaten visar också att variationerna i biogasens sammansättning var stabil, även om biogasens metanhalt observerades oscillera under produktionsprocessen och periodiskt variera inom en vecka.

Språk: Engelska Nyckelord: biogaskvalitet, biobränsle, optisk gasanalysator

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Tiivistelmä

Tämä insinöörityö kuvaa biokaasua kestävänä ja realistisena vaihtoehtona fossiilisille polttoaineille, kuten bensiini ja diesseli. Tässä työssä analysoidaan ja arvioidaan Stormossen Oy:n tuottamaa biokaasun mahdollista käyttöä Wärtsilä Finlandin valmistamissa polttomoottoreissa. Analyysi perustuu biokaasulaadun vaihtelun määrittämiseen sen tuotantoprosessissa, kerätystä orgaanisesta jätteestä. Biokaasun laatua luonnehdittiin metaani, hiilidioksidi ja epäpuhtauksien eri komponenttien koostumuksien variaationa, jotka mitattiin reaali-aikamittauksissa optisella kaasuanalyysiaattorilla. Tulokset osoittivat että tutkitun biokaasun laatu ei täytä Wärtsliän polttomoottoreille asetettuja polttoainevaatimuksia, sillä biokaasu ei saavuta metaani koostumuksen minimivaatimusta. Tulokset näyttävät myös että variaatiot biokaasun koostumuksessa ovat vakaita, vaikkakin biokaasun metaanikoostumus vaihteli tuotannon prosessissa ja vaihteli viikon aikana.

Kieli: Englanti Avainsanat: biokaasulaatu, biopolttoaine, optinen kaasuanalysaattori

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Definition of Terminology and Abbreviations

EEA	-	European Environmental Agency
GHG	-	Greenhouse gas
CBG	-	Compressed biogas
GC	-	Gas chromatograph
CI	-	Confidence Interval
BR1	-	Bioreactor 1 at Stormossen Oy Ab
BR2	-	Bioreactor 2 at Stormossen Oy Ab
LNG	-	Liquefied Natural Gas
VOC	-	Volatile Organic Compounds
VFA	-	Volatile Fatty Acids
MBT	-	Mechanical Biological Treatment
MN	-	Methane Number
RSD	-	Relative Standard Deviation
SD	-	Standard Deviation
Nm^3	-	Normal cubic meter
GWh	-	Gigawatt hours
TWh	-	Terawatt hours

Chemical compounds

H_2S	-	Hydrogen sulphide
O_2	-	Oxygen
N_2O	-	Nitrous oxide
HFCs	-	Hydrofluorocarbons
PFCs	-	Perfluorocarbons
SF_6	-	Sulphur hexafluoride
CO_2	-	Carbon dioxide
CH_4	-	Methane
H_2	-	Hydrogen
$C_2H3O_2^-$	-	Acetate
NH_3	-	Ammonia
N_2	-	Nitrogen
P	-	Phosphorus

1. Introduction

Today sustainability is a key issue in the development of economic sectors, especially in the energy sector that includes industry and transport sectors due to the high rate of global emissions pollution and primary usage of fossil energy sources. That makes the development and adoption of alternative fuels to fossil becoming a crucial aspect of sustainability for the energy sector.

Biogas is one of the realistic sustainable alternatives to fossil transport fuels, such as gasoline or diesel. Biogas is a renewable source of methane produced by anaerobic digestion of biomass. Compressed biogas (CBG) has been used as vehicle fuel since the 1990s. However, in recent years, the usage of the CBG as a traffic fuel has increased and created a high interest in the biogas production for transport applications. [1]

The aim of this thesis is to evaluate waste based biogas produced at Stormossen Oy as fuel for marine engines and power plants in Wärtsilä Finland Oy. The evaluation is based on quantitative analyses of the biogas content for identifying its quality, namely, variation in the biogas composition and impurity levels. Presence of the impurities in the biogas composition has a negative effect during the utilization process such as damage of the equipment, increased flue gas emissions and threat to human health. The variation of the biogas composition influences performance of the engine during the combustion process.

1.1. Background

The thesis has been made within the Hercules 2 project in cooperation with Wärtsilä Finland Oy while the commissioner of the work is the University of Vaasa. Wärtsilä has an interest in using sustainable biogas as an engine fuel and a renewable source of energy. Collaboration between Wärtsilä Finland Oy and Stormossen Oy sets the foundation for the evaluation of the biogas potential adoption for the engine fuel.

Wärtsilä is a global leader in complete lifecycle power solutions for the marine and energy markets. They provide innovative solutions and products for its marine, oil and gas industry customers, such as engines and generating sets, reduction gears, propulsion equipment, control systems and sealing solutions [2]. Together with the other major European engine manufacturer, Groups MAN, Wärtsilä hold 90% of the world’s marine engine market [3].

Stormossen Oy is a regional waste management company that produces 2,4 million Nm^3 of raw biogas as one of the division in its waste management system. The waste based produced biogas contains about 65% of methane (CH_4), the rest is mainly carbon dioxide (CO_2) and minor share of impurities [4]. An additional point of interest for Stormossen is that in the year 2014 it was decided to upgrade the biogas production process for the transport applications only. This decision was based on two reasons.

The first reason is based on the current utilization system. Produced biogas is used for electricity production and heating at the facility or sold to real estate for heating. This utilization system has about 20 % of excess gas flared into the atmosphere [5]. The second reason is energy recovery from Westenergy Oy incineration plant, located at Stormossen facility, which has been in operation since 2012. Source-separated combustible waste is utilized as fuel for electricity and district heating production, which is about 80 and 280 GWh/year respectively [6]. The district heating from Westenergy replaces the Stormossen biogas heating capacity, allowing it to be used for something else [7].

1.2. The Context of the Project

The thesis is done within the HERCULES-2 project, which is a phase of the Research and development (R&D) program HERCULES which was initiated in 2002, in order to develop new technologies for marine engines. The aim of the HERCULES-2 project is to develop a fuel flexible large marine engine, optimally adaptive to its operating environment [3]. This work is part of a subproject *1.1 Fuel flexible engine (4-stroke)*. This subproject belongs to one of the four R&D Work Packages Groups which is called "*Systems for increased fuel flexibility*". The main goals of the sub project are to develop and test measurement technology for intermediate combustion products, plus investigate the impact of switching between different fuels on after-treatment devices and engine components. Together these four groups cover a wide spectrum of marine engine research and development. Work Package 1 leader is Andreas Schmid (Winterthur Gas & Diesel Ltd.) and Deputy Work Package 1 leader is Kaj Portin (Wärtsilä Finland Oy). Participants of Work Package 1 for a 4-stroke engine are Wärtsilä Finland Oy, University of Vaasa and Aalto University [8].

Within the HERCULES-2 project, alternative fuels qualification research is needed in order to determine the full impact of switching between different fuels in 4-stroke fuel flexible engines. Wärtsilä has a high interest in biogas as one of the fuel alternatives due to the availability of the biogas production in the Bothnia region, including Västerbotten, Västernorrland and Pohjanmaa (Östrebotten), where Stormossen Oy is located.

1.3. Purpose

The purpose of this study is to determine the range of biogas quality fluctuations during its production, treatment and storage processes. The quality fluctuation analysis is a part of an evaluation of the feasibility of biogas as a combustion engine fuel.

Biogas quality characterization is described as a variable depending on the production method and biomass source. In order to determine the range of biogas quality fluctuation a research based on Stormossen Oy biogas production sector has been conducted. The research includes the measurements and composition analysis of raw biogas.

1.4. Methodology

The stated purpose is reached within a structured framework that includes a literature review, measurements process, the analysis of collected measurements data and results evaluation.

A literature review was conducted in order to gain more knowledge and understand the position of biogas in the present energy sector. The review describes the theoretical background to worldwide and European energy sector to identify and confirm a need for renewable fuels including the biogas characterization and the background of biogas in Finland and the Bothnia region. The sources used in this literature review include recent statistical data, scientific reports and textbooks within the related study field.

During the measurement process MKS Precisive® analyzer was used to perform onsite online measurements of the biogas along with Micro Gas Chromatograph (GC), CP-4900 for collected gas sample measurements. A number of measurements and their duration time were chosen according to the biogas production process and the time boundaries of the project.

Data Analysis

In order to analyze the measured data sample, descriptive statistical methods are used for analytical summary including sample mean ($\bar{X}$), sample median ($\bar{x}$), sample standard deviation (*S*), relative sample standard deviation (*RS*), and sample range (*R*). Sample mean, formula (1) and median are calculated for identifying location and central tendency in collected data set. $\bar{x}$ is expressed as the middle observation of x_1, x_2, x_3, …, x_n if *n* is an odd number where *x* is a sample of observation from data distribution. Otherwise it is the average of the two middle samples of observation. Concerning variability measuring within a gas content the sample standard deviation and the sample relative standard deviation are identified according to formulas (2) and (3) based on arithmetic average of the sample values variable. The sample range is calculated according to formula (4) to categorize the collected data. [9]

$$\bar{X} = \sum_{i=1}^{n} {X_i}/{n} \qquad (1)$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{(x_1-\bar{x})^2}{n-1}} \qquad (2)$$

$$RS = 100 * S/\bar{X} \qquad (3)$$

$$R = Max\, X - Min\, X \qquad (4)$$

where

n number of samples in data distribution;

X random sample of observation.

“Confidence Interval” (CI) is also included to the collected data analysis system. Mathematically CI can be explained as “a 100(1-*a*)% confidence interval for a parameter *θ* is a random interval [L_1, L_2] such that

$$P[L_1 \leq \theta \leq L_2] \doteq 1 - a \qquad (5)$$

regardless of the value of *θ*” [9, pp. 266]. This means that any parameter *θ* that fits to the interval between L_1 and L_2 within a data set will have a distribution probability less or equal to *a* %. When mean and variable of data distribution are assumed to be unknown, the CI for mean sample value is obtained by formula (6). Random variable follows a T-distribution with *n-1* degrees of freedom.

$$\bar{X} \pm t\frac{s}{\sqrt{n}} \qquad (6)$$

t-values are found from “T-table” according to a level of confidence and the degree of freedom. [9]

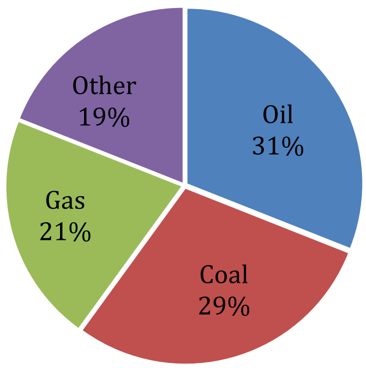
Evaluation of biogas for potential use as the fuel for combustion engines is based on the measured data analysis. The results of the analysis are assessed and compared with Wärtsilä gas fuel requirements and other biogas producing companies such as Jeppo Biogas Oy.

2. Current Energy Situation

This chapter includes a review of research on the current situation in international and European energy sector, promoting the adoption of sustainable biogas as renewable fuel to established energy market.

Global energy demand is increasing due to worldwide economic development and population growth projections according to Roser [10]. Moreover, fossil fuels are still the dominant primary energy supplies (Fig. 1) leading to a continuous uptrend in greenhouse gas emissions that cause environmental impacts such as global warming [11].

“Global warming or ‘climate change’ covers the climate changes following from an accumulation in the atmosphere of greenhouse gases, i.e. long-lived gases which absorb infrared radiation from the earth” [12, pp. 121]. GHG include CO_2, CH_4, nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6). The level of gases has been significantly increasing over the past century. CO_2 is the major GHG emitted into the atmosphere by the combustion of fossil fuels. Oil is the most commonly used fuel, however coal has been determined to produce the biggest amount of CO_2 emissions. In both Fig. 1 and 2 other primary energy supplies are referred, for example, to nuclear, hydro, geothermal, solar, tide, wind, biofuels and waste as the energy supply. [11]



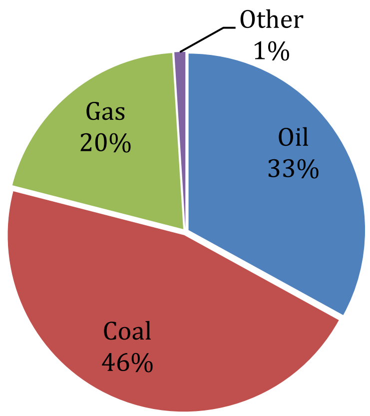


FIG. 1 TOTAL PRIMARY ENERGY SUPPLY PERCENTAGE SHARE IN 2013. [11, pp. 9]

FIG. 2 CO_2 EMISSIONS SHARE FOR TOTAL PRIMARY ENERGY SUPPLY IN 2013. [11, pp. 48, 51, 54, 57]

In the year 2013 two-thirds of global CO_2 emissions were produced by electricity and heat sector together with transport sector (Fig. 3). About 94% of all global CO_2 emissions in the transport sector are emitted by road transport. Such significant shares of emissions within these two sectors can be explained due to the fact that the electricity and heat sector is mainly supplied by coal and gas, while oil is the primal energy supply for the transport sector [11]. Furthermore, according to a dataset at the European Environment Agency (EEA), which includes data on greenhouse gas emissions inventory for the period 1990-2013, greenhouse gas (GHG) emissions, carbon dioxide (CO2) equivalent of the transport sector are still increasing while pollution levels of the other energy sectors are decreasing [13].

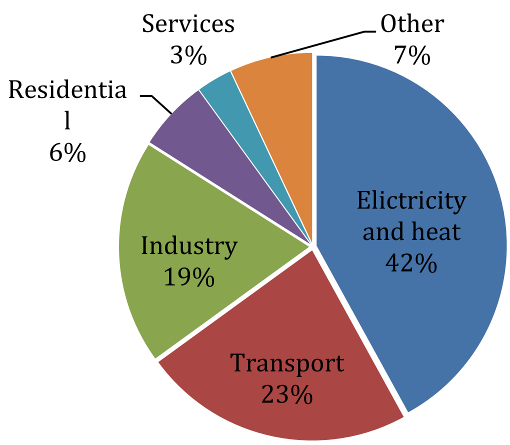


FIG. 3 WORLD CO2 EMISSION BY SECTOR IN 2013. [11, pp. 66]

To reduce GHG emissions and address the problem of global warming the European Union introduced the Decision No 406/2009/EC of the European Parliament and of the Council on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020 [14]. According to this decision, GHG emissions should be reduced by at least 20% by 2020 compared with 1990. Nevertheless, the level of GHG emissions needs to be collectively reduced by 60 to 80 % by 2050, to prevent an increase in overall global annual mean surface temperature more than 2 °C above pre-industrial levels [14]. A significant amount of emissions resulting from energy generation from traditional power plants can be avoided. Renewable energy and fuel have high potential for energy recovery and virgin fuel replacement.

Renewable energy is considered to be an energy, which source is replaced by a continuous natural process that has an equal or higher rate of replacement than consumption rate. Renewable energy sources include hydropower, solar power, wind power, geothermal and biomass that is a source of biofuels and bioenergy. "Bioenergy is the chemical energy contained in organic materials that can be converted into direct, useful energy sources via biological, mechanical or thermochemical processes" [15, pp. 3]. For example, organic waste treatment processes generate electricity and thermal energy as well as produce biofuels [12]. The biofuels such as biodiesel, ethanol, biogas and hydrogen (H_2) can be classified into three generation according to their biomass feedstock, production process and an amount of energy yield per hectare of crop plantation. For example, lignocellulose is a major feedstock for second generation biofuels, of which production process includes biochemical and thermochemical treatments resulting in higher amount of energy yield per hectare [15]. So, for example, biogas can be categorized as a first generation biofuel or as a second generation biofuel according to what feedstock source was used during production, a food crop based biogas is the first generation biofuel, while a waste based biogas is a second generation biofuel.

3. Biogas

Biogas is one of the alternative biofuels for fossil fuel replacement. According to a review on "Biofuels, greenhouse gases and climate change" [15] use of the first generation biofuels causes emission reductions of up to 60% of CO_2 equivalent relative to fossil fuels. CO_2 emissions produced from biofuel combustion, originate from CO_2 are initially emitted in the atmosphere and used in photosynthesis to build plant material creating an integrated cycle. The carbon cycle of the biofuel is much shorter than a carbon cycle of the fossil fuel, due to the transformation process of organic matter into the fossil fuel mineral resources, which takes millions of years [15]. Therefore the use of biogas does not provide net contributions to the atmosphere content of CO_2 [12].

The main biogas components are CO_2 and CH_4, which compositions are determined by the oxidation state of the organic material. For example, the typical value for CH_4 content in biogas from anaerobic digestion is 45-85%, when the typical landfill CH4 gas content is 45-60 %. [16]

3.1. Biogas Production

Anaerobic digestion is a biological conversion process of organic matter into digest used to produce an energy rich gas, biogas. Process steps of the anaerobic digestion are hydrolysis, fermentation or acidogenesis, acetogenesis, and methanogenesis [17]. The process steps occur in order after each other, creating the coherent biomass digestion. The anaerobic digestion process is visualized in Appendix 1 as a flow chart including the steps and organic compounds that take part in the process.

In the hydrolysis and fermentation, enzymes and the complex of anaerobic microorganisms particulate polymers or long hydrocarbons, such as proteins and cellulose, to soluble monomers along with producing organic acids including volatile fatty acids (VFA), CO_2, alcohols, and hydrogen (H_2) [16]. This process can last from a few hours to a few days, depending on type of the polymers. Produced organic acids and alcohols are converted to acetate ($C_2H_3O_2^-$) and H_2 during the acetogenesis process. Then at the last stage of the degradation process, methanogenic bacteria produces CH_4 [18]. The methanogenesis process can be divided into two categories by the type of the bacteria. The first type is aceticlastic microbe that forms 60-70% CH_4 from $C_2H_3O_2^-$ and H_2. The second type belongs to hydrogenotrophs, which produce 30-40% CH_4 from CO_2 and H_2 [16].

One of the main aspects in anaerobic digestion is the digestion temperature condition in a tank digester. There are three digestion types according to temperature ranges: thermophilic digestion (40-60 °C), mesophilic digestion (25-40 °C) and psychrophilic digestion (0-25 °C). The most common types of digestions are thermophilic and mesophilic. The thermophilic digestion allows the fastest digestion process, improved solubility and availability of substrates and better degradation of long chain fatty acids. However, it is more challenging to control the thermophilic digestion process, because it requires more energy input and it has a larger risk of inhibition components compare with the mesophilic process. The inhibitor components may include CH_3, CO_2 and hydrogen ion. [16]

Another aspect is solid concentration level of digesting organic material, which classifies the process into wet or dry fermentation. If the solid concentration is lower than 10% the digestion process is considered for wet fermentation. Dry fermentation is applied for the concentration between 15 % and 35 %. Wet digestion process is dominant among biogas production plants, as it allows the application of completely stirred tank digesters plus continuous feeding process. While dry fermentation requires batch feeding to the tank and it is more challenging to apply proper mixing, which can increase a chance of swimming layers and sediments. [18]

Landfill gas generation is also considered as one of the energy rich gas production methods. It is similar to the biogas, as its generation process is based on anaerobic digestion of disposal waste and contains primary CH_4 and CO_2. However, the landfill gas generation rate is much slower and the gas quality is usually poorer comparing to the biogas [19]. That is why the landfill gas is mostly used for heat and power generation only or flared.

Due to the high content of methane in biogas, it is crucial to have controlled gas capturing and storage systems. Methane gas is a 25 times stronger GHG than CO_2 according to weigh basis [12]. Therefore, the produced biogas, during anaerobic digestion in bioreactors or landfills, should not be released into the atmosphere. If there is an excess of biogas during production process, it should be either stored or utilized by an additional energy recovery system. However, if none of these options are available, the excess biogas needs to be flared [20].

3.2. Biogas Quality

Biogas quality is characterized by the methane, the energy rich component of the gas and impurities concentration level. Presence of the impurities in the biogas can be caused by the organic material contamination and digestion process instabilities. For example, ammonia (NH_3) and long chain fatty acids are inhibitory compounds produced during protein amino acids and lipids degradation. High level of NH_3 contaminates the biogas reducing its quality value. Disturbances in the bioreactors operation, like overloading, can cause the VOCs emitting. [16]

The most common impurities present in the biogas are water vapor, nitrogen (N_2), H2S, NH_3 and various organic compounds; including long hydrocarbons, volatile organic compounds (VOCs) and others. For example, source-separated organic waste based biogas commonly contains traces of organic halogen compounds and heavy metals. The presence of the impurities in the biogas composition may have a negative effect during utilization stage. The biogas can be utilized for [17]:

- Heat production
- Power and heat production
- Combustion engine fuel production
- Injection to the natural gas grid

Motor technology is the most common method used in the first three methods above. The alternative technologies are microgas turbines and fuel cells. In general this kind of equipment is very sensitive to impurities in the gas, such as the catalyst inside the fuel cell [18]. Most of the contaminants cause damage effects on the equipment as described in TABLE 1.

On the other hand, upgrading the biogas for the injection to the natural gas distribution grid is commonly used in the areas, where a natural gas network exists. It requires even higher methane content than, for example, the vehicle fuel, demanding stricter impurity levels requirements and. [17]

TABLE 1 TYPICAL BIOGAS CONTAMINATION COUMPOUNDS TABLE. [18], [21] (a) FOR BIOGAS PRODUCED FROM SEWEGE SLUDGE, LIVESTOCK MANURE OR AGRICULTURAL BIOWASTES. (b) FOR BIOGAS RECOVERED FROM CONVENTIONAL LANDFILLS. (-) INFORMATION NOT DETERMINED

Contaminant	Typical compound composition ,%	Risk
Water vapor	5-10%[a]	Corrosion of pipelines gas storage tanks, compressor and engine technologies, deterioration of lubrication oils
Carbon Dioxide	30-47%[a]	Corrosion of the equipment
Nitrogen	0-3%[a]	NO_x flue gas emissions
Hydrogen sulphide	0-10.000ppm[a]	Corrosion of pipelines gas storage tanks, compressor and engine technologies, deterioration of lubrication oils, SO_x flue gas emissions
Ammonia	0-100ppm[a]	Generation of corrosive products during combustion
Long-chain hydrocarbons	0-200 mg/m3[a]	-
Volatile organic compounds	0-4500mg/m3[b]	Risk for human health threat
Molds and bacteria	-	Risk for human health threat, equipment damage
Halogenated hydrocarbons	20-200ppm(V)[b]	Generation of corrosive products during combustion
Heavy metals	-	Risk for human health threat
Oxygen	0-1%[a]	Explosion hazards
Siloxanes	0-41 mg/m3[a]	Risk of causing abrasion, overheating and malfunctioning in combustion engines and valves
Hydrogen	0-3%[b]	-
Carbon monoxide	0-3%[b]	-

In order to treat the biogas to reduce or remove the contamination, several upgrading technologies and methods are used. The type or a combination of the technologies are chosen according to the biogas composition. The most common upgrading systems are scrubbers, membrane separators, filters, chemicals and bacteria additives. [22]

In conclusion, only a good quality biogas, treated from the contamination components must be utilized to prevent damage of the equipment, followed by higher operating costs, flue gas emissions, or human health. However, the biogas composition variation is another important factor, which also characterize the biogas quality. The range of trace compounds and its composition amounts is directly dependent on the digestion material used. Therefore, the exact biogas composition is unique to each biogas production plant and varies due to heterogeneous sources of organic material. The variation of the biogas composition can also be caused by the digestion process disturbances. For example, the water vapor contamination is a temperature dependent variable. A decrease in the biogas temperature will cause water vapor condensation, additionally trapping water soluble compounds such as NH_3 and CO_2 [23].

Variation in biogas composition has a negative effect on combustion engine performance. The major reason is that proportions of the constituent gases in the biogas, such as CH_4 and CO_2, effect ignitability and the combustion behavior of the gas fuel. Calculated methane number (MN) of the gas provides an indication of the fuel knock tendency, allowing to define engine calibration and its component configuration. The MN fluctuations effects both operating knock margin and ignition capability of the engine. [24]

3.3. Biomethane as an Automotive Fuel

Biogas upgraded to biomethane gas with CH_4 content over 97% is seen as one of the realistic alternatives to gasoline and diesel. The upgrading process involves “gas cleaning” from the impurities and compression to CBG (200-250 bars).

In practice, it is the easiest fuel to adopt for all types of transport, because there is no need to adapt the vehicle engine [15]. Usage of the biomethane as a vehicle fuel, will reduce the GHG within the transport sector. In the current situation, biomethane is one of the most environmentally friendly fuels. Especially waste based biomethane, which is capable of reducing lifecycle GHG emissions significantly [1]. Besides it has a potential to decrease a demand of fossil fuel. In Bothnia region the upgraded biogas would replace approximately 8% of the transport sector’s fuel needs until year 2030, basing on prognoses of biogas production rate expansion with 500GWh/year [7].

From an economical point of view upgrading the biogas and selling it as a vehicle fuel is more profitable than using it for heat and electricity production. The producer receives the best price for selling the vehicle biogas comparing to raw biogas [7]. On the other hand, in order to distribute vehicle biogas or CBG fueling station, a network needs to be built, which requires substantial initial investments.

3.4. Biogas in Finland

In Finland the use of CBG started in 1941 in Helsinki. At that time 53 compressed gas vehicles were running on sewage based biogas from the Kyläsaari and Rajasaari sewage treatment plants [1]. Currently, there are 85 biogas facilities in Finland and the total production rate is about 683 GWh/year, in year 2012. However, the biogas utilization for vehicle fuel is still relatively low. Even though, the consumption of the biogas has increased during the last decade by nine hundred times, in year 2012 only 4 GWh of biogas was upgraded to vehicle fuel [7].

There is a tendency of CBG to increase, based on the total biogas potential in Finland being equal to 17 TWh/year [7]. Moreover, the amount of CBG stations will increase in Finland due to the DIRECTIVE 2014/94/EU on the deployment of alternative fuels infrastructure, which requires to build a whole EU wide LNG and CBG fueling network accessible to the public [25].

3.5. Bothnia Biogas

Wärtsilä Oy Finland has a high interest in the Bothnia region, due to the biogas availability and promotion of the biogas utilization for production of the automotive fuel by Bothnia Biogas project. Bothnia Biogas was a cooperation project between Finland and Sweden. The main goal of this project was to promote biogas production and usage as vehicle fuel in Bothnia region that includes Västerbotten, Västernorrland and Pohjanmaa (Österbotten).

There are at least 25 biogas production facilities in this region. A list of the facilities can be found in Appendix 1, containing short information about the type of the facilities themselves including average production rate. The list of all facilities in Västerbotten and Västernorrland is based on Biogas Survey for 2009-2011 [26], while the information for the facilities in Pohjanmaa is updated until year 2014 [27]. The approximate amount of biogas produced in the Bothnia region in 2012 is 160GWh, while the potential for biogas production in Bothnia region is estimated to be 1200GWh. According to the studies of the project the amount raw material available in Bothnia region, digested to biogas could potentially replace 20% of fuel consumption in the transport sector [7].

Domsjö Fabriker Ab and Norrmejerier have the biggest biogas production facilities in Bothnia region. Both of them are located in Sweden. Together, these two companies produce almost three-quarters of all biogas in Bothnia region. [7]

The two biggest facilities in Pohjanmaa region in Finland are Stormossen Oy and Jeppo Biogas Oy. An average production rate of biogas from these two companies is 35GWh/year. This thesis is done in close cooperation with Stormossen Oy, which biogas production facility is the major source for the research and analysis.

4. Stormossen Oy

The Stormossen Oy main facility and waste treatment plant are located at Koivulahti (Kvevlax) in Mustasaari (Korsholm). The company was founded in 1985 and started to operate in year 1990 [28]. It is owned by the six municipalities Vaasa, Isokyrö, Mustasaari, Vöyri, Maalahti and Korsnäs. The waste treatment plant includes several stations where the waste is utilized as materials, energy, nutrients or deposited in a landfill site [29]. The list of all waste treatment stations located at the facility is presented in TABLE 2.

TABLE 2 STORMOSSEN OY WASTE TREATMENT STATIONS. [30]

Waste Treatment Station	Description
Recycling Station	Municipal waste sorting
Sorting Station	Industrial and construction waste sorting
Contaminated Soil Station	Treatment of contaminated soil
Incineration Plant	Combustible waste is incinerated and utilized as energy at West Energy
Landfill	Deposition of no value waste
Hazardous Waste Landfill	Deposition of Hazardous waste landfill
Leachate Treatment Plant	Treatment leachate from landfills and oil contaminated soil
MBT Station	Treatment of municipal biowaste and organic waste from businesses and other companies to organic material, utilization of treated organic waste to produce biogas and digested sludge
Composting Area	Processing the digested sludge to soil mulch and compost

4.1. Stormossen Biogas

Stormossen Oy biogas production started in year 1990 with one bioreactor (BR1) and later on in 1994 the waste treatment plant expanded with a second bioreactor (BR2) [28]. Both bioreactors are built in the bed rock, however they are separated by different supply systems of raw material. The raw material for the biogas production in BR1 is wastewater sludge from Påttin jätevedenpuhdistamo (Påttska wastewater treatment plant) located in Vaasa.

While the raw material used in the BR2 is collected municipal biowaste plus the organic waste from businesses.

According to the previous years, average biogas production rate is 120 Nm^3/h and 180 Nm^3/h for BR1 and BR2 accordingly. [31] However, the annual average production rate values for year 2015 are lower, about 90 Nm^3/h for both of the reactors, due to rebuilding of the process production. In total Stormossen generates 15 GWh energy per year, which is being used for electricity production and heating at the facility. Moreover, biogas is sold for heating Botnia Hall in Mustasaari [7].

In addition to biogas production from bioreactors, there is also landfill gas. The landfill gas is produced from an old landfill closed in 2004. However, the amount of produced landfill gas is very low. The landfill gas production rate is about 4 Nm^3/h, with a methane content of 30 % or lower. [32] Currently, it is used as the energy source for a steam boiler for water heating.

In future, all biogas produced at Stormossen is planned to be used as an automotive fuel for city buses and local traffic in Vaasa. This decision was supported and agreed with Vaasa city in the spring 2014. According to prognoses, only one-third of produced biogas will be used by the city buses, while the rest will be sold as a vehicle fuel. Public fueling stations, which can be accessed by the public, are planned to be built to distribute the biomethane within the city. A liquefied natural gas (LNG) will be used as a backup fuel source. [7]

In order to achieve a goal of utilizing biogas as vehicle fuel, a stable production process needs to be developed by upgrading the biogas production system. Many changes have already been implemented since the spring 2014, including a conveyor system for biowaste more practical for biomaterial with high water content. Other process upgrades, such as connection to district heating and construction of a pasteurization unit are still in the planning stage. Nevertheless, the major process upgrade that still remains to be constructed is the biogas upgrading unit, where biogas will be refined to biomethane. [5]

4.2. Organic Waste Characterization

The relative composition of two major components in the biogas, produced in anaerobic digestion, are determined by the oxidation state of the waste. Energy rich waste with high content of fats, produces energy rich biogas containing large amount of methane. Waste with high carbohydrates content produces biogas with equal amount of CH_4 and CO_2. The pH of the waste also influences the composition of the gas. [16]

As waste is a heterogeneous source of organic material, the exact composition is unknown and has a wide varying range. That creates challenges in the biogas production process and its composition prediction. This sub chapter determines main characteristics of the waste material used for the biogas production at Stormossen, which are the wastewater sludge and the municipal biowaste.

4.2.1. Wastewater Sludge

The organic material for the biogas production in BR1 is wastewater sludge from Påttin jätevedenpuhdistamo (Påttska wastewater treatment plant) located in Vaasa, where wastewater from Vaasa city and partially from Mustasaari (Korsholm) and Maalahti (Malax) municipalities is treated.

Sewage sludge is one of the most common source of organic matter used for the biogas production due to its availability and low solids content. However, it contains large amount of contaminants that cause the production of impurity gases in the biogas. A list of the contaminants in the sewage sludge from Pått plant is presented in TABLE 3, where N_2 and phosphorus (P) have the biggest contamination level.

TABLE 3 WASTEWATER SLUDGE COMPOSITION AND CONTAMINANTS FROM PÄTTIN JÄTEVEDENPUHDISTAMO (PÄTT WASTEWATER TREATMENT PLANT) FROM 08.02.2016. [33] (a) COMPONENT COMPOSITION IN SLUDGE SOLIDS.

Components	Units	Sample values
Solids	%	18.90
Ash	%	26.00
pH (25 °C)		6.70
Total nitrogen	%[a]	4.60
Total phosphorus	%[a]	1.80
Manganese	g/kg[a]	0.23
Arsenic	mg/kg[a]	2.70
Mercury	mg/kg[a]	0.20
Potassium	g/kg[a]	2.00
Calcium	g/kg[a]	27.00
Chrome	mg/kg[a]	7.40
Copper	mg/kg[a]	220.00
Lead	mg/kg[a]	10.00
Nickel	mg/kg[a]	14.00
Zinc	mg/kg[a]	300.00
Cobalt	mg/kg[a]	3.00
Magnesium	g/kg[a]	2.60
Cadmium	mg/kg[a]	0.34

4.2.2. Municipal Biowaste

The organic material for the biogas production in BR2 is treated municipal biowaste. Biowaste means biodegradable waste, “food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants” [34, art. 3, p. 4.]. The composition of the organic matter in waste is very complex, due to the wide range of chemical compounds and the variety of disposed products. For example, a variety of biowaste composition from households includes paper, garden waste and food leftovers such as fruits, vegetables, bakery products and meat.

Although the municipal biowaste contains great amount of impurities and non-degradable components like plastics, due to manual sorting, it is a great source of organic material for the biogas production. The main components in food waste are proteins and lipids, both have a capability to produce larger amounts of CH_4 from anaerobic digestion than CO_2 [16].

4.3. Biogas Production Process

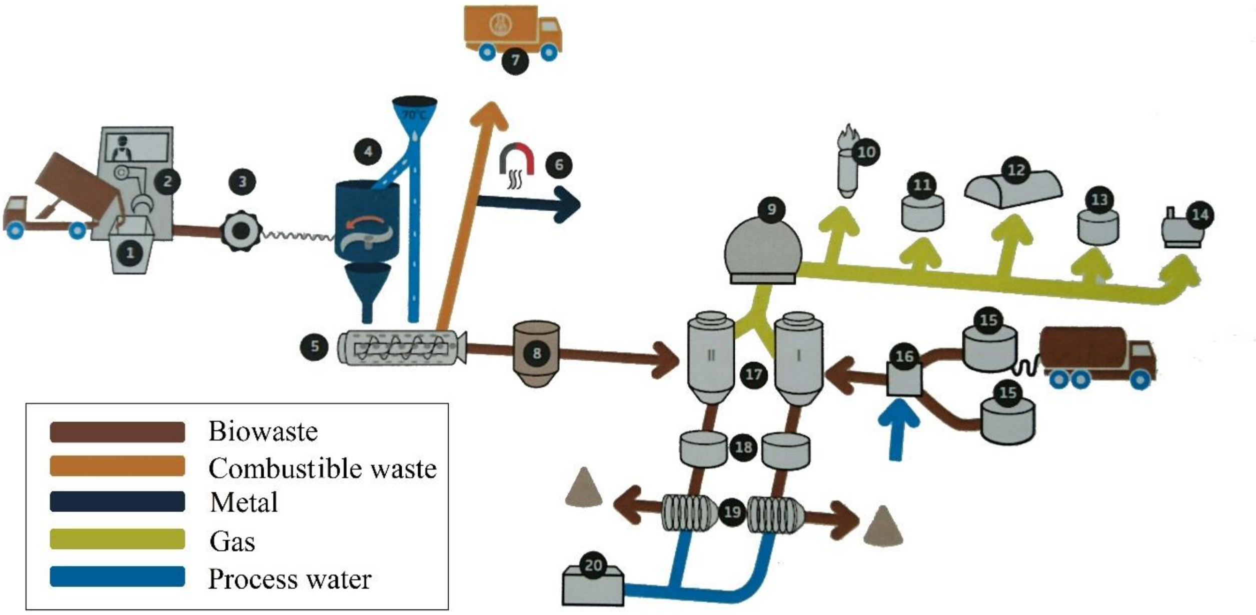


FIG. 4 STORMOSSEN BIOGAS PRODUCTION & UTILISATION PROCESS. [35]

The biogas production process at Stormossen begins with receiving of the biowaste transported to the treatment plant. The biowaste receiving container (1) shown on the Fig. 4 is used for municipal sorted biowaste only, while the wastewater sludge is being collected in tanks (15). The wastewater sludge is being mixed with warm water (16) before it enters the BR1 (17).

The municipal biowaste requires pretreatment for inorganic components separation and stabilization of the organic matter composition, which allows to keep balanced digestion in BR2 (17). Grabs (2) are used for separating the waste from big sized objects before the homogeneous waste mixture is moved to the pre-crushing unit (3). After that the waste is processed in crushing mixer (4), where it is being mixed with warm water. Screw press (5) is used for organic material separation from inorganic components such as paper and plastic, basing on the physical state of the material. All the organic material is separated as liquid and slurry under the pressure, while the dry material is taken out. The separated organic matter is stored in a buffer tank (8) before it reaches the BR2. The dry matter, which mainly consists of inorganic components, goes through magnetic separation unit (6), where magnet diverts the magnetic materials from the waste and utilized together with other combustible waste (7) at Westenergy Oy incineration plant.

Both bioreactors (17) are one stage vertical digester tanks where the organic material is digested under the thermophilic conditions. Digesting slurry is being mixed using an axial stirring that creates a steady stream and a pneumatic stirring methods. During the pneumatic stirring the produced biogas is used as the mixing gas blown from the bottom of the digester. In order to reduce H_2S composition in the biogas a commercial ferrous solution is added directly to the buffer tank (8) previous BR2. Digested sludge is stored in the tanks (18) before it reaches the centrifuge unit (19), where the sludge is dehydrated and afterwards can be utilized for compost. The water from the digested sludge is pre-cleaned in the water treatment unit (20).

Produced biogas from the bioreactors (17) is cooled down to remove the water vapor and collected in gas storage tank (9). Furthermore the biogas is utilized for steam production (11), heating at Botnia Hall in Mustasaari (12), power (14) and heat (13) production at the facility or flared (10).

4.4. Biogas Analyses

In order to identify the biogas quality, onsite measurements were made during the production process, allowing to determining the biogas content and the range of its composition fluctuations. The measurement process consisted of sample measurements and onsite online measurements of the biogas from three different measurement points, separating the measurement data according to the source of the biogas production. The timeframe of the process was evenly divided to weeklong time periods for each measurement point. The measurement points are:

- Biogas exit pipe from bioreactor 1
- Biogas exit pipe from bioreactor 2
- Collected biogas inlet pipe to gas storage

Online measurements were performed on-site by using MKS Precisive® analyzer. MKS is an optical analyzer that provides real-time gas analysis. This analyzer is based on Tunable Filter Spectroscopy sensor platform, which can be utilized from Ultra-Violet through Infra-Red spectral regions [36]. The light source of the spectrometers emits electromagnetic radiation within the selected range of wavelength through sampled gas and then module scans the wavelength of the received light, measures the actual absorption spectra of the gas, and compares them with the pre-loaded calibration spectra [37]. Measured compounds during online biogas monitoring are listed in TABLE 4, which also includes information about calibration concentration range of the analyzer for each compound.

TABLE 4
CALIBRATION CONFIGURATION FOR MKS ANALYZER. [38] (a) C5+ LUMPED IS REFERRED TO THE SUM OF ISO-PENTANE, NEO- PENTANE AND C6+.

Compound	Calibration Concentration
Methane	0-100%
Ethane	0-25%
Propane	0-25%
iso-Butane	0-10%
n-Butane + n-Pentane	0-10%
C5+ lumped [a]	0-10%
Carbon Dioxide	0-100%

The preparation process for online measurements included installation of the MKS analyzer, the heating line and the outlet line for measured gas. The heating line was used in order to prevent the water vapor condensation during the biogas transferring from the pipes to the analyzer. For each measurement point the MKS sample time was set to the slowest mode, 5 seconds.

At least one sample measurement was performed for each measurement point in order to validate measured online data. Biogas samples were collected on-site using Tedlar® Gas sampling bags equipped with two fitting valves allowing to flush the gas and avoid air contamination. The biogas samples analysis has been done by a Micro GC at Wärtsilä facility. This GC is equipped with four independent column channels and a heated sample line with a heated injector to prevent the sample from condensing. Each column channel performs as a miniaturized GC, where gas components are separated within the column and quantity of each component is measured by a detector [39]. The sample measurement process involved construction of a new calibration method due to unique composition of the measured gases in the biogas. Previously, the GC was used for identifying natural gas and flue gas compositions, using the calibration methods adjusted for specific gas composition range, which is significantly different from the biogas.

5. Variation of Biogas Quality

The biogas production is being monitored through the whole process. The parameters are collected and stored in real time of the production process operation allowing to monitor and control the process. The main measured parameters are:

- Temperature: the temperature of the digesting sludge in the reactors, the temperature of mixing water and the temperature of produced and stored biogas
- Pressure: the pressure of the biogas produced in the bioreactors, the pressure of stored biogas
- Flow: of the produced biogas, of the organic material inputs and outputs from the bioreactors
- Digesting sludge level in the reactors
- Methane composition in the biogas

During the online measurement process this monitoring data was collected, to be able to analyze the potential cause of the biogas quality fluctuation basing on the changes in the process parameters. The biogas quality is characterized by its content plus the variation range of the biogas composition. CH_4 and CO_2 gases are the main compounds of the biogas, both of them are also the most important indicators of digestion process conditions. That is why both of the gases were chosen, among other measured compounds, to represent the fluctuation of the quality of the biogas. The variations of the biogas CH_4 and CO_2 compositions are visualized as time graphs and presented in Appendix 3 for each measurement point.

The online measurements data for the biogas produced from the BR1 contains two weeks of measurements, unlike one week of the other measurements data for the biogas produced from the BR2 and the combined gas measurements. This was done because of the time availability and in order to identify the characteristics of the biogas composition fluctuations during several weeks. By observing the major changes in the biogas quality and comparing the measured data with the collected monitoring parameters, the direct influence on CH_4 composition in the biogas was determined by the disturbances in organic material supply and digested sludge flow rates.

Chemical composition of the biogas is presented in TABLE 5. This table includes collected data from the laboratory analysis reports of the biogas composition from Stormossen. It was decided to use the average biogas composition for the time period between years 2013 and 2014 as the actual biogas composition for data comparison, due to the changes in organic materials source in 2012, when the Westenergy incineration plant started to operate.

TABLE 5 LABORATORY GASANALYSIS OF STORMOSSEN OY BIOGAS COMPOSITION FOR THE PERIOD BETWEEN YEARS 2008 AND 2014. [40] (a) CONVERTED DATA USING ONLINE CALCULATOR [41]. (b) TOTAL HALOGEN COMPOUND CONCENTRATION IS ESTIMATED AS A SUM OF HALOGENATED HYDROCARBONS. (c) TOTAL S CONCENTRATION IS CALCULATED FROM TOTAL SULPHIDE COMPOUNDS CONCENTRATION. (d) TOTAL SILICON CONCENTRATION IS CALCULATED FROM TOTAL HYDROCARBONS CONCENTRATION. (*) BELOW THE DETECTION LIMIT. (+) NOT DETERMINED. (-) NO INFORMATION.

	03/2008	04/2008	01/2009	03/2013	03/2014	04/2014	Average 2013-2014
CH_4, %	56.00	65.00	61.00	60.10	59.10	60.00	59.73
CO_2, %	40.00	38.00	38.50	39.10	40.10	39.30	39.50
Oxygen, %	0.50	<1.00	< 1.00	0.10	0.20	0.10	0.13
N_2, %	2.00	1.00	1.00	0.60	0.60	0.60	0.60
H_2S, %	0.12	0.05	0.11	0.046[a]	0.01[a]	0.018[a]	0.02
NH_3, mg/m^3	1.50[a]	1.50[a]	< 0.75[a]	+	< 0.20	< 0.20	< 0.20
Total Halogen Comp.[b], mg/m^3	*	0.01	0.25	<1,70	<1,70	<1,70	<1,70
Total Cl, mg/m^3	-	0.00	0.07	<2,20	<1,40	<1,40	< 1.67
Total F, mg/m^3	-	*	*	<2,20	<1,40	<1,40	< 1.67
Total S[c], mg/m^3	-	-	-	698.0	157.0	229.0	361.3
Total Silicon Comp.[d], mg/m^3	0,40-0,80	0,50-0,70	2.20	10.30	14.00	10.70	11.67
Total Si, mg/m^3	0,15-0,30	0.20	0.80	3.90	5.30	4.00	4.40

The results for descriptive statistics analysis of the online measured data represent the variation of the biogas quality according to the variation of the measured component. The results can be found in Appendix 4 that includes the analysis results for each measurement point separately describing the variation characteristics for each measured compound.

Relative standard deviation (RSD) values for major biogas components, such as CH_4 and CO_2, are equal to 3 and about 5 % respectively for all biogas measurements, including separate and combined biogas from both bioreactors. Such low standard deviation values express consistency and stability of the variance of gas concentration distribution. While the RSD values for trace measured gases, such as propane, iso-butane, n-butane, and long hydrocarbons (C5+) are relevantly high and imply that the variance of the trace gasses concentration distribution is inconsistent and hard to predict.

6. Discussion and Comparison

According to the analysis results for the online measurements, the biogas produced from the sewage sludge, from the BR1 has 3% higher CH_4 content that the biogas produced from the municipal biowaste, from the BR2. However, the online measurements for each measurement point have been performed separately which excludes the equality of the environment conditions such as outdoor temperature. The combined biogas has the highest concentration of methane gas composition comparing to the compositions of the biogas measured directly from the bioreactors, because water vapor content was removed from the combined biogas before it was measured. Therefore, the analysis results of the combined biogas measurements were chosen to represent the actual composition of Stormossen biogas for further comparisons.

6.1. Wärtsilä Gas Fuel Requirements

The analyses results of the online measured data are compared to gas fuel specifications for Wärtsilä gas engines for evaluation of the feasibility of biogas as the combustible engine fuel. The evaluation presents whether the biogas can be used as a gas fuel in case the quality meets the requirements. Compared data for Wärtsilä Oy Finland gas fuel requirements and Stormossen Oy biogas quality is present in Appendix 5.

TABLE 13 in the Appendix 5 includes the property requirements for a gas fuel for Wärtsilä engines and Stormossen Oy biogas related properties from the lab analysis and the online measurements results. Both the MN and low heating value are not clarified for a specific limit in this table, because both of these properties define the engine output and component configuration of the engine, such as gas feed pressure [42]. The Stormossen lab analyzed data, presented in the table, reflects the average biogas composition since year 2013.

According to the comparison it was determined that the biogas produced at Stormossen biogas does not fulfill the specified gas fuel requirements for the Wärtsilä engines, unless it is upgraded to biomethane with higher methane composition. The required minimum limit for CH_4 composition is equal to 70 % volume. All other known properties of the biogas, such as ammonia, chlorine and fluorine component compositions, meet the requirements.

6.2. Jeppo Biogas Oy

The analyses results of the online measured data of Stormossen Oy biogas were also compared to the biogas variation analysis results of the alternative biogas production company, Jeppo Biogas Oy. Jeppo Biogas is an innovative company that already refines their biogas to a high standard biomethane. The company's biogas production plant located in Uusikarlepyy (Nykarleby) in the Northen part of the Pohjanmaa region, has been in operation since 2013 [43]. Jeppo Biogas plant facility generates 20GWh/year producing 3.5 MNm^3 of raw biogas [44].

The main differences between the biogas production companies are the source of organic material, Jeppo Biogas utilizes generally manure, slurry from animal feed and sludge from food industries, while Stormossen uses the sewage sludge and the municipal biowaste.

6.2.1. Jeppo Biogas Production Process

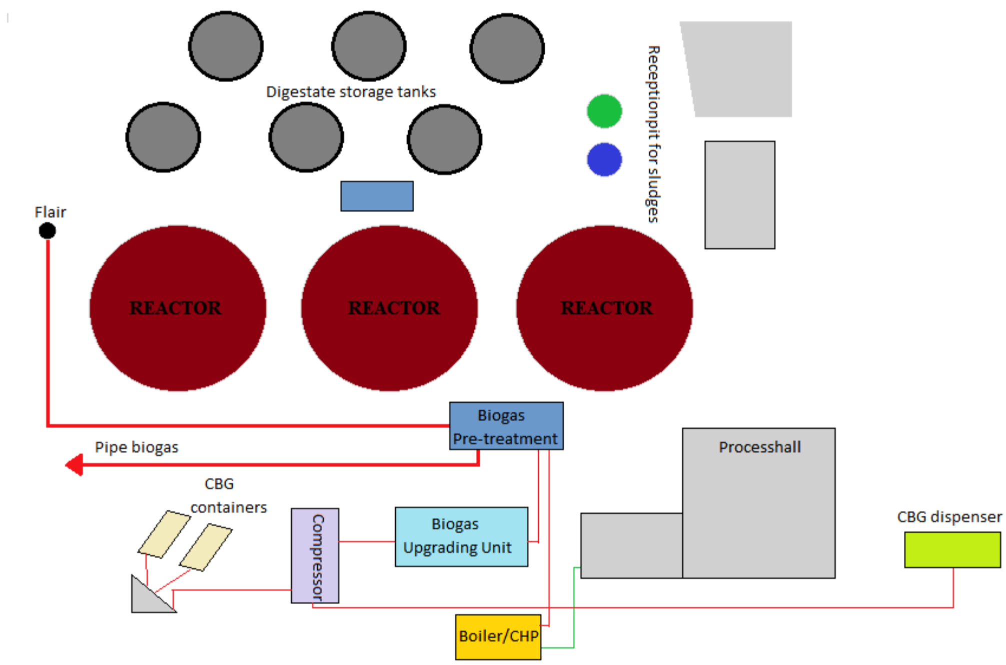


FIG. 5 JEPPO BIOGAS FACILITY LAYOUT. [44], [45]

There are three bioreactors at Jeppo Biogas plant facility, which are $3500m^3$ each. Each tank is supplied with raw material through a pipeline system including storage tanks for digestive sludge. There are six storage tanks located at the facility area as shown on Fig. 5. In addition to the sludge pipeline system there is a gas pipeline system that connects bioreactors with treatment and upgrading units, compressor, process hall boiler and refueling station for vehicle fuel at the facility. [46]

The fermentation process inside the reactors is wet, allowing a continuous supply of raw materials to the bioreactors. Before reaching the bioreactor the biomass mixture of raw materials is pre-treated in order to reduce the size of particles making it easier for microorganism to digest the mixture [46]. TABLE 6 presents ratio of the raw material mixture ingredients. The major raw material used is manure from pigs, cows and other farm animals. Sludge from food industry mostly contains potato waste sludge and potato peel waste from Jeppo Potatis Oy. Green mass referrers to grass, such as hay and straw from fields. The raw material and digested sludge are transported by pipelines from five different suppliers [45].

TABLE 6
RAW MATERIAL MIXTURE. [47]

Manure	73,70 %
Slurry from animal feed and sludge from food industry	16,70 %
Fur sludge from leather factory	4,10 %
Green mass	2,80 %
Other biowaste	2,70 %

In order to maintain the production process online measurements of the temperature in the reactors, raw biogas composition and the flows of biomass mixture and digestive sludge are followed. The biogas composition is characterized by methane, oxygen and sulphur contents measured online. In addition to desulphurization raw biogas cleaning process includes drying to remove the moisture content. The raw biogas production rate varies from 450 Nm^3/h to 600 Nm^3/h [46]. The produced biogas is utilized as heat and power at Jeppo Biogas facility and at a local industry, Mirka Oy, which is connected to the gas production facility by a 4km long gas pipeline [45]. However, only about a half of produces gas is utilized as raw biogas. The rest is upgraded to biomethane or flared. Flaring of biogas is caused by low energy consumption during the weekend days. Moreover, the plant facility together with the local industries using the biogas as the energy source, are not fully operational during the weekends which causes a decrease in energy production need [46]. On the other hand, daily biogas production rate in Jeppo biogas plant is also lower on weekends than on working days. Fractions percentages for biogas utilization are present in Fig. 6.

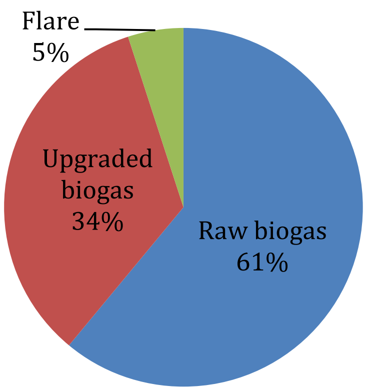


FIG. 6 UTILIZATION OF BIOGAS PRODUCES AT JEPPO BIOGAS.

Jeppo Biogas uses Malmberg's water scrubbing upgrading technology for upgrading the raw biogas to biomethane. Incoming raw biogas is compressed and washed in chemical free water. During the washing process CO_2 and hydrogen sulphide (H_2S) are absorbed by water and separated from methane gas [48]. All three elements are monitored during the upgrading process. Treated biogas contains 98% of methane plus residues of CO_2 and oxygen (O_2). Further upgrading includes gas compression up to 250 bars. The average amount of biomethane production is 250Nm^3/h. The upgraded gas is used as vehicle fuel and energy source for industry. The biomethane is transported in a 5045Nm^3 container [46], [44].

The CBG dispenser located at Jeppo Biogas facility is the first filling station for methane in the Pohjanmaa region. Price for biomethane as a vehicle fuel is 1.40 €/kg. It can also be presented as 0.92 €/L for gasoline liter equivalent which is 30% less than the price of standard gasoline in Finland [49, Jan.2016]. The annual amount of fuel consumed though this station is about 15 tonnes. Biomethane is supplied directly to the station's storage tank, after it has been compressed to 250 bars. However, the pressure decreases to 200 bars while fueling a vehicle [42].

6.2.2. Jeppo Biogas Data

The results for Jeppo biogas data analysis presented in TABLE 7 are based on descriptive statistics as well as the results for the online measurement data of Stormossen biogas. The Jeppo Biogas data includes daily measured values for the biogas CH_4 and the biomethane CO_2 compositions during two months period in 2015, November and December. The number of the biogas data samples is equal to 61 and the degree of freedom, used in CI calculations is determined to be 60. The biomethane CH_4 composition is estimated from the data for CO_2 composition, neglecting the availability of other components.

TABLE 7 JEPPO BIOGAS OY DATA ANALYSIS RSULTS FOR COMPOSITION VARIATION OF RAW BIOGAS AND BIOMETHANE. [50] (a) ESTIMATED VALUES.

	Biomethane, CO2		Biomethane, CH4[a]		Biogas, CH4	
Average:	1.84		98.16		62.12	
Mean:	1.90		98.10		62.48	
SD	0.49		0.49		1.42	
RSD	26.67%		0.50%		2.29%	
Min:	0.70		97.1		58.67	
Max:	2.90		99.3		64.46	
Sample range	2.20		2.20		5.79	
Interval 90%	0.11		0.11		0.3040	
Interval 95%	0.13		0.13		0.3638	
Interval 99%	0.17		0.17		0.4839	
90% range	1.74	1.95	98.05	98.26	61.82	62.43
95% range	1.72	1.97	98.03	98.28	61.76	62.49
99% range	1.68	2.01	97.99	98.32	61.64	62.61

Based on the CH_4 composition variation, such as RSD and sample range, the biomethane quality variation is smaller than the biogas quality variation. During the biogas upgrading process to biomethane the impurity content is removed, resulting in a more consistent final product. This concludes that raw biogas quality variations do not have a significant impact on the quality of the final product, the biomethane.

6.2.3. Data Comparison

In order to validate the measurement results at Stormossen Oy, they were compared with data results from Jeppo Biogas Oy. The data comparison between these two companies is present in TABLE 8, where the analysis results for CH_4 composition of combine gas at Stormossen are compared to the analyzed CH_4 composition variation of biogas at Jeppo Biogas.

TABLE 8 DATA COMPARISON BETWEEN JEPPO BIOGAS OY AND STORMOSSEN OY METHANE COMPOSITION VARIATION IN BIOGAS. [50]

	Jeppo Biogas Oy, Methane		Stormossen Oy, Methane	
Average:	62.12		60.09	
Mean:	62.48		60.33	
Standard Deviation	1.42		1.61	
RSD	2.29%		2.68%	
Min:	58.67		56.96	
Max:	64.46		63.72	
Sample Range	5.79		6.75	
Interval 90%	0.3040		0.0027	
Interval 95%	0.3638		0.0035	
Interval 99%	0.4839		0.0048	
90% range	61.8193	62.4272	60.0898	60.0951
95% range	61.7595	62.4871	60.0890	60.0959
99% range	61.6394	62.6071	60.0876	60.0973
n	61		604460	
n-1	60		604459	
t, 90%	1.671		1.282	
t, 95%	2		1.674	
t, 99%	2.66		2.326	

The differences between data collection methods at Stormossen and Jeppo Biogas, such as the numbers of data samples used for the analyses, and the time, when the measurements were taken, can have an influence on the comparison results. In addition, the Jeppo Biogas data samples represent daily measured values for CH_4 composition, while Stormossen data samples represent more accurate values, with a measuring retention time equal to five seconds. So from one point of view, if more accurate data from Jeppo Biogas would be acquired, the range of data sample distribution could possibly be wider. On the other hand, the Jeppo Biogas data could provide more reliable analysis results due to the long term measurements, which include data for two month period, while the collected data at Stormossen consists of one week of measurements.

Based on the comparison results Jeppo Biogas produces raw biogas with slightly more consistent and higher CH_4 content that Stormossen, which can be explained by the utilization of more homogeneous source of organic matter. Nevertheless, the results show that the margin of the biogas quality fluctuations, measured at Stormossen, is reasonable.

6.3. Quality of Data

Quality of the measured data at Stormossen Oy is considered to be high, as it represents the components composition of measured biogas, according to collected monitoring parameters and the measurement results for the biogas samples made with GC, which can be found in Appendix 6. The results presented in the tables in Appendix 6 contain a few mistakes. Hydrogen peak actually stands for hydrogen sulphide, and ethane peak was determined to indicate ammonia content in the biogas sample, which makes the presented composition values from the tables for both gases incorrect.

The online measurement data in total consists of five weeks of measurement of the biogas composition: two weeks of measurements of the biogas produced from BR1, one week of measurements of the biogas produced from BR2 and two weeks of measurements of the combined gas. However, only one week of measured data of the combined biogas was used for the analyses, excluding all data from the first week of measurements as it was irrelevant to the process and the monitored parameters data. The calculated balance values for the online measurements of the biogas were steadily increasing as presented on Fig. 7, while percentage values for other biogas components were decreasing, indicating the presence of disturbance in set up measurement system or possibility of the analyzer dysfunction.

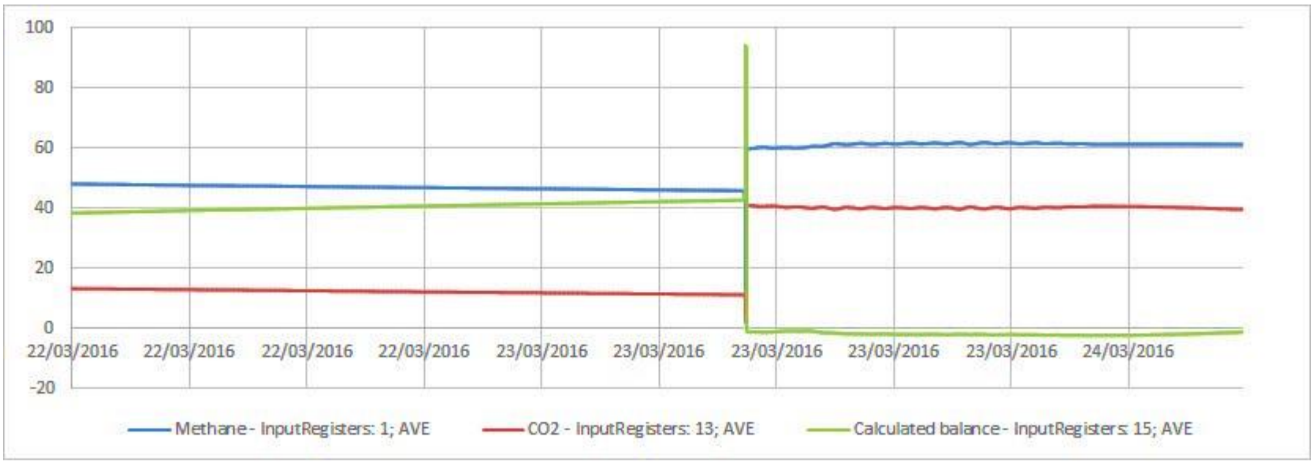


FIGURE 7 ONLINE MEASUREMENS FOR STORMOSSEN OY COMBINE GAS, 22.03-24.03 2016.

It was identified that the set up measurement system was malfunctioning because of clogged seven micron stainless steel pre-filter between heated sample line and MKS analyzer. The analyzer was installed in a non-heated room, which probably caused the pre-filter to become a cold spot, where the biogas was cooled down and formed condensate. As the result, the pre-filter got clogged and the biogas flow through the filter was reduced.

The problem was reduced on the 23rd of March, when the filter was removed from the system. On Fig.3 the difference can be clearly seen between the measurements quality before and after the pre-filter removal.

6.4. Challenges and Limitations

One of the biggest challenge in this work was to find measurement technology for online measurements and sample analyses. This work project required a portable, real time gas analyzer for measuring the main properties of the biogas and it impurity content. The MKS analyzer used for online measurements is an excellent tool for online measurements and monitoring. It is practical, easy to use, the interface software provides fast calculation of the measurement results and does not require addition calibration or validation process. However, the measurement components are limited to CO_2 and short chain hydrocarbons. This resulted in limited number of measured impurity components in biogas, which came one of the limitations in this study.

Sample measurements were taken in order to validate the online measurements, using other analysis equipment, and to increase the number of measured impurity components. Firstly, it was decided to use more than one sample analysis equipment: GC at Wärtsilä facility and Gasmet FTIR analyzer. Unfortunately, it was not possible to use the Gasmet analyzer due to its malfunction, which left the GC to be the only option for the biogas sample analysis in this study.

Gas Chromatograph is a practical tool for gas analysis. However, the gas analysis requires the availability of calibration gases for validation data and construction of the calibration methods. The GC was using the calibration methods adjusted for specific gas compounds, which were not relevant for analysis of the biogas impurity content. Availability of the calibration gases, CH_4 and CO_2, allowed to construct a new calibration method for more precise analysis, due to the unique composition of these gases in the raw biogas. The presence of hydrogen sulphide and ammonia compounds were also determined during the analysis process. However, it was not possible to determine the composition value for these gases, because there was no constructed calibration method or calibration gases either. If in the future the biogas is considered as an alternative fuel for combustion engines, it will be important to develop a biogas analysis system for GC, which will include a complex of calibration methods to measure the level of common contamination compounds in the biogas.

The lack of opportunity to measure the biomethane quality, related to measured raw biogas quality, is one of the main limitations in this work, to evaluate the feasibility of produced biogas as an automotive fuel. The upgraded biogas quality variation would be one of the major points of interest in future research, when Stormossen Oy builds an upgrading unit for the automotive gas fuel production.

7. Conclusions and Recommendations

By evaluating the analysis results of this study the following conclusions were drawn:

1. The biogas produced at Stormossen Oy does not currently meet the Wärtsilä requirements for combustion engines gas fuel. The biogas CH_4 content does not reach the minimum requirement for the engine gas fuel. However, according to the future developments plan of Stormossen Oy, that includes the construction of refining unit for produced biogas [5], the upgraded biogas has a potential to fulfill the Wärtsilä gas fuel requirement, basing on the comparison results from [Ch. 6.2]. In addition, the measured raw biogas is considered clean due to low levels of impurity gases, which makes this gas easy to upgrade.

2. The analysis results of the measured data present the availability of the biogas quality oscillations during production at Stormossen Oy. Concentration oscillations of methane and carbon dioxide gases are clearly present in the biogas produced from both bioreactors, with the oscillations time period being equal to around one hour. However, these oscillations are caused by the pneumatic stirring of digesting material in the bioreactors and considered to be insignificant, due to minor oscillations amplitudes comparing with the biogas fluctuations during a week. In addition, the oscillations are reduced, when produced biogas from both bioreactors is combined.

3. Fluctuations of the biogas quality were also determined during the analysis of the online measurements data at Stormossen Oy. Even though, the variance of the biogas components concentrations was identified to be consistent and stable [Ch.5], a presence of periodic fluctuations during a week time period is clearly observed on the graphs for each measurement point in Appendix 3 and directly influenced by the organic material flow operations. The biggest changes in the biogas concentration of the main components, such as methane and carbon dioxide, occur at the beginning of the week, on Monday, when both inflow and outflow of the organic material in the bioreactors are starting to operate. While the most stable period for the biogas quality is taking place on the weekends, when there is no flow of the material in or out of the bioreactors. In my opinion, the feeding process of the bioreactors should be automated for continuous operation during the whole week, in order to avoid large fluctuations in the biogas quality.

The limitations of this work open up possibilities for further studies, including the biogas quality variations at Stormossen Oy, concerning a wider range of the contamination components as well as a longer time period, and a possibility for formation of the biogas layers in the storage tank with a potential influence on the biogas quality variation. In addition, the construction of the upgrading unit at Stormossen Oy would allow a possibility for a research about the biomethane quality, due to the fact, that in this work the measurements of the biogas quality do not provide predictions for quality of upgraded biogas.

Literature References/Work Cited

[1] A. Lampinen, “Development of biogas technology systems for transport,” Tekniikan Waiheita, 2013, pp. 17-28. [Online]. Available FTP: http://www.ths.fi File: Lampinen_TW-3-2013.pdf. Accessed: Mar. 09, 2016.

[2] Wärtsilä, “About Wärtsilä,” 2016. [Online]. Available: http://www.wartsila.com/about. Accessed: Feb. 03, 2016.

[3] Hercules 2, “The Programme.” [Online]. Available: http://www.hercules-2.com. Accessed: Feb. 02, 2016.

[4] J. Saarela, “Local Biogas Production – Powering Future Energy System,” in Vaasa Gas Exchange, Energy Week, Vaasa, 2016.

[5] J. Saarela, Development Engineer at Stormossen Oy Ab, Discussion. 24.02.2016

[6] Westenergy Oy Ab, “The Plant,” 2013. [Online]. Available: http://www.westenergy.fi/?l=en&p=21&text=The+Plant. Accessed: Mar. 21, 2016.

[7] J. Saarela and J. Pettersson, “Gränsöverskridande färdplan för biogasutveckling i botniaregionen,” Biogas Botnia, 2014, pp. 1-7.

[8] Hercules 2, “Work Package Progress Highlights WP1,” 2015. [Online]. Available FTP: http://www.hercules-2.com Directory: sites/default/files File: WP1.pdf. Accessed: Feb. 02, 2016

[9] J. S. Milton and J. C. Arnold, *Introduction to probability and statistics: Principles and applications for engineering and the computing sciences* .Boston: McGraw Hill Higher Education, 2002, ch. 6.3, pp. 202-206, ch. 7.4, pp. 237, ch. 8.2, pp. 262-266.

[10] M. Roser. “World Population Growth,” 2015. [Online]. Available Telnet: OurWorldInData.org Directory: Data/Population Growth Vital Statistics File: World Population Growth. Accessed: Feb. 16, 2016.

[11] IEA. “CO_2 Emissions from Fuel Combustion. Highlights,” 2015, pp. 7-10. [Online]. Available FTP: http://www.iea.org Directory: publications/freepublications File: CO2EmissionsFromFuelCombustionHighlights2015.pdf. Accessed: Feb. 15, 2016.

[12] M. Z. Hauschild and M. A. Barlaz, “LCA in Waste Management: Introduction to Principle and Method,” in *Solid Waste Technology & Management, 2 volume set.* T. Christensen, Ed., Oxford: Wiley-Blackwell (an imprint of John Wiley & Sons Ltd), 2010, ch. 3.1, pp. 119-121.

[13] “Greenhouse Gas Emissions,” Reference Metadata in Euro SDMX Metadata Structure (ESMS), EEA, code: env_air_gge2015. [Online]. Available: http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do. Accessed: Mar. 16, 2016.

[14] *Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020*, OJ L 140, 2009, p. 1,4. [Online]. Available: http://eur-lex.europa.eu Directory: legal-content/EN/TXT File: ?uri=celex:32009D0406. Accessed: Feb. 19, 2016.

[15] C. Bessou et al., "Biofuels, greenhouse gases and climate change," a review in *Agronomy for Sustainable Development*, 2011, vol. 31, iss. 1, art. 1, pp. 3-6. [Online]. Available: http://link.springer.com. Accessed: Feb. 15, 2016.

[16] I. Angelidaki and D. J. Batstone, "Anaerobic Digestion: Process," in *Solid Waste Technology & Management, 2 volume set.* T. Christensen, Ed., Oxford: Wiley-Blackwell (an imprint of John Wiley & Sons Ltd), 2010, ch. 9.4, pp. 583-585.

[17] J.C. Jansen, "Anaerobic Digestion: Technology," in *Solid Waste Technology & Management, 2 volume set.* T. Christensen, Ed., Oxford: Wiley-Blackwell (an imprint of John Wiley & Sons Ltd), 2010, ch. 9.5, pp. 601, 607-612.

[18] P. Weiland, "Biogas production: current state and perspectives," *Applied Microbiology and Biotechnology,* vol.85, no. 4, pp. 849-860, Sep. 2009.

[19] T. H. Christensen, H. Scharff and O. Hjelmar, "Landfilling: Concepts and Challenges," in *Solid Waste Technology & Management, 2 volume set.* T. Christensen, Ed., Oxford: Wiley-Blackwell (an imprint of John Wiley & Sons Ltd), 2010, ch. 10.1, pp. 687.

[20] M. Caine, "Biogas Flares: State of the Art and Market Review," IEA Bioenergy, 2000. [Online]. Available FTP: http://www.iea-biogas.net Directory: files/daten-redaktion/download/publi-task37 File: Flaring_4-4.pdf. Accessed: Feb. 16, 2016.

[21] R. Muñoz, L. Meier, I. Diaz, and D. Jeison, "A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading," *Reviews in Environmental Science and Bio/Technology,* vol. 14, no. 4, pp. 728.

[22] N. Cui, "Biomethane as Transport Fuel, A Study on Upgrading Technologies and Biomethane Potential in Finland," Bachelor's Thesis, Novia UAS, Vaasa, 2015.

[23] J. Møller, T.H. Christensen and J. C. Jansen, "Anaerobic Digestion: Mass Balances and Products," in *Solid Waste Technology & Management, 2 volume set.* T. Christensen, Ed., Oxford: Wiley-Blackwell (an imprint of John Wiley & Sons Ltd), 2010, ch. 9.6, pp. 620.

[24] CIMAC WG17 'Gas Engines', "Impact of Gas Quality on Gas Engine Performance," CIMAC Position Paper, 2015, pp. 3-4. [Online]. Available FTP: http://www.cimac.com Directory: cms/upload/workinggroups/WG17 File: CIMAC_WG17_Position_Paper_Impact_Gas_Quality_on_Gas_Engine_Performance_2015_Jul.pdf. Accessed: Apr. 02, 2016.

[25] DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 October 2014 on the deployment of alternative fuels infrastructure, OJ L 307, 2014, art. 41, p. 1–20. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0094#ntr4-L_2014307EN.01000101-E0004. Accessed: Mar. 31, 2016.

[26] “Kartläggning av biogas: 2009-2001 i Norrbotten, Västerbotten, Jämtland och Västernorrland,” 2012. [Online]. Available FTP: http://www.biofuelregion.se Directory: UserFiles/file File: 2012%20Kartl%C3%A4ggning%20av%20Biogas%20i%20Norra%20SV.pdf. Accessed: Feb. 12, 2016.

[27] M. J. Huttunen and V. Kuittinen,”Suomen biokaasulaitosrekisteri n:o 18,” University of Eastern Finland, Reports and Studies in forestry and Natural Sciences, Joensuu, 2014. [Online]. Available FTP: http://epublications.uef.fi Directory: pub/urn_isbn_978-952-61-1875-8 File: urn_isbn_978-952-61-1875-8.pdf. Accessed: Feb. 09, 2016.

[28] Stormossen Oy, “History,” [Online]. Available: http://www.stormossen.fi/History. Accessed: Mar. 14, 2016.

[29] Stormossen Oy, “The Company,” [Online]. Available: http://www.stormossen.fi/The_Company. Accessed: Mar. 14, 2016.

[30] Stormossen Oy, “Avfallscentralen,” [Online]. Available: http://www.stormossen.fi/Avfallscentralen. Accessed: Mar. 14, 2016.

[31] J. Saarela, Development Engineer at Stormossen Oy, discussion. [Email]. 25.02.2016

[32] J. Saarela, Development Engineer at Stormossen Oy, discussion. [Email]. 14.03.2016

[33] BotniaLab Oy, “Tutkimustodistut,” for Vaasa Vesi/Pättin puhdistamo, liete 2016-00145-01, 2016.

[34] DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on waste and repealing certain Directives, OJ L 312, 2008, art. 3, p. 4. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1459858010679&uri=CELEX:32008L0098. Accessed: Apr. 03,2016.

[35] Stormossen Oy, Given Information Paper. 24.02.2016.

[36] MKS instruments, “Precisive® TFS™ Sensor Platform,” 2016. [Online]. Available: http://www.mksinst.com/docs/ur/precisivetechnique.aspx. Accessed: Mar. 21, 2016.

[37] “Precisive® 5 Gas Analyzer,” User and Installation Manual, Precisive LLC, 2014, ch. 1, pp. 12.

[38] “Final Span Calibration Verification,” Precisive 5 – 242 model, 018393887, MKS Precisive®, ATN, 2015.

[39] “Micro-GC,” User Manual, Varian Inc., 2009, ch. 1-2, pp. 5-10. [Online] Available FTP: http://www.agilent.com Directory: cs/library/usermanuals/public File: CP501265490%20Rev1.pdf. Accessed: Mar. 22, 2016.

[40] J. Saarela, Development Engineer at Stormossen Oy, Gasanalysis documents. [Email]. 14.01.2016.

[41] Lenntech B.V., “Parts per Million (ppm) converter,” 2016. [Online]. Available: http://www.lenntech.com/calculators/ppm/converter-parts-per-million.htm. Accessed: Apr. 04, 2016.

[42] K. Portin, Program Manager Fuel Systems at Wärtsilä Finland Oy, Wärtsilä gas fuel requirements table. [Email]. 19.01.2016.

[43] Jeppo Biogas Oy Ab, “Jeppo Biogas.” [Online]. Available: http://www.jeppobiogas.fi/home/. Accessed: Jan. 26, 2016.

[44] K. Stenvall, “Jeppo Biogas Ab,” given information paper. 13.01.2016

[45] J. Laitinen, “Biogas, a bridge between agriculture and industry,” Vaasa Energy Week, 2014. [Online]. Available FTP: http://www.biofuelregion.se Directory: UserFiles/file File: Jarno%20Laitinen,%20Doranova.pdf. Accessed: Jan. 21, 2016.

[46] Discussions with Kurt Stenvall, CEO, biogas production at Jeppo Biogas plant, biogas market and biomethane as vehicle fuel. 13.01.2016.

[47] “Rötrest, bioprodukt som används som sådan. Jordförbättringsmedel 3A5,” Varedeklaration, Jeppo Biogas Oy, 2015. [Online]. Available: http://www.jeppobiogas.fi/produkter-and-tjanster/. Accessed: Jan. 26, 2016.

[48] “Biogas upgrading,” in Biogas, Malmberg. [Online]. Available: http://www.malmberg.se/en-us/What-we-do/Biogas/Biogas-upgrading. Accessed: Jan. 26, 2016.

[49] “Finland gasoline prices,” 2016. [Online]. Available: http://www.globalpetrolprices.com/Finland/gasoline_prices/. Accessed: Jan. 27, 2016.

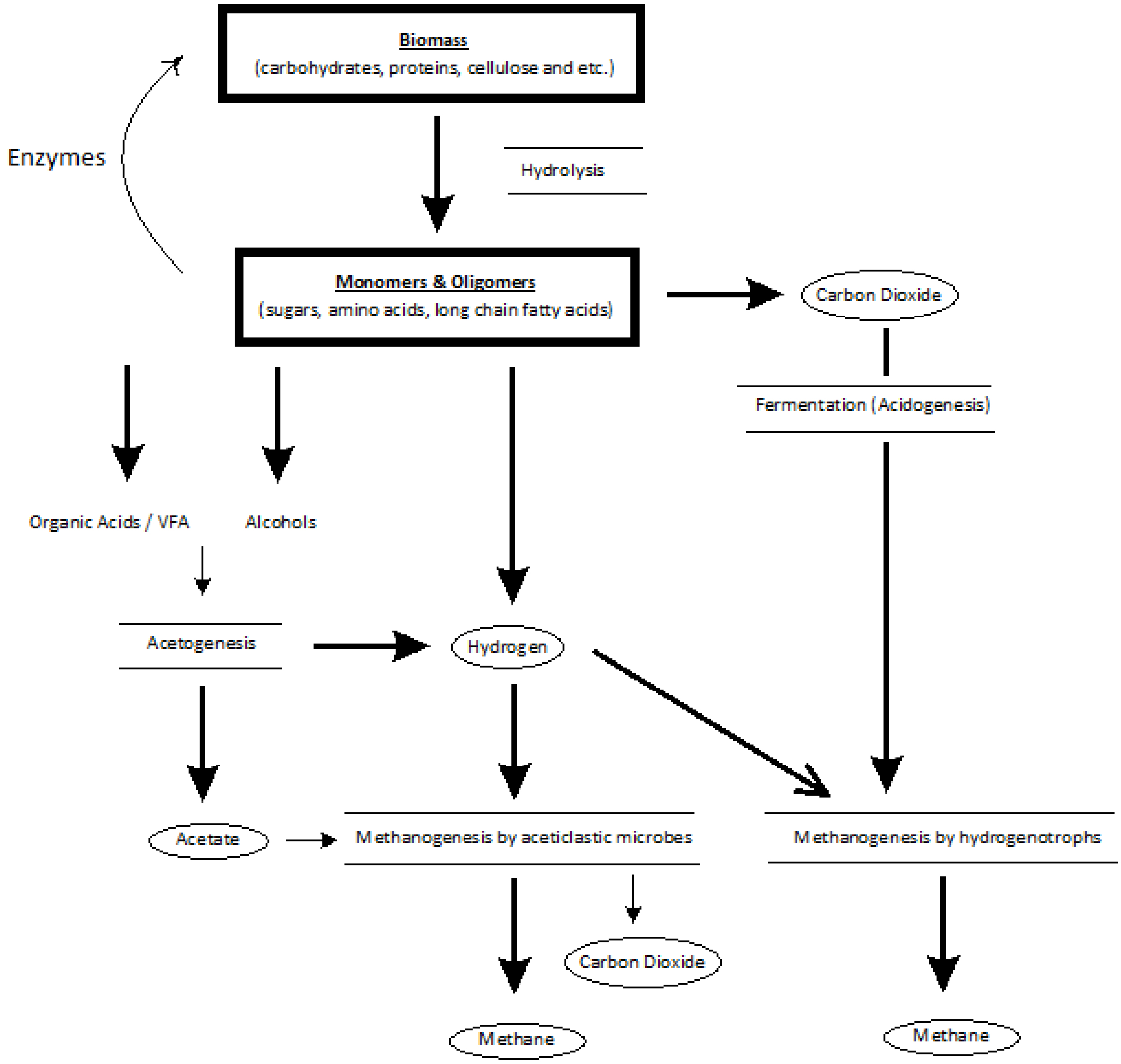
[50] J. Kald, Operation Manager at Jeppo Biogas Oy, Excel data for biogas and biomethane. [Email]. 25.01.2016.

[51] M. Fransson et al., “Råvaruanalys inom projektet Biogas Botnia-biogaspotentialen I Västerbotten, Västernorrland och Österbotten år 201,” Stormossen Oy, 2013. [Online]. Available FPT: http://biofuelregion.se Directory: wp-content/uploads File: Biogaspotential-20131007.pdf. Accessed: Feb. 05, 2016.

[52] Cummins Westport, “Fuel quality calculator.” [Online] Available: http://www.cumminswestport.com/fuel-quality-calculator. Accessed: Apr. 04, 2016.

[53] P.J. Jørgensen, A. B. Nielsen, Ed., “Biogas- green energy: Process, Design, Energy Supply, Environment,” Digisource Danmark A/S, 2009, pp. 4. [Online]. Available FTP: http://www.lemvigbiogas.com File: BiogasPJJuk.pdf. Accessed: Apr. 04, 2016.

Appendix 1 – Degradation of Biomass to CH_4 and CO_2 [17], [18]



Appendix 2 - Biogas Production Facilities in Bothnia Region. a-[51]; b-[7]; c-[28]

Botnia Region		**Municipality**	**Name**	**Owner**	**Plant type**	**Production 2011 (GWh)**
Västerbotten	1[a]	Umeå	Norrmejeriers biogasanl.	Norrmejerier	Industry	22,1
	2[a]	Umeå	Öns ARV	UMEVA	Sewage	10,1
	3[a]	Umeå	Dåva Deponi	UMEVA	Landfill	1,1
	4[a]	Skellefteå	Tuvans biogasanl.	Skellefteå Kommun	Sewage/ codigestion	9,1
	5[a]	Vindeln	Kullabäcklidens lantbruk	-	Agriculture	0,8
Västernorrland	6[a]	Härnösand	Älands avfallsanläggning	HEMAB	Landfill	3,8
	7[a]	Sundsvall	Näfsta gård	-	Agriculture	0,8
	8[a]	Sundsvall	Filanverket	MittSverige Vatten	Sewage	3
	9[a]	Sundsvall	Tivoliverket	MittSverige Vatten	Sewage	3,7
	10[a]	Sundsvall	Essviksverket	MittSverige Vatten	Sewage	0,3
	11[a]	Sundsvall	Blåbergstippen	-	Landfill	3,2
	12[a]	Sollefteå	Hågesta	Sollefteå Kommun	Sewage	1,4
	13[a]	Örnsköldsvik	Må deponi	MIVA	Landfill	1,2
	14[a]	Örnsköldsvik	Bodum	MIVA	Sewage	0,5
	15[a]	Örnsköldsvik	Prästbordet	MIVA	Sewage	0,5
	16[a]	Örnsköldsvik	Knorthem	MIVA	Sewage	0,6
	17[a]	Örnsköldsvik	Domsjö	Domsjö	Industry	80
Österbotten	18[a]	Korsnäs*	Stormossen	Stormossen	Codigestion	15,4
	19[a]	Korsnäs*	Stormossen	Stormossen	Landfill	0,8
	20[a]	Laihia	Lahia Kommun	Lahia Kommun	Codigestion	0,9
	21[a]	Vaasa	Sunnanvik	-	Landfill	1,7
	22[b]	Jeppo	Jeppo Biogas	Jeppo Biogas	Industry	20
	23[c]	Lapua	Heikas Oy	-	-	-
	24[c]	Pedersöre	Lillby Biogas Oy	-	-	-
	25[c]	Maalahti	Malax BioenergiOy Oy	-	-	-

* Potential mistake in the resource information [51], as the name for municipality is Korsholm (Mustasaari).

Appendix 3 – Variation of the Biogas CH_4 and CO_2 Compositions

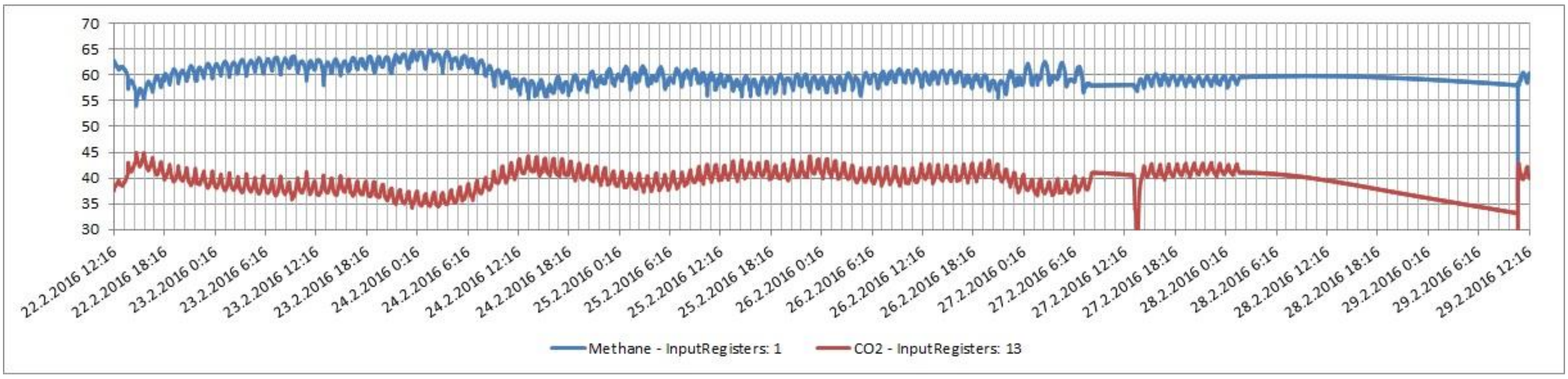


FIGURE 8 VARIATION OF THE BIOGAS METHANE AND CARBON DIOXIDE COMPOSITIONS FOR THE BIOREACTOR 1, WEEK 1.

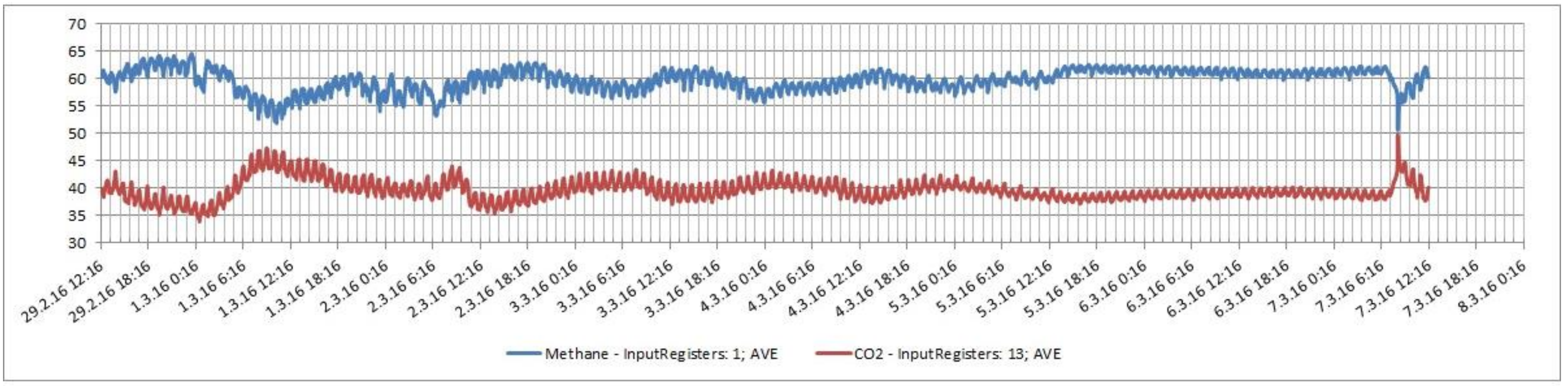


FIGURE 9 VARIATION OF THE BIOGAS METHANE AND CARBON DIOXIDE COMPOSITIONS FOR THE BIOREACTOR 1, WEEK 2.

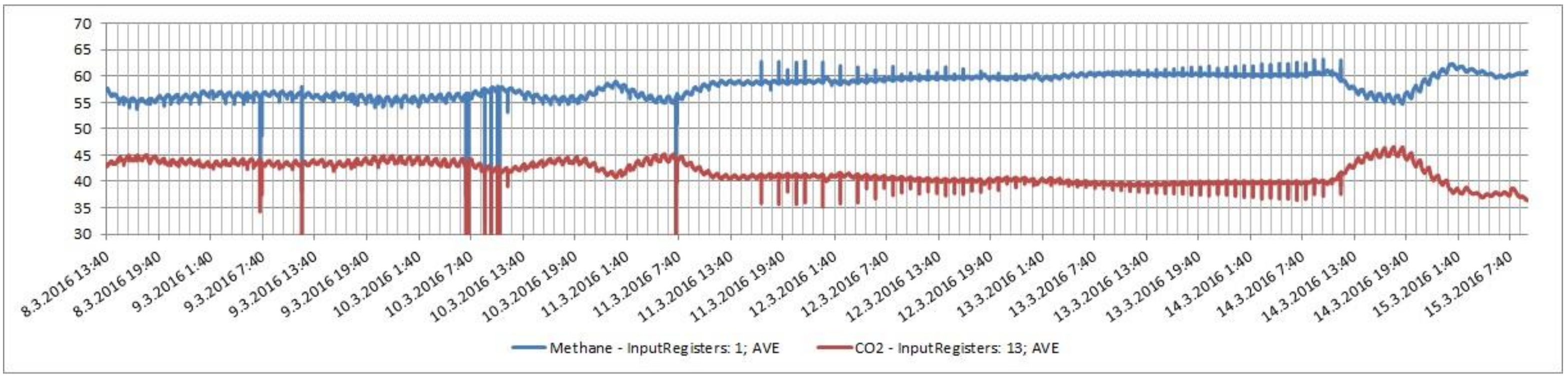


FIGURE 10 VARIATION OF THE BIOGAS METHANE AND CARBON DIOXIDE COMPOSITIONS FOR THE BIOREACTOR 2.

FIGURE 11 VARIATION OF THE BIOGAS METHANE AND CARBON DIOXIDE COMPOSITIONS FOR COMBINED GAS.

Appendix 4 – Analysis Results for the Biogas Online Measured Data from Stormossen Oy

TABLE 9 ANALYSIS RESULTS FOR BIOREACTOR 1 WEEK 1 BIOGAS DATA.

	Methane	Ethane	Propane	Iso-Butane	N-Butane	C5+ lumped	CO2
Average	59.7883	0.00	0.0567	0.2221	0.00	0.0005	39.3551
Median	59.5796	0.00	0.0566	0.2204	0.00	0.0000	39.8005
SD	1.6725	0.00	0.0255	0.0253	0.00	0.0029	2.2895
RSD	3%	0%	45%	11%	12485%	618%	6%
Interval 90%	0.0028	0.00	0.0000	0.0000	0.00	0.0000	0.0038
Interval 95%	0.0036	0.00	0.0001	0.0001	0.00	0.0000	0.0049
Interval 99%	0.0050	0.00	0.0001	0.0001	0.00	0.0000	0.0069
MIN	35.6174	0.00	0.0000	0.1187	0.00	0.0000	10.4022
MAX	64.9024	0.00	0.1936	0.3942	0.02	0.0711	44.9573
Sample Range	29.2850	0.00	0.1936	0.2756	0.02	0.0711	34.5551
90% range	59.7856	0.00	0.0566	0.2221	0.00	0.0005	39.3513
	59.7911	0.00	0.0567	0.2221	0.00	0.0005	39.3589
95% range	59.7847	0.00	0.0566	0.2221	0.00	0.0005	39.3502
	59.7919	0.00	0.0567	0.2222	0.00	0.0005	39.3600
99% range	59.7833	0.00	0.0566	0.2220	0.00	0.0005	39.3482
	59.7933	0.00	0.0568	0.2222	0.00	0.0005	39.3619

n	603835
n-1	603834
t, 90%	1.282
t, 95%	1.674
t, 99%	2.326

TABLE 10 ANALYSIS RESULTS FOR BIOREACTOR 1 WEEK 2 BIOGAS DATA.

	Methane	Ethane	Propane	Iso-Butane	N-Butane	C5+ lumped	CO2
Average	59.8056	0.00	0.0485	0.2414	0.00	0.0001	39.6699
Median	60.0981	0.00	0.0474	0.2391	0.00	0.0000	39.4251
SD	1.9713	0.00	0.0251	0.0240	0.00	0.0012	1.8678
RSD	3%	0%	52%	10%	22365%	1632%	5%
Interval 90%	0.0033	0.00	0.0000	0.0000	0.00	0.0000	0.0031
Interval 95%	0.0042	0.00	0.0001	0.0001	0.00	0.0000	0.0040
Interval 99%	0.0059	0.00	0.0001	0.0001	0.00	0.0000	0.0056
MIN	50.6411	0.00	0.0000	0.1560	0.00	0.0000	33.9210
MAX	64.6064	0.00	0.2131	0.4179	0.01	0.0684	49.7764
Sample Range	13.9653	0.00	0.2131	0.2619	0.01	0.0684	15.8554
90% range	59.8023	0.00	0.0484	0.2413	0.00	0.0001	39.6668
	59.8088	0.00	0.0485	0.2414	0.00	0.0001	39.6729
95% range	59.8014	0.00	0.0484	0.2413	0.00	0.0001	39.6658
	59.8098	0.00	0.0485	0.2414	0.00	0.0001	39.6739
99% range	59.7997	0.00	0.0484	0.2413	0.00	0.0001	39.6643
	59.8115	0.00	0.0485	0.2415	0.00	0.0001	39.6755

n	604646
n-1	604645
t, 90%	1.282
t, 95%	1.674
t, 99%	2.326

TABLE 11 ANALYSIS RESULTS FOR BIOREACTOR 2 BIOGAS DATA.

	Methane	Ethane	Propane	Iso-Butane	N-Butane	C5+ lumped	CO2
Average	58.1643	0.00	0.0772	0.2405	0.00	0.0090	41.7055
Median	58.6696	0.00	0.0766	0.2455	0.00	0.0000	41.3001
SD	1.9907	0.00	0.0247	0.0312	0.00	0.0160	2.0526
RSD	3%	0%	32%	13%	0%	178%	5%
Interval 90%	0.0033	0.00	0.0000	0.0001	0.00	0.0000	0.0034
Interval 95%	0.0043	0.00	0.0001	0.0001	0.00	0.0000	0.0045
Interval 99%	0.0060	0.00	0.0001	0.0001	0.00	0.0000	0.0062
MIN	14.0604	0.00	0.0000	0.1283	0.00	0.0000	11.1336
MAX	63.1883	0.00	0.1955	0.4154	0.00	0.1161	46.5944
Sample range	9.1280	0.00	0.1955	0.2871	0.00	0.1161	35.4608
90% range	58.1610	0.00	0.0771	0.2404	0.00	0.0090	41.7021
	58.1676	0.00	0.0772	0.2405	0.00	0.0090	41.7090
95% range	58.1599	0.00	0.0771	0.2404	0.00	0.0090	41.7011
	58.1686	0.00	0.0772	0.2405	0.00	0.0090	41.7100
99% range	58.1583	0.00	0.0771	0.2404	0.00	0.0090	41.6993
	58.1703	0.00	0.0772	0.2406	0.00	0.0090	41.7117

n	590034
n-1	590033
t, 90%	1.282
t, 95%	1.674
t, 99%	2.326

TABLE 12 ANALYSIS RESULTS FOR COMBINED BIOGAS DATA.

	Methane	Ethane	Propane	Iso-Butane	N-Butane	C5+ lumped	CO2
Average	60.0924	0.00	0.0784	0.1732	0.00	0.0346	41.3845
Median	60.3285	0.00	0.0787	0.1729	0.00	0.0339	40.7897
SD	1.6131	0.00	0.0238	0.0144	0.00	0.0213	1.8078
RSD	3%	0%	30%	8%	0%	62%	4%
Interval 90%	0.0027	0.00	0.0000	0.0000	0.00	0.0000	0.0030
Interval 95%	0.0035	0.00	0.0001	0.0000	0.00	0.0000	0.0039
Interval 99%	0.0048	0.00	0.0001	0.0000	0.00	0.0001	0.0054
MIN	56.9628	0.00	0.0000	0.1189	0.00	0.0000	23.9487
MAX	63.7154	0.00	0.1784	0.2359	0.00	0.1322	44.5646
Sample Range	6.7526	0.00	0.1784	0.1171	0.00	0.1322	20.6159
90% range	60.0898	0.00	0.0784	0.1731	0.00	0.0345	41.3815
	60.0951	0.00	0.0785	0.1732	0.00	0.0346	41.3875
95% range	60.0890	0.00	0.0784	0.1731	0.00	0.0345	41.3806
	60.0959	0.00	0.0785	0.1732	0.00	0.0346	41.3884
99% range	60.0876	0.00	0.0784	0.1731	0.00	0.0345	41.3791
	60.0973	0.00	0.0785	0.1732	0.00	0.0346	41.3899

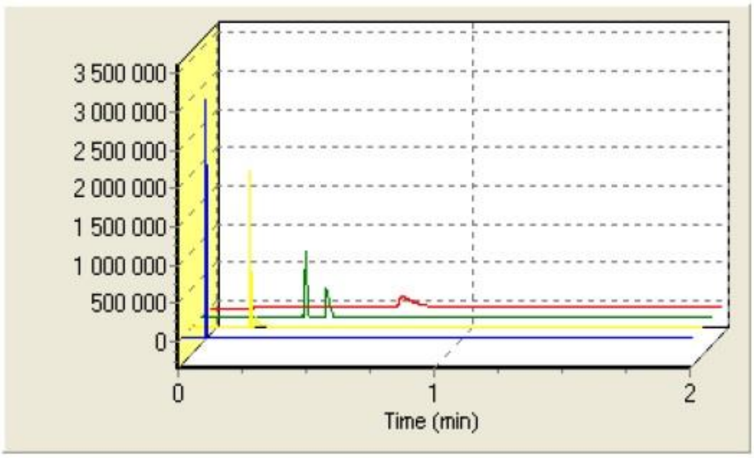
n	604460
n-1	604459
t, 90%	1.282
t, 95%	1.674
t, 99%	2.326

Appendix 5 – Comparison Table of Wärtsilä Oy Finland Gas Fuel Requirements and Stormossen Oy Biogas Quality

TABLE 13 WÄRTSILÄ OY FINLAND GAS FUEL REQUIREMENTS AND STORMOSSEN OY BIOGAS QUALITY COMPARISON. [42] (a) CALCULATED USING ONLINE CALCULATOR. [52] (b) CONVERTED DATA BASING ON THE BIOGAS DENSITY BEING EQUAL TO 1.15 G/M3. [53] (+) NO CLARIFIED LIMITS. (-) NOT DETERMINED.

Property	Unit	Limit	Stormossen Oy biogas lab analyzed composition	Stormossen Oy biogas measured composition
Lower Heating Value (LHV_V), min.	MJ/m^3_N	+	20.29[a,b]	20.1[a,b]
Methane Number (MN), min.		+	140[b]	140.5[b]
Methane (CH_4) content, min.	% v/v	70	59.73	60.09
Hydrogen sulphide (H_2S) content, max.	% v/v	0.05	0.02	-
Hydrogen (H_2) content, max.	% v/v	3	-	-
Water and hydrocarbon condensate bef. engine, max.	% v/v	Not allowed	-	-
Ammonia content, max.	mg/m^3N	25	< 0.20	-
Chlorine + Fluorine content, max.	mg/m^3N	50	< 3.34	-
Particles or solids content in engine inlet, max.	mg/m^3N	50	-	-
Particles or solids size in engine inlet, max.	µm	5	-	-
Gas inlet temperature	°C	0 - 60	-	6

Appendix 6- GC Measurement Results for the Biogas Samples from Stormossen Oy



Galaxie Chromatography Software - Multi-Channel Report

Data File : C:\Galaxie\data\2016\028\22.2.2016 15_43_45_10.DATA
Method File : LAB NG_v4_pump
Sample ID : 22.2.2016 15_43_45_10

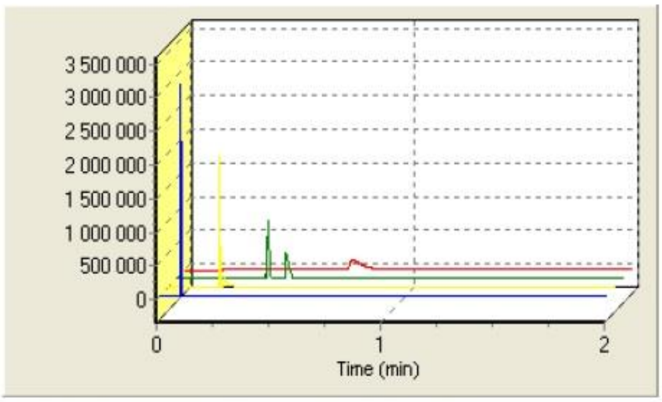
Injection Date: 22.2.2016 15:44:04
Recalc Date : 25.2.2016 17:52:58

Operator : Engine Laboratory
Workstation : D688QH3J
Instrument : Varian 4900 GC

Run Mode : Analysis
Peak Measurement : Peak Areas
Calculation Type : External Standard
Normalized? Yes

#	Peak Name	Channel	RT (min.)	Result (mol-	Norm. %	Area (uV/Sec.)
1	Nitrogen	Channel 1 - CP	0.5678	0.8781	0.9293	2849
2	Methane	Channel 2 - CP	0.4058	58.6645	62.0841	412076
3	Carbon dioxide	Channel 2 - CP	0.4873	34.7465	36.7718	353389
4	Ethane	Channel 2 - CP	0.6987	0.2010	0.2127	2269
5	Propane	Channel 3 - CP	0.0000	0.0000	0.0000	0
6	Propylene	Channel 3 - CP	0.0000	0.0000	0.0000	0
7	iso-Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
8	Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
9	2,2-Dimethylpropan	Channel 3 - CP	0.0000	0.0000	0.0000	0
10	iso-Pentane	Channel 4 - CO	0.2050	0.0009	0.0010	20
11	n-Pentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
12	2,2-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
13	2,3-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
14	3-Methylpentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
15	n-Hexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
16	Cyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
17	2,3-Dimethylpentan	Channel 4 - CO	0.0000	0.0000	0.0000	0
18	2-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
19	3-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
20	n-Heptane	Channel 4 - CO	0.0000	0.0000	0.0000	0
21	Methylcyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
22	Toluene	Channel 4 - CO	0.0000	0.0000	0.0000	0
23	n-Octane	Channel 4 - CO	1.6958	0.0011	0.0012	34
	Totals			94.4921	100.0000	771880

FIGURE 12 STORMOSSEN OY BIOGAS SAMPLE ANALYSIS FROM BR1, 22.02.2016



Galaxie Chromatography Software - Multi-Channel Report

Data File : C:\Galaxie\data\2016\028\25.2.2016 16_42_00_10.DATA
Method File : LAB NG_v4_pump
Sample ID : 25.2.2016 16_42_00_10

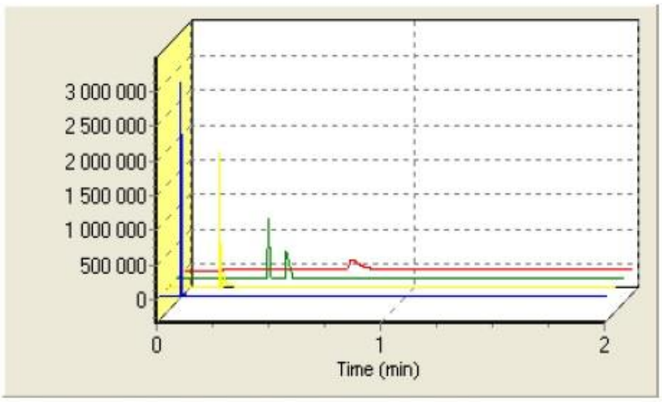
Injection Date: 25.2.2016 16:42:09
Recalc Date : 25.2.2016 16:44:44

Operator : Engine Laboratory
Workstation : D688QH3J
Instrument : Varian 4900 GC

Run Mode : Analysis
Peak Measurement : Peak Areas
Calculation Type : External Standard
Normalized? Yes

#	Peak Name	Channel	RT (min.)	Result (mol-	Norm. %	Area (uV/Sec.)
1	Hydrogen	Channel 1 - CP	0.3538	0.0196	0.0206	648
2	Nitrogen	Channel 1 - CP	0.5650	1.2873	1.3540	4177
3	Methane	Channel 2 - CP	0.4058	57.9130	60.9103	406798
4	Carbon dioxide	Channel 2 - CP	0.4870	35.7837	37.6356	363938
5	Ethane	Channel 2 - CP	0.9202	0.0748	0.0787	845
6	Propane	Channel 3 - CP	0.0000	0.0000	0.0000	0
7	Propylene	Channel 3 - CP	0.0000	0.0000	0.0000	0
8	iso-Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
9	Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
10	2,2-Dimethylpropan	Channel 3 - CP	0.0000	0.0000	0.0000	0
11	iso-Pentane	Channel 4 - CO	0.2052	0.0008	0.0009	18
12	n-Pentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
13	2,2-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
14	2,3-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
15	3-Methylpentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
16	n-Hexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
17	Cyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
18	2,3-Dimethylpentan	Channel 4 - CO	0.0000	0.0000	0.0000	0
19	2-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
20	3-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
21	n-Heptane	Channel 4 - CO	0.0000	0.0000	0.0000	0
22	Methylcyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
23	Toluene	Channel 4 - CO	0.0000	0.0000	0.0000	0
24	n-Octane	Channel 4 - CO	0.0000	0.0000	0.0000	0
	Totals			95.0793	100.0000	776424

FIGURE 13 STORMOSSEN OY BIOGAS SAMPLE ANALYSIS FROM BR1, 25.02.2016



Galaxie Chromatography Software - Multi-Channel Report

Data File : C:\Galaxie\data\2016\0310\8.3.2016 15_21_22_10.DATA
Method File : LAB NG_v4_pump
Sample ID : 8.3.2016 15_21_22_10

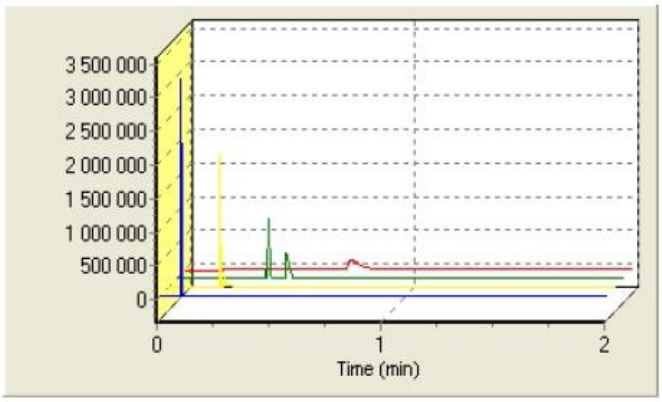
Injection Date: 8.3.2016 15:21:34
Recalc Date : 8.3.2016 15:38:34

Operator : Engine Laboratory
Workstation : D688QH3J
Instrument : Varian 4900 GC

Run Mode : Analysis
Peak Measurement : Peak Areas
Calculation Type : External Standard
Normalized? Yes

#	Peak Name	Channel	RT (min.)	Result (mol-	Norm. %	Area (uV/Sec.)
1	Hydrogen	Channel 1 - CP	0.0000	0.0000	0.0000	0
2	Nitrogen	Channel 1 - CP	0.5593	0.6660	0.6853	1922
3	Methane	Channel 2 - CP	0.4068	53.7705	55.3310	381952
4	Carbon dioxide	Channel 2 - CP	0.4868	42.7429	43.9833	392849
5	Ethane	Channel 2 - CP	0.0000	0.0000	0.0000	0
6	Propane	Channel 3 - CP	0.0000	0.0000	0.0000	0
7	Propylene	Channel 3 - CP	0.0000	0.0000	0.0000	0
8	iso-Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
9	Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
10	2,2-Dimethylpropan	Channel 3 - CP	0.0000	0.0000	0.0000	0
11	iso-Pentane	Channel 4 - CO	0.2052	0.0004	0.0004	8
12	n-Pentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
13	2,2-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
14	2,3-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
15	3-Methylpentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
16	n-Hexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
17	Cyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
18	2,3-Dimethylpentan	Channel 4 - CO	0.0000	0.0000	0.0000	0
19	2-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
20	3-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
21	n-Heptane	Channel 4 - CO	0.0000	0.0000	0.0000	0
22	Methylcyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
23	Toluene	Channel 4 - CO	0.0000	0.0000	0.0000	0
24	n-Octane	Channel 4 - CO	1.7207	0.0000	0.0000	0
	Totals			97.1798	100.0000	782295

FIGURE 14 STORMOSSEN OY BIOGAS SAMPLE ANALYSIS FROM BR2, 08.03.2016



Galaxie Chromatography Software - Multi-Channel Report

Data File : C:\Galaxie\data\2016\0312\23.3.2016 14_04_16_10.DATA
Method File : LAB NG_v4_pump
Sample ID : 23.3.2016 14_04_16_10

Injection Date: 23.3.2016 14:04:33
Recalc Date : 23.3.2016 14:08:14

Operator : Engine Laboratory
Workstation : D688QH3J
Instrument : Varian 4900 GC

Run Mode : Analysis
Peak Measurement : Peak Areas
Calculation Type : External Standard
Normalized? Yes

#	Peak Name	Channel	RT (min.)	Result (mol-	Norm. %	Area (uV/Sec.)
1	Hydrogen	Channel 1 - CP	0.0000	0.0000	0.0000	0
2	Nitrogen	Channel 1 - CP	0.5558	3.1226	3.2674	9013
3	Methane	Channel 2 - CP	0.4065	53.5594	56.0423	380452
4	Carbon dioxide	Channel 2 - CP	0.4873	38.8875	40.6903	357414
5	Ethane	Channel 2 - CP	0.0000	0.0000	0.0000	0
6	Propane	Channel 3 - CP	0.0000	0.0000	0.0000	0
7	Propylene	Channel 3 - CP	0.0000	0.0000	0.0000	0
8	iso-Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
9	Butane	Channel 3 - CP	0.0000	0.0000	0.0000	0
10	2,2-Dimethylpropan	Channel 3 - CP	0.0000	0.0000	0.0000	0
11	iso-Pentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
12	n-Pentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
13	2,2-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
14	2,3-Dimethylbutane	Channel 4 - CO	0.0000	0.0000	0.0000	0
15	3-Methylpentane	Channel 4 - CO	0.0000	0.0000	0.0000	0
16	n-Hexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
17	Cyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
18	2,3-Dimethylpentan	Channel 4 - CO	0.0000	0.0000	0.0000	0
19	2-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
20	3-Methylhexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
21	n-Heptane	Channel 4 - CO	0.0000	0.0000	0.0000	0
22	Methylcyclohexane	Channel 4 - CO	0.0000	0.0000	0.0000	0
23	Toluene	Channel 4 - CO	0.0000	0.0000	0.0000	0
24	n-Octane	Channel 4 - CO	0.0000	0.0000	0.0000	0
	Totals			95.5695	100.0000	751347

FIGURE 15 STORMOSSEN OY BIOGAS SAMPLE ANALYSIS FOR COMBINED GAS, 23.03.2016