Anna-Maria Rauhala and Mari Tervo

SETTING UP A MONITORING PROGRAM FOR CO-DIGESTERS

Bachelor's thesis
Environmental Engineering Degree Programme

February 2011

MIKKELIN AMMATTIKORKEAKOULU
Mikkeli University of Applied Sciences

KUVAILULEHTI

MIKKELIN AMMATTIKORKEAKOULU
Mikkeli University of Applied Sciences

Opinnäytetyön päivämäärä

10.2.2011

Tekijä(t)
Anna-Maria Rauhala ja Mari Tervo

Koulutusohjelma ja suuntautuminen
Ympäristöteknologian ko.

Nimeke

Setting up a monitoring tool for co-digester/ Monitorointityövälineen työstäminen sekamädättämölle

Tiivistelmä

Tutkimuksen tavoitteena oli tehdä monitorointityöväline sekamädättämöille. Työ rajattiin koskemaan tilakohtaisia mädättämöitä. Monitorointiohjelman toimivuutta testattiin opinnäytetyön toimeksiantajan antamilla uskottavilla fiktiivisillä tiedoilla.

Opinnäytetyön aihe saatiin Alankomaista Van Hall Larensteinin korkeakoulusta. Yhteistyöhenkilöinä toimivat Jos Theunissen ja Xantho Klijnsma. Opinnäytetyö on osa Kestävän energian monitorointi (SIA/RAAK SEM) projektia.

Mädätys tarkoittaa hapettomissa olosuhteissa tapahtuvaa prosessia, jossa lanta ja muut raaka-aineet muuttuvat bakteeritoiminnan avustuksella biokaasuksi ja mädätysjäännökseksi. Prosessi mahdollistaa tilakohtaisen energiatuotannon ja auttaa muodostamaan suljettuja ravinnesyklejä hygieenisen ja hajuttomamman mädätysjäännöksen avulla.

Monitorointiohjelma on jaoteltu seuraavasti: yleiset tiedot, tekniset näkökohdat, laskentamalli ja tilojen välinen vertailu. Monitorointityövälineen avulla voidaan tehdä sisäinen ja ulkoinen analyysi. Teknisissä näkökohdissa määritellään parametreja, joita valvomalla saadaan yleiskuva laitoksen toiminnasta.

Tietoja saatiin kahdesta tilasta, joilla on erilaiset mädätysprosessit. Syöttämällä tiedot luotuun ohjelmaan saatiin vertailukelpoisia arvoja ja niiden avulla tehtiin analyysit. Saadusta yleiskuvasta oli havaittavissa ongelmia toisella tilalla.

Monitorointityöväline toimii tällä hetkellä perusvälineenä ja luo toimivan pohjan jatkokehitykselle. Työvälineeseen on koottu peruslaskentamalleja ja hyödyllisiä parametreja.

Asiasanat (avainsanat)
Anaerobinen mädätys, sekämädätys, monitorointityöväline, prosessiparametrit

Sivumäärä	Kieli	URN
59+11	Englanti	URN:NBN:fi:mamk-opinn2011a1759

Huomautus (huomautukset liitteistä)

Ohjaavan opettajan nimi

Aila Puttonen

Opinnäytetyön toimeksiantaja
Jos Theunissen,
Van Hall Larenstein, Alankomaat

DESCRIPTION

MIKKELIN AMMATTIKORKEAKOULU Mikkeli University of Applied Sciences	**Date of the bachelor's thesis** 10.2.2011
Author(s) Anna-Maria Rauhala and Mari Tervo	**Degree programme and option** Degree Programme in Environmental Engineering

Name of the bachelor's thesis

Setting up a monitoring tool for co-digester

Abstract

The aim of this bachelor's thesis was to set up a monitoring tool for farm-scale co-digesters. After setting up the monitoring table it was tested with plausible data given by the employer of the thesis.

The assignment for the thesis was given by Jos Theunissen and Xantho Klijnsma from Hogeschool Van Hall Larenstein, The Netherlands. The thesis is part of Sustainable Energy Monitoring (SIA/RAAK SEM) project.

In anaerobic co-digestion manure and co-substrates are inserted into airless container. In absence of oxygen bacteria will produce biogas. Anaerobic co-digestion serves two aims: produces energy in the form of biogas and enables processing of manure and co-substrates which can be for example biowaste. The process closes the nutrient circle with the utilization of more hygienic digestate.

Monitoring table includes general data, technical aspects, calculation model and comparison between farms. The monitoring table allows the internal and external analysis of farms. Technical aspects show the parameters that should be measured from the digesters in order to monitor the process and to utilize the monitoring tool.

The data was given for two farms with different kinds of processes. By utilizing the monitoring table comparable values were calculated and by using them general performance overview was created. With that overview internal and external analysis were made and it revealed problems in the other farm.

The created monitoring table gives a solid foundation for further development. At this moment the program is a basic tool and even now it can be used to make an overall image of a co-digestion process. It also functions as a collector of general formulas that can be used for the calculations.

Subject headings, (keywords)

Anaerobic digestion, co-digestion, monitoring program, process parameters

Pages	Language	URN
59+11	English	URN:NBN:fi:mamk-opinn2011a1759

Remarks, notes on appendices

Tutor	Bachelor's thesis assigned by
Aila Puttonen	Jos Theunissen, Van Hall Larenstein, the Netherlands

TABLE OF CONTENTS

1 INTRODUCTION

Co-digestion means anaerobic digestion of a homogenous mixture of two or more substrates in order to produce biogas (Braun & Wellinger 2010, 4). Anaerobic co-digestion has many environmental benefits by producing renewable energy and lowering emissions. This process can help the Netherlands to reach their environmental goals.

Anaerobic co-digestion is efficient method to produce biogas, but its efficiency varies depending on various parameters. In this thesis we have collected those parameters, some that are measured and some that are calculated. Based on those parameters we analysed two farms internally and compare those farms to each other in order to determine which parameters affect the efficiency.

The assignment for the thesis was given while we were studying in Van Hall Larenstein, Leeuwarden, The Netherlands. The thesis is part of Sustainable Energy Monitoring (SIA/RAAK SEM) project, in which the project manager is Mr. Xantho Klijnsma. In Finland supervisor was Mrs. Aila Puttonen and in the Netherlands Mr. Jos Theunissen and Mr. Xantho Klijnsma.

In the thesis we first introduce anaerobic digestion on many sides, the technical parameters, the produced biogas and its utilisation, possible emissions from digestion system, benefits and disadvantages of anaerobic digestion. Theoretical part was written by using literature, electronic literature, Internet pages and inquiries from the employer of the bachelor’s thesis. We introduce our monitoring table and the results found. Finally we analyse the given data, calculated results and compare plants to each other by making internal and external analysis.

2 AIM OF THE THESIS

The aims of the thesis were to set up monitoring system for anaerobic co-digesters and by using that system, compare the functioning of the digesters in different farms. In comparison part data from farmers was analysed. Calculation tools had to be developed in monitoring system to enable the comparison and analysis. We have chosen to make a monitoring spreadsheet by using Excel. In this spreadsheet we collected data, did calculations and made it possible to do comparison easily. In analysis basic comparing parameters are explained by using other measured parameters.

Analysis and comparison focused on digester optimal functioning and efficiency of the digester. By making comparison one can make conclusions on digesters and their functioning as well as give advises based on analysing.

Research questions were made to see the objectives for the thesis. In addition to the main research question, sub research questions were made. Main research question: what are the most useful and practical parameters to analyse and compare co-digesters? In this question useful means those parameters that give descriptive data about the digester performance and can be used to calculate other parameters.

Sub research questions:

- What kind of spreadsheet is most useful for data collecting and most helpful when comparing digesters? How can we set it up so it is easy to use and has a compact overview?
- For making calculations, what kind of data should farmers collect? And how often should they collect the necessary data?
- How to measure efficiency; where it is defined as output divided by input?
- What parameters are necessary and most interesting for the comparison?

3 CO-DIGESTION

In anaerobic co-digestion manure and co-substrates are inserted into airless container. In absence of oxygen bacteria produce biogas. (Deutsche Gesellschaft... 2004, 53.) Anaerobiosis involves a number of chain reactions each performed by different bacteria (Srinivas 2008, 74). In this chapter basic description is given on biological and chemical background for co-digestion.

3.1 Biomethanation

In anaerobic digestion (AD) process bacteria decompose organic matter. Decomposition is done in order to produce the energy necessary for their metabolism. Methane is a by-product in this process. (Deutsche Gesellschaft... 2004, 57.)

The biomethanation, also called fermentation, can be divided into four stages each performed by specific bacteria. The first stage is hydrolysis which initiates fatty acid production. In this stage carbohydrates are converted to sugars, fats into fatty acids and proteins into amino acids. The second stage is acidogenesis. In this stage sugars, fatty acids and amino acids are converted into carbonic acid, alcohols, hydrogen, carbon dioxide and ammonia. The third stage is acetogenesis. In this stage carbonic acid, alcohols, hydrogen, carbon dioxide and ammonia are turned into acetic acids, carbon dioxide and hydrogen. Last and fourth stage is methanogenesis which is methane formation. In this stage of the process acetic acid, carbon dioxide and hydrogen are converted into methane and carbon dioxide. These stages are presented in figure 1. The end products are biogas – mixture of methane and carbon dioxide, and processed organic matter, also known digestate. (Srinivas 2008, 74-75.) (Brinton 2006, 43-44.) (Deutsche Gesellschaft... 2004, 57-59.)

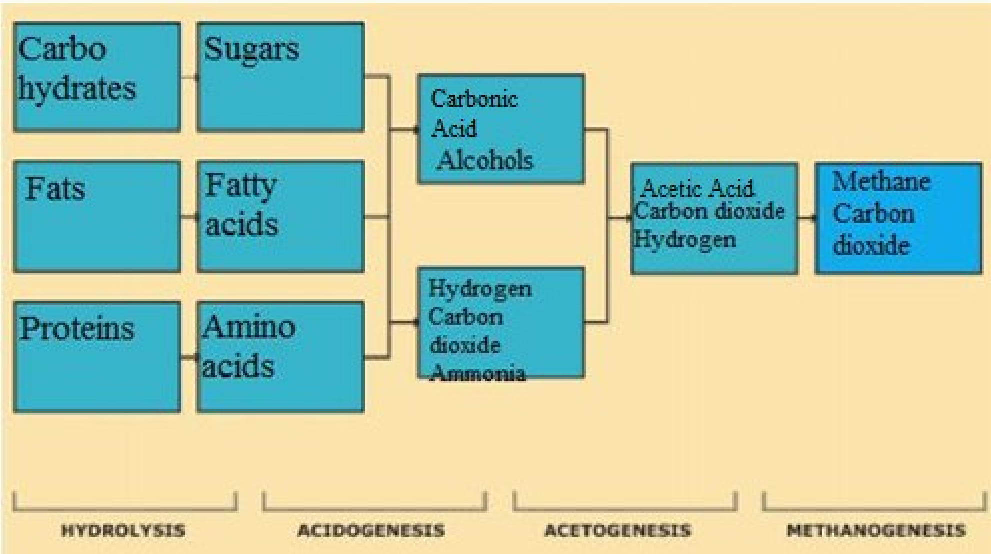


Figure 1: Stages of biomethanation (Deutsche Gesellschaft…2004, 57). Figure is altered.

3.2 Bacteria

Anaerobic digestion process is based on bacterial metabolism. In the four stages of digestion process, different bacteria are essential and can be found in different domains. Necessary bacteria for the process have the ability to grow by producing methane from the methyl group of acetate or several methylated compounds. They also have the ability to reduce carbon dioxide to methane with hydrogen or carbon monoxide as the electron donor. Since the process is anaerobic, bacteria need to survive in anaerobic conditions. Most bacteria involved in this process are mesophilic and have the pH optima for growth between 6.5 and 7.5. (Wall et al. 2008, 155-157.)

As an example *Ruminococcus* and *Clostridium* can be important in the first stage of fermentation that produces the needed fatty acids. After that other bacteria can then oxidize the larger fatty acids down to acetic acid and release energy in form of methane. (Brinton. 2006, 44.) Possible bacteria and microbes can also be for example in different stages: *Actinomyces, Aerobacter, Bacillus, Cellulomonas, Enterobacter, Escherichia, Lactobacillius, Pseudomonas, Staphylococcus* and *Streptococcus* (Nag 2007, 29).

3.3 Biogas formation

Production of methane is the energy-yielding metabolism, characteristic for all methanogens. There are two pathways how the methane production can happen. The pathway where methane production happens from the methyl group of acetate is presented in reaction 1. (Wall et al. 2008, 157-159.)

$$CH_3COO^- + H^+ \rightarrow CH_4 + CO_2 \quad (1)$$

The second pathway is the carbon reduction and it can occur in three ways.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (2a)$$

$$4\,HCO_2H \rightarrow 3CO_2 + CH_4 + 2H_2O \quad (2b)$$

$$4CO + 2H_2O \rightarrow 3CO_2 + CH_4 \quad (2c)$$

The reduction of CO_2 with electrons derived from oxidation of hydrogen is presented in reaction 2a. The other carbon reductions that produce methane and carbon dioxide are shown in reactions 2b and 2c. (Wall. et al. 2008, 157-159.)

4 DESCRIPTION OF CO-DIGESTERS SYSTEM

The general system is built from storages, digester, and generator and is shown in figure 2. In this chapter system description is given. Anaerobic digestion can be applied at range of scales depending on the amount of biomass inserted. Systems can range from farm-scale digesters to large centralised anaerobic digesters (CADs). (Deutsche Gesellschaft... 2004, 54.) Our focus is on farm-scale digesters using CHP (Combined Heat and Power). Typically AD system is designed according to the feedstock's dry matter content, the volatile fatty acids, the necessary retention time and the gas yield (Kayser et al. 2009, 41).

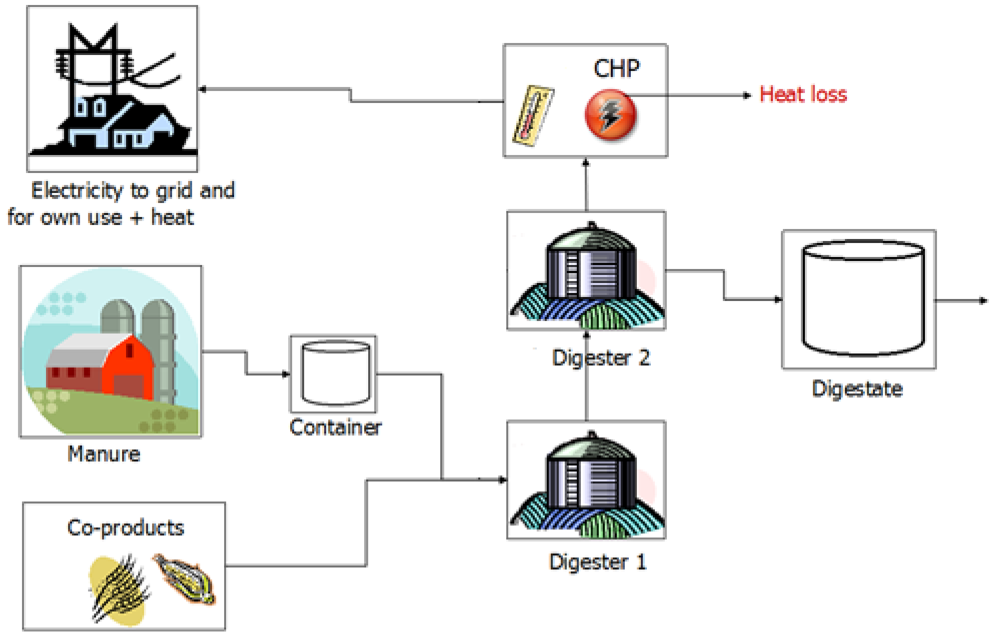


Figure 2: Co-digestion plants system description (Rauhala & Tervo 2010)

4.1 Storages before the process

Many kinds of units can be used as manure storage, for example cellars, silos and manure bags. Methane production that happens in storage will lower the biogas yield in digester and can cause other problems, for example in case of open cellar methane emissions can cause problems for animal well-being. Therefore the manure should be transported from storage to the digester as soon as possible. Transportation is usually done by a pump. (Deutsche Gesellschaft… 2004, 54.)

In co-digestion, the additional biomass is called co-substrate. The possible difference between manure and co-substrates in fluidity and facilitating co-substrates' dosing will generally require separate storage. (Deutsche Gesellschaft... 2004, 54.) Ideally the stored biomass should have total solid (TS) contents of between 30-40%. Silos must have sufficient storage capacity for continuous digester operation over the year. (Braun et al. 2010, 6.)

4.2 Pre-treatment of co-substrates

Since co-substrates may require different kind of pre-treatments, a specific pre-treatment place might be necessary. Pre-treatments can be for example mechanical treatment, preheating and thermal treatment. Mechanical treatment can mean for example chopping or grinding. Thermal pre-treatment may be required in order to fulfil sanitation requirements. (Deutsche Gesellschaft... 2004, 54-55.) The selection of a necessary pre-treatment process must always be waste specific, in compliance with the digestion process applied and adjusted to the product quality (Braun & Wellinger, 2010, 9).

4.3 Digester

The digester is a cube-shaped or cylindrical waterproof container with an inlet which the fermentable mixture is brought in. Often the digester is equipped with an overflow pipe to lead the sludge out into a drainage pit. (Wal et al. 1979.) In the digester the biomass, including manure and co-substrates, are heated, stirred periodically and the fermentation process takes place. End products, that can also be called output, are biogas and digestate. Stirring is necessary in order to mix new substrate with the old substrate, to improve the penetration of bacteria, securing even temperature, preventing and disturbing the build-up of sedimentary layers. Stirring is necessary also in order to improve metabolism of the bacteria by removing the gas bubbles. (Deutsche Gesellschaft... 2004, 55.)

Digesters construction material can be concrete, steal, brick or plastic, but brass and copper should not be used due to the fact that they corrode easily. (Soininen et al. 2007, 16.) Digesters are usually built from concrete especially digesters that are bigger than 2000 m^3 due to low price, long age and formability. Steel is used when reactor volume is about 1000 m^3. It has good sealing properties but it is easily damaged by corrosion if it is not pre-processed well. Stainless steel is expensive so it limits it usage to only laboratory circumstances. Plastic is corrosion free and leak-free but it has low durability in larger digesters. Brick and wood is not common in digesters and they are only used in developing countries. (Hatsala & Raimovaara 2004, 13.)

4.4 Product storages

Digestate is usually stored in a post-digestion storage tank where additional biogas may be produced. Storage serves as a digestate tank because all of it cannot be used directly. (Deutsche Gesellschaft... 2004, 55.) More detailed information is in chapter 6.2.

Produced biogas can be stored either in the digester or in external gas storage unit before it is utilized (Deutsche Gesellschaft... 2004, 55). The gas holder is normally an airproof steel container that cuts of air to the digester and collects the produced biogas. Usually the gas holder is equipped with a gas outlet. (Wal et al. 1979.) More detailed information is give on chapter 6.1.1.

4.5 Combined Heat and Power (CHP)

After filtering and drying, biogas from digester is suitable as a fuel. Biogas inserted in an internal combustion engine which, combined with a generator, can produce electricity. Biogas can also supply useful energy after combustion in form of hot air, hot water or steam. (Speight, 2008, 236.) The gas engine can also be a CHP unit which will convert the biogas into electricity and heat (Deutsche Gesellschaft... 2004, 55).

CHP unit can utilize at best 90 % of the energy content of the biogas. The utilization share of electricity varies between 15 - 38 % and the rest is utilized as heat (Tervahartiala 2007, 29). But usually it is divided as followed: the electricity utilization is about

30 % and the heat utilization is about 50 % (Soininen et al. 2007, 19). The motor type of the CHP has an effect on this operating efficiency. In farm scale the motor types are mostly gas motors or micro turbines. When selecting CHP unit the amount of produced biogas and the wanted amount of electricity should be taken into account. Also engine power and need for maintenance are important criteria. (Tervahartiala 2007, 29-30.)

4.5.1 Micro turbines

The micro turbines' sizes range from 25 kW to 250 kW. The gas is burned in an external combustion chamber. In the turbine, the energy of the formed combustion gas is converted into mechanical energy. Micro turbines are the least polluting type of CHP techniques but they have lower efficiencies in producing electricity compared to the other techniques. (Sinkko 2009, 35.) Compared to the gas motors, the micro turbines have higher investment costs but lower maintenance costs (Soininen et al. 2007, 20).

4.5.2 Gas motors

The gas motors' sizes are usually around 20-30 kW_e, but they are also available even from 2-3 kW_e. These motors are divided into compression ignition engines (diesel gas engine) and spark ignition engines. A small amount of liquid fuel is fed into cylinder of the diesel gas engine which lights up the gas-air mixture. The mechanical labour of the engine is converted into electricity by a generator. (Soininen et al. 2007, 19-20.)

4.5.3 Stirling motors

Technique of Stirling motors is based on closed cycle, where the volume of the used gas changes according to the temperature of the cylinder (Sinkko 2009, 32). The burning of the fuel takes place outside the cylinder (Soininen et al. 2007, 20). The Stirling motors accept many kinds of biomasses as a fuel because of the burning location. The Stirling motor is appreciated for its silence and longer periods between maintenances. (Sinkko 2009, 32.) Low operation costs and low emissions are advantages of these motors. The Stirling motors are still hard to get and their electricity efficiency is lower than the other techniques, but in future they can be economically used to produce electricity and heat. (Soininen et al. 2007, 20.)

5 SUBSTRATES

"Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates." (Braun & Wellinger 2010, 4). Term co-digestion is not dependent on the ratio of the used substrates. There are two major benefits when co-digestion is used: addition of co-substrates helps to produce more gas and agricultural biogas production from manure alone is not economically feasible. (Braun & Wellinger 2010, 4.)

Basically biogas plant can use as a substrate any kind of biodegradable material except for lignified material such as wood (Kayser et al. 2009, 40-41). In farm-based digesters mainly animal manure is used as the basic substrate. Co-digestion provides possibility of closed nutrient cycles and dealing residue materials in a way that produces few emissions. (Fachagentur Nachwachsende Rohstoffe 2009, 9.)

In order to optimize the biogas yield and economic performance of the plant, it is important to choose input materials that, when mixed together, form the necessary C/N-ratio and contain neither inhibiting nor toxic components (Kayser et al. 2009, 41). EU has published a guideline "Biological treatment of bio-waste" that includes a list of organic wastes and by-products allowable for anaerobic co-digestion. Some of the usable materials and their theoretical biogas production are shown in table 1. (Braun & Wellinger 2010, 7.)

Table 1: Organic waste and by-products for co-digestion with their approximate biogas yields in m3 per ton organic solids (Braun & Wellinger 2010, 6)

Materials	**Theoretical biogas production [m^3/ton]**
Harvest residues (Straw, stems etc.)	375
Animal manures (Food industry waste)	200-500
Yeast and yeast like products (Yeast- sludge from breweries etc.)	400-800
Residues from animal feed production (Expired feed)	500-650
Slaughterhouse waste (Flotation sludge, animal fat etc.)	550-1000
Wastes from plants- and animal fat production (Plant oil, oil seed etc.)	1000
Pharmaceutical wastes (Bacterial cells etc.)	1000-1300
Waste from pulp- and paper industry	400-800
Biowastes from source separated collection	400-500
Market waste	500-600
Sewage sludge	250-350

Co-substrates can be acquired from either internal or external sources or they can be an energy crop. Internal source means for example leftover silage or other agricultural wastes. External sources can be for example waste originating from food processing industry. (Deutsche Gesellschaft... 2004, 60-61.)

Substrates can be delivered to the plant in different ways depending on their properties. Liquid or pasty substrates are usually delivered in tank trucks and content is pumped into buffer tanks. Solid substrates are emptied into a reception pit where they are diluted and then pumped into the process. (Kayser et al. 2009, 41.) Unloading of the material should be done in a closed building to avoid odour emissions (Braun & Wellinger 2010, 10).

In this chapter more detailed description is given on substrates and they are divided into different groups. The simplest division is manure and co-substrates.

5.1 Manure

Anaerobic digestion of manure is primarily done for energy production (Braun & Wellinger 2010, 4). The EU Act for Animal By-Products (ABPs) not intended for human consumption (Regulation EC Nr 1774/2002) divides animal by-products into 3 categories. Manure is in category 2 which means that manure can be fed into digester without any pre-treatment. (Kirchmayr et al. 2003, 5.) “Manure is according to the ABP-Regulation excrements and/or urine of farmed animals with or without litter and guano, either unprocessed, processed or transformed in biogas plants or composting plants.” (Kirchmayr et al. 2003, 8). The composition of manure varies depending on the type of the animal and by farm. The dry matter content can vary by the use of water on farm and by type of animal. (Deutsche Gesellschaft... 2004, 59-60.)

5.2 Co-substrates

Adding co-substrates to manure is a way to increase biogas yield. Generally co-substrates have a higher biogas yield per wet ton than manure. (Deutsche Gesellschaft... 2004, 60.) Co-substrates can be a number of organic substrates which are anaerobically easily degradable without major pre-treatment. Among these are leachates, slops, sludge, oils, fats and whey. Some possible co-substrates require pre-treatment steps, for example municipal bio-waste, food leftovers and harvest residues. Only limited substances are badly suitable for process due to either high cost of pre-treatment, inhibiting components, poor biodegradability, hygienic risks or expensive transport costs. For example straws, lignin rich material and some slaughterhouse animal by-products are not suitable for AD process. (Braun & Wellinger 2010, 6.)

5.2.1 Agricultural and Industrial Wastes

The most common AD application is the digestion of animal manure because it produces a valuable fertilizer and biogas (IEA Bioenergy 2005, 6). Agricultural wastes include also harvest residues such as stems, sugar beet toppings and fibrous materials (Braun & Wellinger 2010, 6).

Industrial wastes consist of organic solid wastes from various industries and are increasingly treated in biogas plants. Anaerobic digestion of industrial wastes is becoming a standard technique. Some substances may be hard to digest as a sole substrate but in a mixture with manure or sewage sludge they are not a problem. Most of the wastes from the food industry have a high gas potential and therefore a popular substrate by plant operators. (IEA Bioenergy 2005, 7.)

5.2.2 Animal By-Products

EU Act for ABP products not intended for human consumption divides animal by-product in three categories. Category 1 contains those materials with the highest risk for public health, animals or environment and therefore cannot be processed in a biogas plant. These materials are such as specified risk material (SRM), animals suspected of being infected with BSE (Bovine spongiform encephalopathy), products with increased concentrations of environmental contaminants, solid materials from wastewater treatment in Category 1 processing plants, products from establishments in which SRM is removed, and catering waste from international means of transportation. (Kirchmayr et al. 2003, 7.)

Category 2 materials may be processed in a biogas plant after sanitation or some materials can be processed without pre-treatment. Category 2 includes all animal by-products which can be allowed neither to Category 1 nor to Category 3. These are manure, digestive track content, milk not fit for human consumption, killed or fallen animals, and solid materials in waste water streams of slaughterhouses. (Kirchmayr et al. 2003, 7.)

Category 3 contains all those animal by-products from animals fit for slaughter but not intended for human consumption as well as ABPs from food production and catering waste. These ABPs may be processed in biogas plant equipped with hygienisation unit. (Kirchmayr et al. 2003, 10.)

5.2.3 Other substrates

Organic wastes from households and municipalities are a potential feedstock for anaerobic digestion. Source separation provides the best quality feedstock for anaerobic digestion. (IEA Bioenergy 2005, 8.) Digestion of sewage sludge provides major benefits when recycling the digested sludge back. The process sanitises and reduces odour potential from the sludge. (IEA Bioenergy 2005, 6.)

Energy crop means crops especially grown for anaerobic digestion process in attempt to increase biogas production (Deutsche Gesellschaft... 2004, 60). Energy crops are for example maize, sunflower, grass, beet, clover, cereal, hemp, flax, potato and turnip (Braun et al. 2010, 5).

Energy crops are increasingly added to agricultural digesters. Crops are used for digestion directly after harvest. The harvest time can affect the bio-degradability and hence the methane yield. For a year- round availability of substrates, the crops are usually stored in silage clamps. Under some circumstances crops can be dried by using for example surplus heat from a CHP. (Braun et al. 2010, 5.)

6 END PRODUCTS

Anaerobic digestion aims to produce biogas that has a high content of methane (Metaenergia Oy 2011). Compared to natural gas biogas has the advantage to be renewable source and has positive effects on the environment (Hatsala & Raimovaara 2004, 18). Biogas may be used for producing electricity and heat. Anaerobic process converts wastes into digestate that is more odourless and more hygienic. Digestate is better as a fertilizer than unprocessed manure. Also the volume of waste decreases when processed anaerobically to digestate. (Metaenergia Oy 2011.) In this chapter end products are explained. Utilisation of biogas and digestate is more explained in the chapter 11.

6.1 Biogas

Biogas is a non fossil gas from renewable material. Its properties can be compared to natural gas and therefore biogas can replace fossil fuels (Liuksia 2009, 36). The produced biogas in anaerobic process contains mostly methane (50-80 %) and carbon dioxide (20- 50 %) (Deutsche Gesellschaft... 2004, 59). The most common methane content in biogas is 65-70 %. When using cattle waste as feedstock, the produced biogas contains typically 50 % of methane. When using fatty meat wastes, the methane content could be around 80%. Heating value of biogas is related to its methane content. (Hobson & Wheatley 1993, 240-241.) Biogas has higher energy levels when the methane content is higher (Deutsche Gesellschaft... 2004, 59). Energy content of one cubic meter of methane is approximately 10 kWh. If the methane content in biogas is 60 %, one cubic meter of produced biogas has the energy value of roughly 6 kWh. (Fachagentur Nachwachsende Rohstoffe 2009, 9.)

Biogas contains small amounts (each less than 1 %) of nitrogen (N_2), hydrogen (H_2), ammonia (NH_3) and hydrogen sulphide (H_2S) (Deutsche Gesellschaft... 2004, 59). The biogas contains also moisture and traces of volatile fatty acids. They can be in the biogas due to volatilisation and in fine water droplets. (Hobson & Wheatley 1993, 240.) Biogas production will be close to the theoretical maximum if all the process parameters are in optimal range. Important parameters in the substrate concerning biogas content are dry matter, organic matter and organic dry matter. (Deutsche Gesellschaft... 2004, 59.)

Organic material that is fed into the anaerobic digester has specific gas production rate. For example if fats are fed into the digester, its biogas production rate will range from 1.2 to 1.6 m^3/kg of degraded organic material whereas proteins and carbohydrates have the rate around 0.7 m^3/ kg of degraded organic material. (Liuksia 2009, 37.)

The following formula shows how to calculate the total biogas production (formula 1):

$$Biogas\ production\ [m^3] = amount\ of\ substrate\ (ton) * DM\ (\%) * OM\ (\%\ of\ DM) * maximum\ biogas\ production\ (m^3/ton_{ODM}) \quad (1)$$

In the formula DM (%) is percentage of dry matter in the substrate and OM (% of DM) is the organic fraction of the dry matter. (Deutsche Gesellschaft... 2004, 59.)

6.1.1 Biogas storage

Biogas can be collected, directed straight into use or be rerouted back to the reactor to mix the input. Before the biogas can be used it may need to be pre-processed e.g. pressurizing or drying out the moisture. (Hatsala & Raimovaara 2004, 15&18.) Gas storage vessels can be categorised by the pressure they operate as low-pressure (0.005-0.5 bar), intermediate (5-20 bar) and high-pressure (200-300 bar) storage tanks. The low-pressure tanks can be built from flexible foils and those are used mostly in farms. The intermediate and the high pressure tanks are constructed as steel pressure vessels and gas bottles. (Deutsche Gesellschaft... 2004, 71.) In most cases pressure in storage tank is adjusted under 50 mbar and the storage can hold usually the volume of biogas that is produced in 12 hours (Soininen et al. 2007, 18).

Gas storage can be located inside the digester (internally) on top of the digestate or outside of the digester (externally). Above the feedstock, there is an expandable material when biogas is stored internally. If the storage is small, the expandable material is not needed. (Deutsche Gesellschaft... 2004, 71.) An example of internal biogas storage is in figure 3.

Figure 3: Internal biogas storage (Siemens Water Technologies 2011)

As an example of external storage of biogas is a gas bag. It has a long life span because the biogas is stored at low pressure hence not stressing the material. Gas bags have advantages: they can be made with low costs to any size up to 2000 m^3 and the used foil does not corrode. On the other hand gas bags need to be protected from weather and damage. (Deutsche Gesellschaft... 2004, 71-72.) Figure 4 is a gas bag. Biogas storage is also used when malfunction of installations occur (Soininen et al. 2007, 18).

Figure 4: External biogas storage – A gas bag (Novatech GmbH 2011)

6.1.2 Pre-treatment of biogas

Normally pre-treatment of biogas before utilisation is needed, in order to remove compounds, such as carbon dioxide, hydrogen sulphide and moisture. Moisture lowers the heat value of biogas and it is removed by condensing the biogas. Pressurising the produced biogas is needed when it is utilised as a fuel for traffic. (Soininen et al. 2007, 18-19.)

Biogas may contain hydrogen sulphide which needs to be removed due to its corrosive effect on for example engine and piping when reacting with oxygen. The removal can be done by inserting 2-6 vol. % of air into digesters upper half. The hydrogen sulphide will be oxidised by bacteria into sulphur and then it will be removed among the digestate as elementary sulphur. If air is correctly inserted, the concentration of hydrogen sulphide may go down by 95%. There is a danger that biogas can become very explosive if too much air is added. (Deutsche Gesellschaft... 2004, 73.)

6.2 Digestate

Digestate is pumped out of the reactor to a storage space, to pre-processing if needed and from there to utilisation (Soininen et al. 2007, 18). Digested manure has some good qualities compared to unprocessed manure. Slowly degrading organic compounds do not degrade in digestion hence they still function well as soil improver. Digested manure has less odours, pathogens and seeds. It is more homogenous compared to untreated manure. (Deutsche Gesellschaft... 2004, 61-62.) Digestate may be stored in normal liquid manure vessels. The containers can be covered and also the formed biogas can be collected. Loading rate and retention time have effect on this biogas production in the container. (Soininen et al. 2007, 21.)

Nutrients in the feedstock have a great impact on the fertilizer value of the digestate. In the digestion process the nutrients in the organic compounds are altered; for example part of organic nitrogen converts into ammonium. The total amount of nitrogen in digestate is still the same as in the feedstock. (Lukehurst et al. 2010, 7-8.)

When matching the wanted nutrients in digestate to the farmed field's nutrient requirements, it will minimise the unnecessary negative impacts on the environment as well as maximise the farmer's profits. Thus nitrogen, phosphorus, potassium and sulphur amounts should be taken into account when applying digestate into fields. Mineral nitrogen is immediately available for the crops after spreading the digestate. The excessive amounts of phosphate can lead to eutrophication of waters and diffuse pollution. (Lukehurst et al. 2010, 10.)

Heating of the biomass in the digester has a reducing effect on the amount of pathogens and seeds. Thus the hygiene of the digested manure is better compared to unprocessed manure, but added co-substrates may bring additional pathogens and seeds. Sludge that is used as a feedstock, from for example animal production or certain wastes from households may contain risk of pathogens unlike sludge from for example vegetable production. If pathogens are a risk, digestate needs sanitation by heating the digestate for 1 hour at 70 °C. Sanitation is mostly needed when feedstock comes from an external source and also when the types of seeds in the co-substrate are not clear. Typically sanitation can happen before or after digestion in a separate tank that is heated. (Deutsche Gesellschaft... 2004, 62-63.)

6.2.1 Digestate separation

As a post-processing after the digestion, digestate can be separated into liquid and solid by sedimentation. Other way of separating is by mechanical separation devices such as centrifuge. (Palva et al. 2009, 85-86.) But centrifuges have high investment and operating costs (Lukehurst et al. 2010, 14). Advantages in separation can be found for example in a situation of phosphor overload. Phosphor stays only in the solid part of the digestate. (Palva et al. 2009, 85-86.) Chemicals can be used to enhance the separation efficiency for example chemicals that coagulate and possibly flocculate can be added before centrifuging (Lukehurst et al. 2010, 13- 14).

The solid portion contains only a little of nutrients and therefore the liquid portion has large part of the nutrients. Processing solid portion further more like composting could lead to quality compost. If it is not processed, it maybe utilised as a soil conditioner or a low grade fertilizer. The liquor portion is mostly used as fertilizer in the farm where it is produced and also it is reused in the digesting process. (Monnet 2003, 23 -24.)

6.2.2 Drying of the digestate

Drying of the digestate can be done either mechanically or thermally. For mechanical drying many different types of machinery are used. When choosing the right machinery, the following things should be noticed: dry matter content of the digestate, space requirements, energy consumption, requirements for quality of the dehydrated digestate and machinery's capacity. The mechanical drying requires polymers that improve the drying. For drying the digestate from wet process, there are techniques such as a screw press. (Latvala 2009, 51.)

The method in which water is vaporised by heating the digestate is known as thermal drying. This method is used for reducing volume of the digestate, before incineration or for hygienisation purpose. Thermal drying can increase dry matter content even up to 90 %. This method is used in biogas plants for making digestate more usable and more marketable. (Latvala 2009, 52.)

6.2.3 Composting

The digestate can be composted for example with so called reactor compost that speeds up the early stages of composting. The digestate that is composted may be utilised as a fertilizer or it can be taken to a landfill site. The product from composting is stable. It does not have any unnecessary weed seeds, pathogens or compounds that inhibit growth of the plants. During the composting it might be necessary to insert some new blend components to the digestate. This is because the organic material in the digestate might already be run out in biogas process. The mass should also be turned or aerated so the process that needs air can begin. (Latvala 2009, 54.)

7 PROCESS PARAMETERS

In this chapter basic parameters that affect the process are presented and general overview of the process performance is given. These parameters are mostly easy to measure and some of them give the first indications of stress in the system. Some of the parameters are directly measured but some have to be calculated.

7.1 pH

An efficient digestion occurs at a neutral situation and therefore a successful pH range for anaerobic digestion is between 6.0 and 8.0 (Wal et al. 1979). The growth rate of methanogens is greatly reduced below pH 6.6 whereas an excessively alkaline pH can lead to problems in bacterial performance and cause failure of the process (Ward et al. 2008, 7931).

Low pH is often resulting of overloading the digester (Wal et al. 1979). If the pH lowers enough, the methane producing bacterial metabolism slows down and acetate turning into methane decreases. Acetate is still being produced which causes the pH still to drop. Methane production will go to full-stop and all biological activity shuts off. This results in tons of hazardous waste in the reactor that must be emptied out before process can slowly be started again. Starting the process again may take months. (Finkemeyer 2007, 3-4.)

7.2 Temperature

Temperature in digester can vary in three ranges in which specific bacteria are most active. Process called psychrophilic is where temperature is under 30°C. In mesophilic process, temperature ranges between 30 °C and 40 °C. Highest activity is in thermophilic process in which temperature ranges between 40°C and 55°C. (Deutsche Gesellschaft... 2004, 57.) Increase in methane production from the thermophilic process has to be balanced against the increased energy requirement for maintaining the reactor at the higher temperature than in mesophilic (Ward et al. 2008, 7931). The system can be self-powered by the exothermic digestion process but usually it requires additional heat provided by burning some of the produced biogas (Mash 2008, 30). The choice of temperature range is often influenced by climatic conditions. For example in warmer climates, the extra energy requirement in order to reach thermophilic conditions is lower. (Wal et al. 1979.)

The optimum temperature for methanogenesis may not necessarily be the optimum for other processes in the anaerobic digestion (Ward et al. 2008, 7931). Most farm-scale digesters operate in the mesophilic range because it is less sensitive to changes and therefore it is easier to control than the thermophilic process (Deutsche Gesellschaft... 2004, 57). For optimum process stability, the temperature should be carefully regulated within a narrow range (Wal et al. 1979). Even small changes in temperature have been shown to reduce biogas production rate (Ward et al. 2008, 7931).

7.3 Hydraulic retention time (HRT)

Retention time indicates the time the substrates are inside the digester. Required time for optimal biogas production is dependent on the temperature, dilution of the feedstock, loading rate etc. (Wal et al. 1979.) When biogas production is near the theoretical maximum, the retention time in psychrophilic process is 40-100 days; in mesophilic process 25-40 days and in thermophilic process 15 - 25 days (Deutsche Gesellschaft... 2004, 57).

The hydraulic retention time can be calculated by using formula 2 (Theunissen 2010):

$$HRT\ [day] = \frac{reactor\ volume[m^3]}{volumetric\ flow\ rate[\frac{m^3}{day}]} \tag{2}$$

7.4 Organic and dry matter and related parameters

Dry matter (DM) is the residual substance after complete elimination of water (Braun et al. 2010, 18). Organic matter (OM) is the organic fraction (%) of the dry matter. Organic dry matter (ODM) is the organic part of the substrate and can be calculated by multiplying the organic matter and the dry matter (ODM=OM*DM). (Deutsche Gesellschaft... 2004, 57.)

Organic loading rate (OLR) is a measure of the biological conversion capacity of the anaerobic digestion system. OLR is particularly important parameter in continuous system. (Verma 2002, 8.) Organic loading rate is closely related to term organic matter. Organic loading rate is calculated by using formula 3 and it stands for organic matter divided by reactor volume divided by day. (Deutsche Gesellschaft... 2004, 57.)

$$OLR[\frac{\frac{\mathrm{kg_{OM}}}{\mathrm{m^3}}}{\mathrm{day}}] = \frac{OM[kg]}{V_{reactor}[m^3]/day} \quad (3)$$

Organic loading rate should be between 0.5 and 5 kg of organic matter per m^3 of digester tank per day. Optimum range is between 1 and 3 $kg_{OM}/m^3/day$. (Deutsche Gesellschaft... 2004, 57.) High organic loading rate increases instability in the process (Finkemeyer 2007, 5). Feeding the system above its sustainable OLR, results in low biogas yield due to accumulation of inhibiting substances (Verma 2002, 8).

7.5 Reactor volume and Flow rate

The term ‘reactor volume’ usually means the volume that substrates can fill, not the size of the whole reactor building (Finkemeyer 2007, 4).

Flow rate is the overall daily substrate flow measured either on cubic meter per day or ton per day. It is one of the most important and basic control parameters. (Braun & Wellinger 2010, 11.) The mass flow rate is given by the amount of feedstock added per day. In this thesis it is assumed that all feedstock is fed into the reactor where it is suspended in water. The volumetric flow rate of the feedstock can then be estimated by assuming that the density of all particles is more or less the same as for water. So, one ton of feedstock is the same as 1 m^3. (Theunissen 2010.)

7.6 VFA/TIC

VFA/TIC means the ratio of volatile fatty acids to total inorganic carbon. It is the first measurable indication that the system is in stress. (Riuji 2005, 26.) Volatile fatty acids

(VFAs) are one of the many carbon substrates used by microorganisms (Fothergill et al. 2000, 389).

The VFA-rich substrate from aerobic thermophilic pre-treatment provides methanogens with more readily available substrate. It has been shown that the thermophilic pre-treatment and adding secondary digestate in dual-digestion system will increase VFA concentration. Since VFAs, specifically acetate, are used in methanogenic reactions, the VFA-rich substrate can be used to enhance the anaerobic digestion. (Fothergill et al. 2000, 389.)

VFAs can accumulate because of instability causes by ammonia in the process. This leads to more acidic pH and decreasing concentration of fatty acids (FAs). Process can run more stable but with a decreased methane production. This can happen due to the interaction between FA, VFA and pH. (Chen et al. 2007, 4046.)

7.7 Other parameters

In this chapter two parameters are presented, but these parameters are not in the monitoring program. These parameters are good when evaluating digestion process and are thus taken into account in the theoretical part.

7.7.1 Frequency of mixing

Mixing ensures exposure of new surfaces to bacterial action and it prevents stratification and slowing-down of bacterial activity. Mixing also promotes uniform dispersion of the incoming material throughout the fermentation mass and thereby stirring accelerates digestion process. (Wal et al. 1979.) In digester, the produced gas will only surface automatically if there is less than 5% dry matter in the substrates. In all other cases mixing is necessary in order to avoid pressure build-up. (Deutsche Gesellschaft... 2004, 58.) When stirring is inadequate or solid materials are not well shredded, gas production may be affected by the formation of a scum (Wal et al. 1979).

7.7.2 C/N-ratio

Nitrogen (N) is necessary in substrate because it is an essential element for the bacterial metabolism and by converting to ammonia it helps maintain the pH by neutralising acids. Excessive amount of nitrogen in the substrate can lead to excessive ammonia formation that can result in toxic effects. (Deutsche Gesellschaft... 2004, 58.)

The relationship between the amount of carbon and nitrogen present in the substrates is expressed as the C/N-ratio. If ratio is high, it indicates rapid consumption of nitrogen by methanogens and leads to lower gas yield. Lower value indicates ammonia accumulation and thus pH rises which is toxic to methanogenic bacteria. (Verma 2002, 8.) C/N-ratio should be from 20:1 to 40:1 although more extreme values can still result in efficient digestion (Deutsche Gesellschaft... 2004, 58).

8 INHIBITION OF ANAEROBIC CO-DIGESTION

In biogas process, inhibition stands for a harmful effect that is caused by a chemical or physical factor and it disturbs biological process in the digester. If inhibition occurs it can be seen as dropping of biogas production or methane concentration. (Latvala 2009, 36.) Inhibitive compounds can be categorised into two groups: compounds formed as intermediate products from degradation of biomaterial or compounds in material that will be processed (Luostarinen 2009, 4). For example ammonia can in small amounts increase the methane content of biogas and increase the biogas production (Soininen et al. 2007, 15).

Inhibition can be reduced or even be removed. First possibility is a dilution for example by adding liquid. Second possibility is to adjust the microbes to the environment by increasing the amount of inhibitive compound slowly or by using specific bacterium population. Adjusting process variables such as pH and temperature may also reduce inhibition. Pre-treatment for removing the inhibitory compound or material can be done before anaerobic digestion. (Luostarinen 2009, 8.)

8.1 Partial pressure of hydrogen

It is important in balanced biogas process that transfer of hydrogen between micro-organisms is from producer to consumer and the partial pressure of hydrogen is low. Hydrogen consumers play a major part in a well working process. In order to have the decomposition reaction functioning well the partial pressure of hydrogen should be low. When the partial pressure is low the acetogenic micro-organisms form hydrogen that is energy rich. On the contrary, high partial pressure of hydrogen causes the acetogenic micro-organisms to form reduced compounds, which give less energy. (Luostarinen 2009, 5.)

When the partial pressure of hydrogen is relatively high, formation of acetate will reduce and instead of turning into methane substrate will turn into propionic acid and butyric acid. Also the production of methane will alter to formation of ethanol. The consumers such as methanogens help to keep the partial pressure of hydrogen low. (Liuksia 2009, 20 & 22.)

8.2 Long chain fatty acids

Long chain fatty acids (LCFAs) are introduced into the digester when treating fatty materials. LCFAs are inhibitory already at low concentrations only to gram-positive bacteria. Therefore LCFA is inhibitory to methanogens. Thermophiles are more sensitive to the presence of LCFAs compared to the mesophiles because of different structure of cell membranes. LCFA inhibition can be reduced by adding calcium which then forms insoluble fatty acid salts. (Chen et al. 2007, 4055.)

8.3 Ammonia (NH_3)

Ammonia is the main source of nitrogen to the digester bacteria. The digester failure is in relation to high ammonia concentration. (Hobson & Wheatley 1993, 49-50.) Ammonia inhibition can happen by changing intracellular pH or inhibiting specific enzyme reaction. Ammonia can also cause proton imbalance or potassium shortage by diffusing passively into the cell. Methanogens are the least resistant anaerobic micro-organism type and therefore most likely to fail growth because of ammonia inhibition. (Chen et al. 2007, 4045.)

Ammonia forms from bacterial action when proteins or non-protein nitrogenous compounds are microbially degraded (Hobson & Wheatley 1993, 51). In the digestion process, ammonia is either as an ammonium ion or as dissolved ammonia gas (Mignone 2005, 1-2). Ammonium ion and ammonia gas are in equilibrium and their concentrations are related to the pH of the environment (Hobson & Wheatley 1993, 50): when pH is 7.2 or lower the ammonium ion is formed and when pH is greater than 7.2 the ammonia gas is formed (Mignone 2005, 1-2). Ammonia gas is more inhibitive compared to the ammonium ion (Hobson & Wheatley 1993, 50).

When analysing ammonia toxicity, total ammonia and pH needs to be measured. If pH is above 7.4 and total ammonia concentration is between 1500-3000 mg/l in digestion liquid, a chance for inhibition caused by ammonia gas may exist. (Mignone 2005, 2.) According to Hobson and Wheatley (1993, 50) experiments show that inhibition of mesophilic digestion begins when pH is normal (slightly over 7) and ammonia concentration is around 1700-1800 mg/l. When ammonia concentrations grow, inhibition grows rapidly as well. When controlling inhibitory effect of ammonia, the input should be diluted or the pH level should be maintained between 7.0 and 7.2 by addition of hydrochloric acid. Ammonium ion causes toxicity if total ammonia concentration is over 3000 mg/l. High concentrations are controlled by diluting the input or adding sodium cation the amount that depends on how much over 3000mg/l the ammonium concentration is. (Mignone 2005, 2.)

8.4 Sulphide

The sulphate reducing bacteria (SRB) reduce sulphate into sulphide in AD process. This sulphate reduction results into inhibition. According to Chen et al. (2007, 4047) methane production is inhibited due to "--competition for common organic and inorganic substrates from SRB." Also various bacteria groups are inhibited by the toxicity that sulphide causes. (Chen et al. 2007, 4047.) In digesters, sulphide is produced from feedstock's amino acids. Sulphide is needed in production of sulphur amino acids in bacteria and it allows anaerobes to grow as it is a chemical reducing agent. Sulphide toxicity can be reduced in different ways such as bacteria's adaptation to the changed environment, taking away sulphate from feedstock and precipitation of sulphide. Also gas stripping action of methane and carbon dioxide can remove gaseous hydrogen sulphide. (Hobson & Wheatley 1993, 57-58.) Controlling soluble sulphides happens either by adding iron salts or/and eliminating sulphur containing material (Mignone 2005, 5).

8.5 Light metal ions

The light metal ions can be inserted into the digester as pH control chemicals or they may get into the digesting matter from degradation of organic matter. Aluminium inhibits anaerobic digestion when it competes with iron and manganese or affects microbial growth by causing adhesion to the cell membrane. When adding $Al(OH)_3$, acetogenic and methanogenic bacteria are inhibited. (Chen et al. 2007, 4049- 4050.)

Calcium is important for the growth of certain methanogens and its addition can have a positive impact on digester. Too much calcium may cause precipitation of carbonate and phosphate. This may lead to for example scaling of the reactor and pipes. (Chen et al. 2007, 4050.) In concentrations of 75-400 mg/l calcium, sodium, potassium and magnesium are not inhibitory but actually stimulate the digestion (Hobson & Wheatley 1993, 57). In small amounts, they are needed for microbial growth as nutrients but in excessive amounts they slow the growth and may cause inhibition or toxicity (Chen et al. 2007, 4049).

Toxicity of potassium is reduced by sodium, magnesium and ammonium. Low concentration of sodium is important for methanogens. At high concentrations, sodium may interfere with bacteria metabolism and activity. Concentration of sodium ions has an effect on the inhibition and over 8000 mg/l sodium is very inhibitory to methanogens in mesophilic range. (Chen et al. 2007, 4050-4051.)

8.6 Heavy metals

Heavy metals contaminate digester feedstock and affect digesters bacteria. Also heavy metals affect the environment when they are discharged with the digestate. (Hobson & Wheatley 1993, 56.) Methanogens are more affected by the toxicity of heavy metals than the acidogens. Heavy metals do not degrade biologically and may accumulate to inhibitory levels. (Chen et al. 2007, 4052.) It is difficult to define heavy metal concentration that is inhibitory because of the ease that heavy metals take part in reactions with ammonia, carbonates and sulphides (Mignone 2005, 2). Total metal concentration, form of the metal (chemical) and factors in the process e.g. pH, determine the heavy metals effect on microorganisms: either stimulatory or inhibitory (Chen et al. 2007, 4052).

The toxicity of heavy metals can be controlled by using ferrous sulphide (FeS) for precipitation. When using this control method, a chance for sulphide toxicity exists, production of hydrogen sulphide or corrosion problems caused by sulphuric acid. For these reasons ferrous sulphide should be used as the sulphide for control. (Mignone 2005, 3.) Fe^{2+} (iron ion) would be released, when heavy metals combine with the sulphide in FeS. Iron ion is quite non-toxic until concentration is several hundred mg/l. (Chen et al. 2007, 4053.) By setting the pH value around 8, by adding sodium carbonate, heavy metal poisoning in digester can be recovered (Hobson & Wheatley 1993, 56).

8.7 Antibiotics

It is important to prevent pesticides and medicament such as antibiotics from getting into the feedstock in farm scale digesting (Soininen et al. 2007, 15). Antibiotics can get into digester when e.g. diseases in farm animals are treated, but only for a short time. The dilution with other wastes makes it only temporary. Antibiotics regulate bacterial growth. Some antibiotics do not have any effect on digester metabolism, but some e.g. lincomysin could completely stop the digester. (Hobson & Wheatley 1993, 54-55.)

9 TYPES OF ANAEROBIC DIGESTION PROCESSES

There have been many researches about anaerobic digestion and there are many kinds of processes for different feedstock and needs. Choosing a process has lots of factors that need to be taken into account: quality and volume of the input material, financial, biological and geographical aspects. Processes can be divided in different ways and many process solutions are available. (Hatsala & Raimovaara 2004, 10.) Anaerobic digesters can be categorised by amount of dry matter, loading type, temperature and amount of process stages (Palva et al. 2009, 84). In this chapter anaerobic digestion processes and reactor types are presented.

9.1 Process classification: dry matter, loading and temperature

When separating AD systems by dry matter, the solid and liquid ratio is important. AD is considered "wet" if total dry solids (TDS) is below 15 % and "dry" when TDS is above this. (Evans 2001, 102.) Wet process has advantages: the stability of the process and high biogas production. Disadvantages in wet process are higher energy costs due to heating of the input, drying of the digestate and a large reactor size because of high water content. Also the energy consumption is higher due to that the separated liquid needs to be cleaned before discharging it into the nature. (Hatsala & Raimovaara 2004, 10.) In many cases wet processes are fully mixed unlike dry processes (Palva et al. 2009, 84).

The advantages of dry process are the low costs for heating and installing. Also the process does not need much water and therefore the reactor can be smaller. Due to the fact that the process is dry the mixing is harder and controlling the process is more demanding. (Hatsala & Raimovaara 2004, 10.)

Biogas reactors can be divided into three groups by their regime of loading: continuous, semi-continuous and batch reactors (Deutsche Gesellschaft... 2004, 63). In continuous reactors, the input is being loaded into the reactor constantly and in semi-continuous reactors this is being done a few times a day. In batch reactors, the materials are processed in the reactor for a certain time for example between 4 to 6 weeks. After digestion, the material is taken out and a new batch is fed to the reactor. New batches include always microbe inoculants. Often batch reactor is a dry process due to difficulty of mixing and moving of the material. (Palva et al. 2009, 84.)

One distinction of AD processes is operating temperature: mesophilic or thermophilic. During the process the temperature should not change more than two degrees. (Soininen 2007, 15.) Also psychrophilic temperature is possible but rarely used due to microbe activity which enhances as temperature increases (Palva et al. 2009, 84).

9.2 Multiple phase processes

Biogas process can be divided into couple of stages and most common is to have two of them. At first, the acid fermentation happens and after this formation of methane. (Palva et al. 2009, 84.) Multiple phase processes have many reactors and different temperatures in them. This process is also best available considering gas production and degradation of organic material. (Hatsala & Raimovaara 2004, 11.) An advantage in multiple phase process is that the optimal conditions can be adjusted for each digestion phase. By doing this, digestion efficiency and biogas production increase. (Soininen et al. 2007, 16.) Installing this process is more expensive and also operating costs are higher. Control requires more attention in multiple phase process compared to single stage process. (Hatsala & Raimovaara 2004, 11.)

9.3 Reactor types

When choosing a reactor some criteria needs to be taken into account such as dry matter content of the substrate, the desired retention time, investment costs and current manure storage (used as a digester tank or storage after digestion) (Deutsche Gesellschaft... 2004, 65).

Reactors can be divided as followed into three groups based on their structure (Soininen et al. 2007, 17-18):

1) Plug-flow reactor: Biomass is fed continuously and it is a horizontal reactor where material goes through horizontally. Loaded feedstock should have solid content around 11-13 %.
2) Complete-Mix reactor: In farm scale digesting usually complete-mix reactors are used. Feedstock's solid content is normally from 3 to 10 %.
3) Covered lagoons: Most simple of these three. Its structure is a pool that is covered with a material which does not allow any gas to get through it. It functions best when it is loaded with material that has less than 3% solid content.

Deutsche Gesellschaft... (2004, 64) describes also two digester types that are a horizontal and an upright digester.

Horizontal reactor

Horizontal reactors are quite small and their volume is around 50-150 m^3. A horizontal reactor can be seen in figure 5. They have a large steel tank which size is limited because they are transported in one piece and they are only horizontally mixed. Dry matter content can be up to 15-20 %. The heating arms that heat the input are installed on the axle of the mixer. The input goes in from the one side of the reactor and comes out from the opposite end. The input goes through the reactor on an even pace. External biogas storage is always needed. As an advantage, the capacity can be higher when retention time is shorter. (Deutsche Gesellschaft... 2004, 64.)

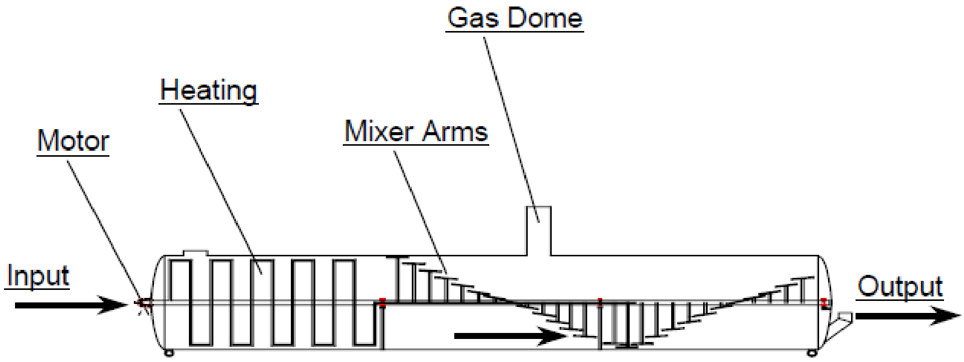


Figure 5: Horizontal reactor (Fischer & Krieg 2011)

Upright reactor

An upright reactor's volume ranges from 300 to 1500 m^3 and can be found in a shape of a cylinder (figure 6). Dry content can be up to 10-15 % but mostly it is below 10 %. Heating is organised either by heating the input externally before loading or internally by hot water tubes on the reactors walls. The content of the upright reactor is mixed and the mixing system can vary. Normally biogas storage is above digesting material with a flexible roof. The upright digester can be built less expensively than the horizontal one due to less expensive material and simpler construction. (Deutsche Gesellschaft... 2004, 65.)

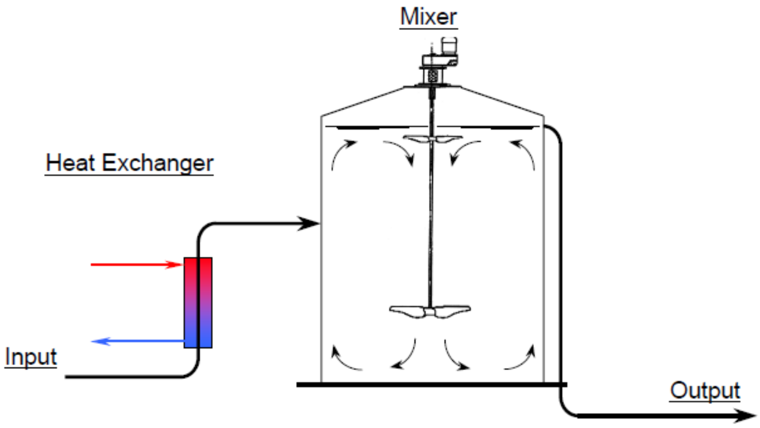


Figure 6: Upright reactor (Fischer & Krieg 2011)

9.3.1 Continuous reactors

The feedstock is fed into a continuous reactor little by little and the relevant amount is discharged at the same time (Soininen et al. 2007, 17). The continuous reactors are good when digesting a large volume of input (Hatsala & Raimovaara 2004, 18). The continuous reactor type is usually either complete mix reactor or plug-flow reactor. Higher solid content feedstock is more often used in plug-flow reactors than in complete mix reactor. (Soininen et al. 2007, 17.) For regulating the amount of biomass in the processing vessel, an overflow control mechanism or pumped return mechanism is often used (Evans 2001, 103).

Complete mix reactor is simple and most common wet process reactor where mixing of the reactor happens continuously. Retention time is from 2 to 4 weeks. This reactor type is used in farms that handle liquid manure. (Hatsala & Raimovaara 2004, 18.) Therefore the solid concentration is 3-10 %. Reactor is made from steel or concrete and shape can be circular. The formed biogas accumulates in the top of the reactor where it can be further utilised. (Speight 2008, 278.)

Plug-flow reactor is used in dry processes and is a horizontal reactor (Hatsala & Raimovaara 2004, 18). The input pushes the digesting material to the opposite end. Plug-flow reactor commonly consists of a manure collection system, a mixing pit and the digester which is long, rectangular vessel and has an airtight cover. (Speight 2008, 278.) Reactor is not mixed at all. Plug-flow reactor cannot process pig manure due to its low content of fiber. (Hatsala & Raimovaara 2004, 18.) Solid content is between

11-13 % and retention time varies from 20 to 30 days. Also as an advantage plug-flow reactor does not need much maintenance. (Speight 2008, 278.)

9.3.2 Semi-continuous reactors

Semi-continuous reactor is also known as Fed-batch reactor. The features of the batch and the continuous reactors are combined in Fed-batch reactor and their operation has two stages. First stage is batch phase, also known as growth phase, when a little amount of feedstock is pumped into the reactor and processed a while. The second stage is feeding phase (production phase): more feedstock is fed steadily until reactor is full. After the gas production is finished, the reactor is emptied. (Soininen et al. 2007, 17.) Thus reactor operates like batch reactor until it is full and after that operates like continuous reactor (Deutsche Gesellschaft... 2004, 64). Semi-continuous reactor is good for regular or steadily increasing waste streams (Evans 2001, 103).

For Fed-batch reactors, it is common that reactor size is big therefore it demands lot of space (Hatsala & Raimovaara 2004, 17). Reactor size is larger because the amount of input that takes to make it full does not have to be available immediately. This is mostly used when dry matter content is lower. (Sura 2008, 6.) When process capacity is the same, digester tank is usually larger in semi-continuous than in a batch one due to internal biogas collection. Compared to batch systems, semi-continuous processes produce more biogas and more steadily. (Evans 2001, 103.) Deutsche Gesellschaft... (200, 64) writes differently about the biogas production of semi-continuous process: "The major disadvantage of this process originates from the fact that a part of the digestate will not be completely digested, and hence the biogas yield is lower than for other process options." Due to shorter retention time, the digester's sanitation effect is not as good as in the batch or the continuous process. (Deutsche Gesellschaft... 2004, 64.)

A lagoon is an example of a Fed Batch reactor. It is a simple way to have material digested. It is a mesophilic or a psychrophilic reactor and the input has low content of solids. Organic material is processed from weeks to months. (Hatsala & Raimovaara 2004, 17.)

9.3.3 Batch reactors

At first, feedstock is loaded into batch reactor and then digestion process in reactor can happen (Verma 2002, 23). Once reactor is filled it is not interrupted (Evans 2001, 103). After digestion is finished, reactor is unloaded and fed with a new batch of feedstock. Batch process can be divided into three different types. First type is a single stage batch system where the material is re-circulated to the top of the reactor. The feedstock loaded to this unstirred reactor is pre-mixed with inoculants. (Verma 2002, 23.) Inoculants are mostly digested material from previous process and it contains microbes that are already adjusted to the process (Sura 2008, 11).

The second type of batch process has more than one reactor. From first reactor the digestate is re-circulated to the second reactor. Methanogenesis happens in the second reactor. Inoculation is guaranteed between the reactors by re-circulating the digestate from methanogenic reactor to the first reactor. The third batch process is an upflow anaerobic sludge blanket (UASB) reactor i.e. hybrid batch-UASB process. The first reactor is a basic batch reactor and the second one where the methanogenesis occurs is an upflow anaerobic sludge blanket reactor. (Verma 2002, 24.)

10 EMISSIONS FROM BIOGAS SYSTEM

Digestate has always fewer odours compared to untreated manure, but odour emissions, greenhouse gas emissions and harmful emissions can be formed when plant has a fault situation. Harmful emissions such as ammonia, methane, nitrous oxide and spores of the microbes can come from distribution to the field and from storing after digestion. Methane emissions also may be released when a leak occurs and spores of the microbes are released from biowaste containers and from loading of the input. (Latvala 2009, 59-60.)

Organic material produces greenhouse gases when degrading. When it happens in nature, emissions go straight to the atmosphere unlike in biogas plant where these greenhouse gases are stored and utilised. Therefore biogas production reduces greenhouse gases like methane which is 21 times stronger polluter than carbon dioxide and nitrous oxide which is 310 times stronger polluter than carbon dioxide. When biogas is used for energy production, it replaces use of fossil fuels thus also reducing emissions caused by use fossil fuels. (Latvala 2009, 59-60.) Most of nitrogen in digestate is in water-soluble form hence vegetation can use it more easily. This reduces the use of artificial fertilizers and therefore reduces the nitrous oxide emissions that are created when producing artificial fertilizers. (Finnish Biogas association 2010.)

Other effects to the environment from a biogas plant are noise and traffic. The noise comes from e.g. motors, burners, compressors and exhauster. Its environmental impact is marginal. The traffic is usually heavy traffic and it causes some noise, vibration and rising of the dust. (Kangas 2009, 58.)

Odour emissions

The spaces where the digestion process takes place are usually closed because of odours that come from the process for example mechanical or thermal drying. In some cases odours might need processing. (Latvala 2009, 60.) Odours can come from inorganic gases produced in digestion such as hydrogen sulphide and ammonia (Liuksia 2009, 51). Concentration of hydrogen sulphide is relative to the undesirable odours and it can be removed by combining it to the digestate by using ferrous salt (Kangas 2009, 53).

When the input is transported to the plant or to the digester itself disturbing odour emissions can be formed. Odour emissions are released also when digested product is stored, utilised, dried thermally or mechanically. The way that the biogas reactor is fed can cause odour emissions more or less. The amount of these emissions depends on for example whether the loading system is covered or not. Also the input material has importance to odour emissions: biowaste produces more odours and then the loading system would need to be covered. (Latvala 2009, 60.)

Odours can be prevented from spreading and causing harm by sealing, pressurising and covering the production spaces, location of the plant, air removal in containers and processing of the odour gases which will be regularly monitored. A biofilter is a processing method for gaseous biodegradable and odorous compounds. When either sulphur or ammonia concentration is high, a removal process is required, that can be a two staged method (washing and filtering+ additional treatment), chemical wash or ozone treatment. (Kangas 2009, 53-55.)

11 BENEFITS AND DISADVANTAGES OF CO-DIGESTION

Biogas can be used for all applications designed for natural gas, especially after gas is processed. Biogas can be utilised as a biogas fuel in vehicle which uses the same engine and vehicle configuration as natural gas. The gas quality demands are strict so the raw biogas from a digester has to be upgraded. (IEA Bioenergy 2005, 5.) But biogas utilisation in traffic has too low demand at the moment for it to become common (Palva et al. 2009, 90).

Biogas can be produced from plants not being competitive with food production. Even fields, not suitable for food production, can be used for the growing of energy crops. Also numerous organic wastes from different sources can be valuable substrates for anaerobic digestion. Therefore the increasing food demand does not have to be endangered by energy crops. (Braun et al. 2010, 15.)

When plants are well designed, risks to human health, for example handling of the pathogenic feedstock, can be prevented. Fire and explosion risks may also occur. The biogas plant can create traffic and hence cause costs and emissions. Thus it is important to choose the location well and not have long distances between destinations. (Monnet 2003, 28.)

11.1 Heat and electricity

Combined heat and power plant is a long established technology which utilises biogas. The engine sizes range from approximately from 12kW$_e$ on small farms up to several MW$_e$ on large-scale sites. (IEA Bioenergy 2005, 12.) Since CHP units usually turn 2/3 of the energy contained in biogas into heat, continuous heat consumption year around should be assured. The produced electricity can be sold to the public power grid and produced heat can be sold to the local district heating network. (Braun et al. 2010, 8.)

11.2 Digestate

Farm scale digesters use the digested slurry without further treatment as a fertilizer on farm land. Local laws and standards may put regulations on storage units, for the spreading, the amount of co-substrate permitted, the total yearly amount of nitrogen and heavy metals. (Braun & Wellinger 2010, 11.) Solid fractions are often separated from digestate and the separated liquid is in some cases re-circulated for substrate homogenisation (Braun et al. 2010, 8).

When digestate cannot be used as a fertilizer, there is need to find other ways for utilisation. For example separated and composted solid fertilizer can be other way to use. But in this case the digestate would need drying which makes investment and operation costs higher. Also some waste waters are produced when digestate is dried which requires processing or other utilisation. (Soininen et al. 2007, 21-22.)

11.3 Economical aspects

Investment costs in digestion process are relatively high. A lot of appliances are needed such as containers, pumps for different uses and compressors. (Liuksia 2009, 35.) This system has also significant operational costs. Anaerobic digestion system isn't economically feasible when used only as energy source. The products of anaerobic digestion e.g. fertilizer need to be utilised to have a feasible system. (Monnet 2003, 28.)

The payback time of farm scale biogas plants lies between 9-13 years. Co-digestion helps to produce more gas compared to single-substrate digestion and therefore more electricity at only marginal additional cost. The increased biogas productivity compensates the high investment and running costs. Co-digestion also offers additional income from gate fees paid for the waste materials digested. (Braun & Wellinger, 2010, 5 & 13.)

12 MATERIALS AND METHODS

Our thesis has more properties of a quantitative research method than a qualitative research method. Therefore quantitative is defined. Also in this chapter the execution of the thesis is explained.

The ways of research are related to chosen methods. Quantitative research method is used when measuring quantitative properties of something whereas qualitative research method is used when qualitative properties are being measured. Both methods are usually presented as opposite methods although they can be used simultaneously. Characteristic of the phenomenon is crucial when choosing the method of research. (Likitalo & Rissanen 1998, 10.)

Normally quantitative method has theory based logic. In this method the phenomenon is observed on theory base, progress happens from theory to practice and from general to detailed. Quantitative research method has different properties. These properties are for example the aim to have results from measuring, problems and hypothesis are based on theory, many measurable empirical quantities, objectivity, often collected data is numerical, several cases and the effect of the person who is doing the research is eliminated. (Likitalo & Rissanen 1998, 10.)

Execution of the research in the bachelor’s thesis

The research material was given us by our employer of the thesis Mr. Jos Theunissen. The monitoring program and processing of the given material was done with the Microsoft Office Excel 2007 program. While planning the thesis, we gave suggestions on data we thought we might need. After consideration of those wishes, Mr. Theunissen created monitoring data for two imaginary farms for two months. In the created data there was additional information but not all wished data was gotten.

In order to execute the monitoring table, a wide literature study was made to have a deeper understanding of the process. By using that understanding we began to gather lists of possible, essential parameters that should be studied closer and could be useful in the monitoring table. The lists developed and finally got the form now seen in the monitoring table. Then we started to make lists of parameters we could calculate and collect usable formulas. After deciding the parameters we started to put them in Excel. These decisions made the basic structure of the monitoring table and that was altered to make it more readable and simple.

Instructions for data treatment were given by Mr. Jos Theunissen and Mr. Xantho Klijnsma. These instructions were given us in the meetings which took place in the Netherlands. Inquiries were made via e-mail to Mr. Jos Theunissen when bachelor's thesis was written in Finland. The inquiries were informal and they were made when more instructions were needed.

13 RESULTS

In this section, the monitoring program is explained as the sheets and the calculations are defined. Also the most essential results are shown in form of tables which are samples from the monitoring program. The division of the tables follows the structure of the monitoring table. The sheets are explained following the order in the monitoring program. Not all data is presented in the tables. The monitoring table where all the data can be found is presented in appendix 1.

13.1 General data

The first sheet in the monitoring table is called General data and it is presented in appendix 1: page 1. In this sheet, name and date of starting of the farm and information on the CHP [kW_{el}] are required. Farms own electricity and heat usage are divided into different parameters which are direct electricity use in farm, electricity use for digester, heat used in farm, heat used in digester and sold heat. These parameters are inserted into the monitoring table in the units of kWh/month or MJ/month. A figure of a digestion process is in the general data sheet and is also in appendix 1. Some of the parameters in the monitoring program are numbered according to the figure. The general data for farm 1 and farm 2 is presented in tables 2 and 3 respectively.

Table 2: General data/Farm 1

Farm 1: electricity and heat usage	Farm 1 /January	Farm 1/February
Direct electricity use in farm [kWh/month]	2020	2120
Electricity use for digester [kWh/month]	18230	18622
Heat used in farm [MJ/month]	26375	25430
Heat used for digester [MJ/month]	324000	314650
Sold heat [MJ/month]	0	0

Table 3: General data/ Farm 2

Farm 2: electricity and heat usage	Farm 2/January	Farm2/February
Direct electricity use in farm [kWh/month]	1628	1180
Electricity use for digester [kWh/month]	14250	13924
Heat used in farm [MJ/month]	16380	16730
Heat used in digester [MJ/month]	224050	214570
Sold heat [MJ/month]	0	0

13.2 Technical insert

Technical and measured information is presented in the technical insert sheet. The sheet is divided into overview of used manure, overview of used co-products, technical aspects, overview of output and digestate. Limit or optimum range is presented to help noticing the exceeding of the value. Limit for pH is 6.0 – 8.0 (Wal et al. 1979), for temperature 30 – 40 ˚C (Deutsche Gesellschaft... 2004, 57), for hydraulic retention time 25-40 days (Deutsche Gesellschaft... 2004, 57), for VFA/TIC less than 0.3 (Guo et al. 2011, 2) and for organic loading rate 0.5-5 $kg_{OM}/m^3/d$ (Deutsche Gesellschaft...2004, 57).

13.2.1 Overview of used manure and overview of co-products

In the overview of used manure and co-products, the input materials are inserted and calculated. This part of monitoring program is presented in appendix 1: page 3 (farm 1) and page 6 (farm 2). The input is given as ton per day and calculated as a percentage of total feedstock. Also total manure and total substrates are calculated by summing the amounts of their inputs. Total feedstock includes total used manure and total used substrates. Price for the manure or the substrates can be inserted if needed.

All the farms used cattle manure as their manure substrate. Farm 1 used corn and food waste as their co-substrates and farm 2 used potato residues and grass from roadsides. The amounts are shown in table 4.

Table 4: Overview of feedstock

Feedstock [ton/day]	Farm 1/ January	Farm1/ February	Farm 2/ January	Farm2/ February
Manure	19,8	22,5	26,0	27,9
Substrate 1	15,5	18,2	10,3	17,1
Substrate 2	4,1	4,1	15,3	10,9
Total	39,4	44,9	51,6	55,9

13.2.2 Technical aspects

Technical aspects are parameters describing the functioning of the digester: pH, temperature in digester [˚C], hydraulic retention time [day], organic loading rate [$kg_{OM}/m^3/day$] , reactor volume [m^3], volumetric flow rate of feedstock [m^3/day] and VFA/TIC. This part of monitoring program is presented in appendix 1: page 4 (farm 1) and page 7 (farm 2). These parameters are more explained in the chapter 9. Organic dry matter (ODM) is calculated as total organic dry matter of all feedstock per day (formula 4).

$$ODM\left[\frac{ton}{day}\right] = \frac{total\ ODM\ of\ manure\left[\frac{ton}{month}\right] + total\ ODM\ of\ co\text{-}products\left[\frac{ton}{month}\right]}{days\ of\ the\ according\ month} \quad (4)$$

Dry matter is calculated as total DM of all feedstock per day (formula 5):

$$DM\left[\frac{ton}{day}\right] = \frac{total\ DM\ of\ manure\left[\frac{ton}{month}\right] + total\ DM\ of\ co\text{-}products\left[\frac{ton}{month}\right]}{day\ of\ certain\ month} \quad (5)$$

Dry matter % of total input is calculated dividing total dry matter content by total feedstock (formula 6):

$$DM\ \%\ of\ total\ [\%]\ =\ \frac{DM\ [\frac{ton}{day}]}{total\ feedstock\ [\frac{ton}{day}]}\ *\ 100\ \% \quad (6)$$

Organic dry matter % of dry matter can be calculated dividing organic dry matter by dry matter (formula 7):

$$ODM\ \%\ of\ DM\ [\%]\ =\ \frac{ODM\ [\frac{ton}{day}]}{DM\ [\frac{ton}{day}]}\ *\ 100\ \% \quad (7)$$

Organic dry matter % of total input is calculated by multiplying dry matter % of total input with organic dry matter % of total dry matter (formula 8):

$$ODM\ \%\ of\ total\ [\%]\ =\ DM\ \%\ of\ total\ [\%]\ *\ ODM\ \%\ of\ DM\ [\%] \quad (8)$$

Farm 1 has two digesters whereas farm 2 has one digester. Given information is presented for the concerned digester. Technical aspects for the farm 1 are shown in table 5. The corresponding values for the farm 2 are presented in table 6.

Table 5: Technical aspects of the farm 1

	Farm 1/January		**Farm 1/February**	
Technical aspects	Digester 1	Digester 2	Digester 1	Digester 2
pH	6,5	7,2	6,5	7,2
Temperature in digester [°C]	38,6	39	38,8	39,1
Hydraulic retention time [d]	31,7	31,7	27,8	27,8
Reactor volume [m^3]	1250	1250	1250	1250
Flow rate [m^3/d]	39,4	39,4	44,9	44,9
VFA/TIC	0,37	0,14	0,33	0,12
Organic dry matter (ODM) [ton/d]	6,2	6,2	7,0	7,0
Dry matter (DM) [ton/d]	7,2	7,2	8,3	8,3
DM (% of total)	18 %	18 %	18%	18%
ODM (% of DM)	86 %	86 %	85%	85%
ODM (% of total)	16 %	16 %	16%	16%
Organic loading rate (OLR) [$kg_{OM}/m^3/d$]	4,93	4,93	5,63	5,63

Table 6: Technical aspects of the farm 2

Technical aspects	**Farm 2/January**	**Farm 2/February**
pH	7	6,3
Temperature in digester [°C]	39,1	39
Hydraulic retention time [d]	57,2	52,8
Reactor volume [m^3]	2950	2950
Flow rate [m^3/d]	51,6	55,9
VFA/TIC	0,28	1,14
Organic dry matter (ODM) [ton/d]	6,8	6,1
Dry matter (DM) [ton/d]	8,2	7,4
DM (% of total)	16 %	13 %
ODM (% of DM)	82 %	83 %
ODM (% of total)	13 %	11 %
Organic loading rate (OLR) [$kg_{OM}/m^3/d$]	2,30	2,08

13.2.3 Overview of output

This part of monitoring program is presented in appendix 1: page 5 (farm 1) and page 8 (farm 2). Overview of output section includes parameters that are products of the co-digestion system: biogas production [m^3/day], gas composition: methane content [%], total electricity produced [kWh/month] and [MJ/month], average electricity produced [kWh/day] and [MJ/day], “unavoidable” heat losses [MJ/day], potentially useful heat per day [MJ/day] and also potentially useful heat per day as percentage of total energy produced. Total electricity produced per month is calculated by summing all electricity produced (electricity produced by CHP1 [kWh/month] + electricity produced by CHP2 [kWh/month]).

“Unavoidable” heat losses [MJ/day] are 10% of the energy in the biogas value and calculated according to the formula 9. The heat loss is an assumption given by Jos Theunissen (2010).

$$\text{“}Unavoidable\text{"} heat\ losses\ [\frac{MJ}{day}] = 0{,}1 * energy\ in\ the\ biogas\ [\frac{MJ}{day}] \qquad (9)$$

Potentially useful heat per day needs the values of energy in the biogas electricity production and heat losses (formula 10).

$$Potentially\ useful\ heat\ [\frac{MJ}{day}] = energy\ in\ the\ biogas\ [\frac{MJ}{day}] - electricity\ production\ [\frac{MJ}{day}] - heat\ losses\ [\frac{MJ}{day}] \qquad (10)$$

The data for the overview of output is shown in table 7. The table includes both farms and has given and calculated values.

Table 7: Overview of output

Overview of output	**Farm1/ January**	**Farm1/ February**	**Farm2/ January**	**Farm2/ February**
Biogas production [m^3/day]	3649	4178	2901	2595
Methane content	53 %	51 %	52 %	48 %
Total electricity per month [kWh/month]	217463	226668	179250	144909
Average electricity per day [kWh/day]	7015	8095	5782	5175
"Unavoidable" heat losses [MJ/d]	6923	7657	5400	4477
Potentially useful heat per day [MJ/d]	37054	39773	27785	21663
Potentially useful heat per day [%]	54 %	52 %	51 %	48 %

13.2.4 Overview of digestate

In this section, the parameters describe the quality and amount of digestate: digestate production [ton/month], digestate production per day [ton/day], dry matter DM [%] and [ton/day], organic dry matter ODM [%] and [ton/day], the amounts of nitrogen and phosphate [g/kg]. This part of monitoring program is presented in appendix 1: page 5 (farm 1) and page 8 (farm 2). Dry matter and organic dry matter are calculated as in formulas 11 and 12.

$$DM\left[\frac{ton}{day}\right] = digestate\ production\ per\ day\left[\frac{ton}{day}\right]\cdot DM[\%] \qquad (11)$$

$$ODM\left[\frac{ton}{day}\right] = DM\left[\frac{ton}{day}\right]\cdot ODM[\%] \qquad (12)$$

The overview of digestate for both farms is presented in table 8. The table includes given and calculated values.

Table 8: Overview of digestate

Digestate	Farm1/ January	Farm1/ February	Farm2/ January	Farm2/ February
Digestate production [ton/month]	1060	1075	1393	1355
Digestate production per day [ton/day]	34,2	38,4	44,9	48,8
Dry matter (% of total)	7 %	7 %	9 %	8 %
Organic dry matter (% of DM)	57 %	54 %	66 %	69 %
DM [ton/day]	2,2	2,6	4,2	4,0
ODM [ton/day]	1,3	1,4	2,8	2,7
Nitrogen [g/kg]	4,8	5,0	6,0	5,8
Phosphate [g/kg]	1,0	0,9	0,9	0,9

13.3 Calculations

Calculations based on given data are done in the sheet named calculations. Calculations deal with biogas, electricity and heat production, digester evaluation and efficiencies. Calculation model is presented in appendix 1: page 9.

13.3.1 General evaluation

The biogas per reactor volume [$m^3/(m^3_{reactor}d)$] is calculated in general calculations (formula 13).

$$Biogas\ per\ reactor\ volume[\frac{\mathrm{m}^3}{\mathrm{m}^3_{\mathrm{reactor}}\mathrm{d}}] = \frac{Biogas\ production\ per\ day[\frac{m^3}{d}]}{Reactor\ volume[m^3]} \quad (13)$$

Methane production is important value in order to compare different digesters as the methane content relates to the quality of the biogas. Methane production [m^3/d] is calculated as shown in formula 14.

$$Methane\ production[\frac{m^3}{day}] = CH_4\ content\ [\%] * biogas\ production\ per\ day[\frac{m^3}{day}] \quad (14)$$

Energy in biogas [MJ/d] is calculated as shown in formula 15.

$$Energy\ in\ the\ biogas\ [\frac{MJ}{day}] =$$
$$Biogas\ production\ per\ day\left[\frac{m^3}{day}\right] * heating\ value\ of\ biogas[\frac{MJ}{m^3}] \qquad (15)$$

In formula 15, a factor called heating value of biogas is used and it is calculated by using formula 16. In the formula, a constant called heating value of methane is used and it has a value of 35,8 MJ/m^3. (Theunissen 2010.)

$$Heating\ value\ of\ biogas[\frac{MJ}{m^3}] =$$
$$Methane\ content\ (\%) * heating\ value\ of\ methane[\frac{MJ}{m^3}] \qquad (16)$$

The relations between electricity and total feedstock are studied by using formula 17 and it has the unit of [kWh/ton].

$$Electricity\ production\ per\ total\ feedstock[\frac{kWh}{ton}] = \frac{Electricity\ production\ [\frac{kWh}{month}]}{Total\ feedstock[\frac{ton}{month}]} \qquad (17)$$

The same relation is also given in unit [MJ/ton]. The general evaluation calculations for both farms are shown in table 9.

Table 9: General evaluation

General evaluation	Farm1/ January	Farm1/ February	Farm2/ January	Farm2/ February
Biogas production per $m^3_{reactor}$ [$m^3/(m^3_{reactor}d)$]	1,5	1,7	1,0	0,9
CH_4 production [m^3/day]	1934	2139	1508	1251
Electricity production per total feedstock [kWh/ton]	178	181	112	93
Heating value of biogas [MJ/m^3]	19,0	18,3	18,6	17,3
Energy in the biogas [MJ/day]	69231	76573	54001	44771
Energy in the biogas [MJ/month]	2146168	2144050	1674044	1253585

13.3.2 Digester evaluation

Conversion efficiency of organic dry matter and specific CH_4 production indicate the digester's performance and are in digester evaluation part in the monitoring table. Organic dry matter (ODM) conversion efficiency indicates the rate that the digester transforms ODM to biogas and other substances. It is calculated by using formula 18.

$$ODM\ conversion\ efficiency\ [\%] = \frac{ODM_{in}[\frac{ton}{day}] - ODM_{out}[\frac{ton}{day}]}{ODM_{in}[\frac{ton}{day}]} \quad (18)$$

Specific methane production [m^3/ton_{ODM}] indicates the ratio between produced methane and organic dry matter (formula 19).

$$Specific\ methane\ production[\frac{m^3}{ton}] = \frac{CH_4\ production[\frac{m^3}{day}]}{mass_{ODMin}[\frac{ton}{day}]} \quad (19)$$

The results for calculations made in order to produce digester evaluation are presented in table 10. The table includes both farms.

Table 10: Digester evaluation

Digester evaluation	**Farm1/ January**	**Farm1/ February**	**Farm2/ January**	**Farm2/ February**
ODM conversion efficiency	80 %	80 %	59 %	55 %
Specific CH_4 production [m^3/ton_{ODM}]	314	304	223	204

13.3.3 Efficiencies

Different kinds of efficiencies are calculated in order to determine how well the plants are operating. The calculated efficiencies try to consider the plant's operations in many aspects: the efficiency of the CHP, the net electric efficiency and the net total energy efficiency.

The efficiency of the CHP is calculated by using formula 20.

$$Electric\ efficiency[\%] = \frac{average\ electricity\ per\ day[\frac{MJ}{day}]}{energy\ in\ the\ biogas[\frac{MJ}{day}]} \tag{20}$$

The net electric efficiency is calculated by using formula 21.

$$Net\ electric\ efficiency[\%] = \frac{Electricity\ production[\frac{MJ}{month}] - electricity\ consumption\ by\ the\ plant[\frac{MJ}{month}]}{Energy\ in\ the\ biogas[\frac{MJ}{month}]} \tag{21}$$

The net total energy efficiency is calculated by using formula 22. The factor 'useful heat' means heat used in the farm, other than heating of the digester, and sold heat.

$$Net\ total\ energy\ efficiency[\%] = \frac{electricity\ production[\frac{MJ}{month}] - electricity\ consumption\ by\ the\ plant[\frac{MJ}{month}] + useful\ heat[\frac{MJ}{month}]}{energy\ in\ the\ biogas[\frac{MJ}{month}]}$$

(22)

Efficiency calculations for both farms are presented in table 11.

Table 11: Efficiency evaluation

Efficiency	Farm1/ January	Farm1/ February	Farm2/ January	Farm2/ February
Electric efficiency (CHP η_{el})	36 %	38 %	39 %	42 %
Net electric efficiency	33 %	35 %	35 %	38 %
Net total energy efficiency	35 %	36 %	36 %	39 %

13.4 Comparison between farms

In the monitoring table, there is a sheet called comparison between farms and its main task is to collect essential data so that plants can easily be compared and differences are more easily noticed. Some of the parameters are given and some are calculated, but all of them are linked to previous sheets. Comparison is divided to four main aspects: technical aspects, overview of the output, energy amounts from the digester to the CHP and efficiencies. Also comparison is done on digester evaluation and those results are already shown in table 10. Comparing plants to each other may result to improvement of the digesters. Comparison between farms is presented in appendix 1: pages 10-11.

13.4.1 Technical aspects

In technical aspect, plants are compared to each other in terms of pH, temperature, hydraulic retention time, reactor volume, flow rate and feedstock. These parameters give the overall view on plants operation and comparing them to other plants will reveal inconsistencies. The values are presented in table 12.

Table 12: Comparison between farms on technical aspect

Technical aspects	Farm1/ January		Farm1/ February		Farm2/ January	Farm2/ February
Digester	1	2	1	2		
pH	6,5	7,2	6,5	7,2	7	6,3
Temperature in digester [°C]	38,6	39	38,8	39,1	39,1	39
Hydraulic retention time [day]	63,5		55,7		57,2	52,8
Reactor volume [m^3]	2500		2500		2950	2950
Flow rate [m^3/day]	39,4		44,9		51,6	55,9
Feedstock [ton/day]	39,4		44,9		51,6	55,9

13.4.2 Overview of output

To compare the output of the digesters, comparisons are made in following parameters: biogas production per reactor volume, methane production, gas composition specially the methane content and biogas production per ton of feedstock. These values are presented in table 13.

Table 13: Comparison between farms on overview of output

Overview of output	Farm1/ January	Farm1/ February	Farm2/ January	Farm2/ February
Biogas production per reactor volume [$m^3/(m^3_{reactor}d)$]	1,5	1,7	1,0	0,9
CH_4 production [m^3/d]	1934	2139	1508	1251
Methane content	53 %	51 %	52 %	48 %
Biogas production per ton of feedstock [m^3/ton]	92,6	93,1	56,2	46,4

13.4.3 Energy amounts from CHP

While comparing plants to each other, one obvious aspect is the produced energy. That comparison contains the parts: average electricity per day, potentially useful heat per day and total electricity per month. These values are presented in table 14.

Table 14: Comparison between farms based on energy amounts from CHP

Energy amounts from CHP	Farm1/ January	Farm1/ February	Farm2/ January	Farm2/ February
Average electricity per day [kWh/day]	7015	8095	5782	5175
Total electricity per month[kWh/month]	217463	226668	179250	144909
Potentially useful heat per day [MJ/day]	37054	39773	27785	21663

13.4.4 Efficiency

Farms are also compared to each other on efficiencies. Those efficiencies are the electric efficiency of the CHP, net electric efficiency and net total energy efficiency. These values are presented in table 15.

Table 15: Comparison between farms based on efficiencies

Efficiency	Farm1/ January	Farm1/ February	Farm2/ January	Farm2/ February
Electric efficiency (CHP η_{el})	36 %	38 %	39 %	42 %
Net electric efficiency	33 %	35 %	35 %	38 %
Net total energy efficiency	35 %	36 %	36 %	39 %

14 ANALYSIS

In this chapter we analyse the performance of the farms. In internal analysis the most essential parameters are compared and external analysis is comparison between farms.

14.1 Internal analysis

Internal analysis means analysing the data of farms and comparing given and calculated data between months. Since we have data only for two months, the analysis is only indicative, but it also enables easy comparison. Internal analysis concentrates to all the basic parameters given and calculated that are presented in chapter 13.

14.1.1 Farm 1

In farm 1, there are two digesters and it uses cattle manure, corn (substrate 1) and biowaste (substrate 2) as feedstock. In February, the farm uses 12% (5.5 ton) per day more feedstock than in January. The amount of manure and corn increases while the amount of biowaste stays the same.

Both digesters are mesophilic and are at the same size, 1250 m^3. Digester 1 is more acid than digester 2 but both stay within the normal digester-working pH limit which is between 6.0 and 8.0. Hydraulic retention time (HRT) decreases 12.3% from January (31.7 days) to February (27.8 days) in both digesters. The values are inside the optimum range. Respectively the flow rate increases from January to February from 39.4

m^3/day to 44.9 m^3/day. Ratio VFA/TIC fluctuates in digester 1 between 0.33 and 0.37 which is around the threshold value 0.3. In digester 2 the ratio is around 0.1 and it is much below the threshold. Even though the amount of dry matter increases from January to February, its percentage of total feedstock remains even. Organic dry matter does not show any major changes. Organic loading rate has a limit range of 0.5-5.0 kg_{OM}/m^3/day. In January, the value is within the limits and in February it exceeds the limit slightly (5.6 kg_{OM}/m^3/day) which can increase instability in the process.

The most obvious parameter to notice when analysing output is the biogas production. In farm 1, the biogas yield increases 12.7 % from January to February. This can be due to increase in feedstock that also grows about 12 %. The quality of the biogas stays almost the same when observing methane content. Electricity production increases by 13.3% and heat production increases by 6.8% which is an obvious consequence from the growth in biogas production. The heating value of biogas decreases due to the slight decrease in methane content, but the total energy in the biogas increases due to the growth in biogas yield.

Organic dry matter conversion efficiency reveals the percentage of organic dry matter that the digester transforms and since the value describes its efficiency, the higher the value the better. In farm 1, the efficiency is relatively high: 80% for both months. Specific methane production indicates how much methane is produced per ton of organic dry matter. The value is a bit over 300 m^3/ton in both months.

Digestate production stays constant and is around 1000 ton per month. The features of digestate are closely related to the features of the feedstock. Nitrogen content is around 5 g per kg of digestate both months. Phosphate is around 1 gram per kilogram of digestate.

The electric efficiency shows that the CHP produces electricity from the total energy in the biogas at a rate of approximately 35%. There is no major difference between months. Net electric efficiency shows how much electricity is available to be sold to the grid as a percentage of the energy in the biogas. In farm 1, the efficiency is around 30 % and there is not major fluctuation between months. Net total energy efficiency shows the percentage of the outgoing energy from the total energy in the biogas and the efficiency is around 35%. Net total energy efficiency does not change much from the net electric efficiency since the farm does not sell heat. This would also be an easy way to increase the efficiency.

14.1.2 Farm 2

In farm 2, there is one digester and it uses cattle manure, potato residues (substrate 1) and grass from roadsides (substrate 2) as feedstock. The total amount increases 4.3 ton per day from January to February. Amount of cattle manure stays relatively the same whereas the amount of potato residues increases from 10.3 to 17.1 ton per day and grass from roadsides decreases from 15.3 to 10.9 ton per day.

Temperature is mesophilic and reactor volume is 2950 m^3. Acidity increases between months but it remains in limit range, but in February the pH is 6.3 which is low and is only barely inside the limit. This pH can reduce the growth rate of methanogens since the pH is below 6.6. Since the methanogens' growth might be affected the biogas production can be smaller than it normally should be. Hydraulic retention time (HRT) decreases 7.7 % from January to February. HRT is clearly over the optimum range both months. Flow rate increases from January to February hence the amount of feedstock grows. In January, the ratio VFA/TIC is just below the threshold but on the contrary in February the ratio is clearly over the limit which can indicate stress in the system. Dry matter decreases from 16% to 13% of total feedstock which can be consequence from change in substrates rate. Organic dry matter instead remains the same in the both months. Organic loading rate is at healthy level on both months.

In farm 2, biogas production decreases 10.5% which indicates that the changes between January and February have not been to the right direction. This lowering in biogas yield can be explained by the changes in VFA/TIC, hydraulic retention time and the dry matter content. Also the lowering of pH affects the biogas yield. The changes in parameters indicate that the process might be in light stress. This can be result from growth in feedstock quantity. The quality of the biogas lowers little when observing methane content. Electricity and heat production decreases, which is a consequence from the decrease in biogas production. The heating value of biogas decreases due to the slight lowering in methane content and the energy in the biogas decreases also due to the lowering in biogas yield.

Organic dry matter conversion efficiency is not as high it could be. The efficiency varies from 59% to 55% and thus indicates that the digester does not transform organic dry matter into biogas as effectively as possible. Specific methane production is around 200 m^3 per ton of organic dry matter. Low values on both parameters continue to indicate stress in digester.

Digestate production stays constant and is around 1400 ton per month. Nitrogen content is around 6 g per kg of digestate both months. Phosphate content is around 1 gram per kilogram of digestate.

The electric efficiency shows that the CHP produces electricity from the total energy in the biogas on efficiency of approximately 40 %. There is no major difference between months. Net electric efficiency in farm 2 is around 35-38 %. The net total energy efficiency is around 36-39 %. Net total energy efficiency does not change much from the net electric efficiency since the farm does not sell heat. This farm could easily increase this efficiency by selling heat.

14.2 External analysis

External analysis can also be called comparison between farms. In this chapter, we compare the farms to each other in order to see the differences, to determine the reasons for the differences and try to find out how to compare different kind of plants.

14.2.1 Technical aspect

On technical aspect, the main difference between digesters is the size: farm 2 is bigger when considered digester size, feedstock and the flow rate. On operational aspect, the difference is that farm 1 has two digesters whereas farm 2 has one. On farm 1, the hydraulic retention time is longer than in farm 2.

The technical aspects are better on farm 1 as shown in internal analysis. For example there are differences in VFA/TIC values and hydraulic retention time. All basic technical aspects affect the biogas production as well as reasons we cannot determine from the given data, such as inhibitory factors.

14.2.2 Overview of output

Biogas production per reactor volume takes into consideration the difference in size and makes it possible to compare biogas production between farms. In farm 1 the production is steadily higher than in farm 2 which shows that the farm 1 works better and is more stable. This is also due to the hydraulic retention time, reactor volume, VFA/TIC, acidity and substrates. There is no big difference in methane content between farms so the quality of the biogas is same.

Biogas production per ton of feedstock is much better on farm 1 than it is on farm 2. This is a clear indication that farm 1 has better substrates or that their digesters are able to use the substrates more effectively. Also the two-stage digester on farm 1 might be better than the one-stage digestion on farm 2. This can also explain the big difference in biogas production per ton of feedstock.

14.2.3 Energy amounts from CHP

The farm 1 has higher biogas production thus it also has higher electricity production. Farm 1 is able to enhance its performance from January to February whereas farm 2 produces less electricity than the farm 1 from the beginning. But farm 2 also worsens its performance from January to February. The heat production follows the same pattern as the electricity production and is also bound to the biogas production.

14.2.4 Digester evaluation

Digester evaluation is based on two parameters: organic dry matter (ODM) conversion efficiency and specific methane production. On both parameters, farm 1 is working better than the farm 2.

ODM conversion efficiency is noticeably higher on farm 1 (around 80%) than on farm 2 (around 55%). This maybe consequence of many reasons: farm 2 shows signs of stress on many points as indicated on internal analysis in chapter 14.1.2. Also the digester type might have an effect and the health of the digester bacteria can affect ODM conversion efficiency.

Specific methane production is observably higher on farm 1 than on farm 2. This is caused by higher biogas production of farm 1 since there is not a big difference on organic dry matter content in feedstock.

14.2.5 Efficiency

All the calculated efficiencies are analysed in more detail in internal analysis in chapter 14.1.11 and 14.1.12. On efficiencies, both farms are on same scale as neither sells heat. On both farms, we have made an assumption that 10 % of the heat is lost and as our calculations are based on this assumption we were not able to make calculations on thermal efficiency. Electric efficiency is almost the same on both farms since the CHPs are almost as effective.

15 CONCLUSIONS

The most useful and practical parameters have been described in the theoretical and in the results part: electricity and heat usage in farm and CHP, sold heat, input measurements, pH, temperature in digester, hydraulic retention time, organic loading rate , reactor volume, volumetric flow rate of feedstock and VFA/TIC, organic dry matter, dry matter, biogas production, methane content, total electricity produced, "unavoidable" heat losses, potentially useful heat, digestate production, ODM in digestate, DM in digestate, nutrients: nitrogen and phosphate, biogas per reactor volume, methane production, energy in biogas, heating value of biogas, electricity production per total feedstock, ODM conversion efficiency, specific CH_4 production, electric efficiency, net electric efficiency and net total energy efficiency. These parameters are the most essential and descriptive when considering the digester and CHP functioning and all of these parameters can be used to compare farms.

Data should be measured as often as possible but a good guideline would be monthly. From there it is easy to calculate the daily amounts. For the monitoring table data were given in monthly periods. The data should be measured in the units that are defined in the results part. Also these units are shown in the monitoring table after the parameter.

The efficiencies are calculated as we have defined in the research question: output divided by input. Net electric or net total energy efficiencies would be more descriptive and comparable if the heat would be sold. Electric efficiency of the CHP is the most basic and essential efficiency parameter. For digester evaluation, the ODM conversion efficiency is important.

16 DISCUSSION

Basically we have tried to create a logical monitoring tool for co-digesters and by using that as a guideline made an overview on anaerobic digestion. At start, we gave a theoretical overview on the subject, presented the parameters and calculations, showed the result and based on those made the internal and external analysis. The used information is based on reliable sources and calculations were inspected by Mr. Jos Theunissen. Results appear to be in possible range and therefore indicate that the calculations are correct and the given data is realistic.

The monitoring tool is at the moment working and simple. In the future it could be developed to more detailed direction with wider range of calculated parameters. It eases the making of basic internal and external analysis. The analysis that we made revealed that the easiest way for the farms to enhance their efficiency would be selling heat. Also the analysis showed that the farm 2 has a stress process that affected its performance.

The monitoring tool can be upgraded to serve farm-scale co-digesters and help farmers to analyse and enhance their performance. This thesis can also give an up-to-date overview on the subject as information from many sources and countries is collected.

Van Hall Larenstein is planning, according to Mr. Xantho Klijnsma, to continue the monitoring table as student project in the near future. This could be done by adding financial section, thermal and other efficiencies. Since the farmers appreciate the economical aspect it would be extremely useful to calculate financial aspects. Possible continuing is also to explain farmers what data they should measure, how it is measured and how often it should be done. Also the cost of these measurements should be considered in economical aspect. It would also be important to test the monitoring table with real data from farms since we were not able to do so. It would be useful to consider other possible program than Excel to execute the monitoring table in order to accomplish more professional outcome.

BIBLIOGRAPHY

Braun, Rudolf, Weiland, Peter & Wellinger, Arthur 2010. Biogas from Energy Crop Digestion. IEA Bioenergy, Task 37- Energy from Biogas and Landfill Gas Publication, 01/2010. PDF-document. http://www.iea-biogas.net/Dokumente/energycrop_def_Low_Res.pdf No update information. Read 3.12.2010.

Braun, Rudolf & Wellinger, Arthur 2010. Potential of Co-digestion. IEA Bioenergy, Task 37- Energy from Biogas and Landfill Gas Publication. PDF-document. http://www.iea-biogas.net/Dokumente/Potential of Codigestion short Brosch221203.pdf No update information. Read 3.12.2010.

Brinton, Will 2006. Microbiological matrimony – compatibility of digestion and composting. BioCycle 09/2006. PDF -document. http://www.woodsend.org/pdf-files/BrintonSept.pdf No update information. Read 3.1.2011.

Chen Ye, Cheng Jay J. & Creamer, Kurt S. 2007. Inhibition of anaerobic digestion process: A review. PDF-document. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V24-4NCK272-3-1&_cdi=5692&_user=1084922&_pii=S0960852407001563&_origin=search&_coverDate=07%2F31%2F2008&_sk=999009989&view=c&wchp=dGLbVlW-zSkzS&md5=6bc3432dfb0665fa2bcd769ee1997a3a&ie=/sdarticle.pdf No update information. Read 28.11.2010.

Deutsche Gesellschaft fur Sonnenenergie ECOFYS (Firm) Staff 2004. Planning and Installing Bioenergy Systems : A Guide for Installers, Architects and Engineers. Earthscan Canada.

Evans, Gareth 2001. Biowaste and Biological Waste Treatment. United Kingdom: James & James (Science Publishers) Ltd.

Fachagentur Nachwachsende Rohstoffe 2009. Biogas – an introduction. German Federal Ministry of Food, Agriculture and Consumer Protection. PDF-document http://www.fnr-server.de/ftp/pdf/literatur/pdf_329-biogas---an-introduction_engl.pdf Updated January 2009. Read 3.1.2011.

Finkemeyer, Jörn 2007. Biokaasulaitosten kannattavuus Saksassa – analyysi seurantatutkimuksesta. Bachelor Thesis, Häme University of Applied Sciences. PDF-document. http://portal.hamk.fi/portal/page/portal/HAMKJulkisetDokumentit/Koulutus/Koulutusohjel-mat/maaseutuelinkeinot/Portletit/Maaseutuelinkeinojen_kon_portletit/Finkemeyer_J%C3%B6rn.pdf No update information. Read 29.11.10.

Finnish Biogas association 2010. Ympäristö. PDF-document. http://www.biokaasuyhdistys.net/index.php?option=com_content&view=category&layout=blog&id=55&Itemid=80 No date information. Read 2.12.2010.

Fischer, Torsten & Krieg, Andreas 2011. Planning and construction of biogas plants. PDF-document. http://www.kriegfischer.de/texte/planning%20and%20construction%20of.pdf. No date information. Read 3.1.2011.

Fothergill, S., & Mavinic, D.S. 2000. VFA production in thermophilic aerobic digestion of municipal sludges. Journal of Environmental Engineering.

Guo J., Li X.P., Xu P., Dong R.J. & Clemens J.2011. Process control and fluxes of medium size agricultural biogas plants management at ambient temperature: a case study in Beijing. PDF -document. http://www.ramiran.net/ramiran2010/docs/Ramiran2010_0279_final.pdf. No date information. Read 7.1.2011.

Hatsala, Antti & Raimovaara, Markku 2004. University of applied sciences of Häme. Biokaasun tuotanto- ja käyttömahdollisuudet Kanta-Hämeessä. PDF-document. http://midgard1.nebula.fi/attachment/ee246cbb04c1da363116122aebb56633/19264351e78bffbf4327fe0f8f522694/Biokaasun+tuotanto-+ja+hy%C3%83%C2%B6tyk%C3%83%C2%A4ytt%C3%83%C2%B6mahdollisuudet. No update information. Read 25.11.2010.

Hobson, Peter N. & Wheatley, Andrew D. 1993. Anaerobic digestion – Modern theory and practice. England: Elsevier science publishers Ltd.

IEA Bioenergy 2005. Biogas Production and Utilisation, Task 37 - Energy from Biogas and Landfill Gas Publication. PDF-document. http://www.iea-biogas.net/Dokumente/Brochure%20final.pdf. No update information. Read 3.12.2010.

Kangas, Ari 2009. Biokaasulaitoksen BAT ja ympäristölupa. Biokaasukoulutus. Lahti: Evira. PDF-document. http://www.evira.fi/attachments/kasvintuotanto_ja_rehut/lannoitteet/muut/koulutus_biokaasulaitokset.pdf No update information. Read 3.12.2010.

Kayser, Katrin & Backes, Katharina 2009. Optimizing Biogas Yield With Substrate Selection, BioCycleInternational.

Kirchmayr, Roland, Scherzer, Rudolf, Baggesen, Dorte L., Braun, Rudolf & Wellinger, Arthur 2003. Animal by-products and anaerobic digestion, Requirements of the European Regulation (EC) No 1774/2002, IEA Task 37 Energy from Biogas and Landfill Gas Publication. PDF-document. http://www.iea-biogas.net/Dokumente/IEA_ABP-Brochure_en_2.pdf No updateinformation. Read 3.12.2010.

Latvala, Markus 2009. Biokaasun tuotanto suomalaisessa toimintaympäristössä - Paras käytettävissä oleva tekniikka (BAT). Helsinki: Edita Prima Oy.

Likitalo, Heikki & Rissanen, Riitta 1998. Tutkimusmenetelmät – Menetelmätietoutta tradenomiopiskelijoille. Helsinki: Hakapaino Oy.

Liuksia, Saku 2009. Jätevesilietteen mesofiilisen mädätysprosessin muuttaminen termofiiliseksi. Master's thesis. Helsinki University of Technology. Faculty of Engineering and Architecture. WWW-document. http://civil.tkk.fi/fi/tutkimus/vesihuoltotekniikka/opinnaytteet/liuksia2009.pdf No update information. Read 22.11.2010.

Lukehurst, Clare T., Frost, Peter & Al Seadi, Teodorita 2010. Utilisation of digestate from biogas plants as biofertiliser. PDF-document. http://www.iea-biogas.net/Dokumente/Task37_Digestate_brochure9-2010.pdf No update information. Read 8.12.2010.

Luostarinen, Sari 2009. Biokaasuprosessi: prosessiin vaikuttavat tekijät ja eri teknologiat. Biokaasukoulutus. Lahti: Evira. PDF-document http://www.evira.fi/attachments/kasvintuotanto_ja_rehut/lannoitteet/muut/koulutus_biokaasulaitokset.pdf No update information. Read 24.11.2010.

Mash, George 2008. Rise of the Anaerobic Digester, Renewable Energy Focus. Volume 9. Issue 6, 11-12/2008.

Metaenergia Oy 2011. Biokaasu. WWW-document. http://www.metaenergia.com/biokaasu.htm No date information. Read 4.1.2011.

Mignone, Nicholas A. 2005. Biological inhibition/Toxicity control in municipal anaerobic digestion facilities. PDF-document http://www.awpca.net/Biological%20Inhibition.pdf. Updated 27.3.2005. Read 28.11.2010.

Monnet, Fabien 2003. An introduction to anaerobic digestion of organic wastes. Remade Scotland: Biogasmax. PDF-document. http://www.biogasmax.co.uk/media/introanaerobicdigestion__073323000_1011_24042007.pdf No update information. Read 8.12.2010.

Nag, Ahindra 2007. Biofuels Refining and Performance. India: McGraw-Hill Professional Publishing.

Novatech GmbH 2011. Biogas storage vessels. WWW-document. http://www.novatechgmbh.com/228.0.html?&L=1 No update information. Read. 3.1.2011.

Palva, Reetta, Alasuutari, Sakari & Harmoinen, Taina 2009. Lannan käsittely ja käyttö. Keuruu: Otavan kirjapaino Oy.

Rauhala, Anna-Maria & Tervo, Mari 2010. Mikkeli University of Applied Sciences. Degree programme of environmental engineering.

Riuji, Lohri Christian 2005. Research on anaerobic digestion of organic solid waste at household level in Dar Es Salaam, Tanzania, Bachelor Thesis, Zurich University of Applied Sciences, Switzerland. PDF-document. http://www.novaquatis.eawag.ch/organisation/abteilungen/sandec/publikationen/publications_swm/downloads_swm/anaerobic_digestion.pdf No update information. Read 3.1.2011.

Siemens Water Technologies 2011. Biogas storage. WWW-document. http://www.water.siemens.com/EN/APPLICATIONS/SLUDGE_BIOSOLIDS_TREATMENT/BIOGAS_STROAGE/Pages/default.aspx No date information. Read 3.1.2011.

Sinkko, Taija 2009. Pienen mittakaavan CHP-laitokset osana hiilineutraalia maaseutuyhteiskuntaa. Master's thesis. Lappeenranta University of Technology. Faculty of Technology. PDF-document. http://www.doria.fi/bitstream/handle/10024/44579/nbnfi-fe200903061225.pdf?sequence=3 No update information. Read 5.12.2010.

Soininen, Hanne, Kiukas, Iiro & Mäkelä, Leena 2007. Biokaasusta bioenergiaa eteläsavolaisille maaseutuyrityksille. Mikkeli: Mikkeli University of Applied Sciences.

Speight, James 2008. Synthetic Fuels Handbook. McGraw-Hill Professional Publishing.

Srinivas, T. 2008. Environmental Biotechnology. India: New Age International.

Sura, Juha-Pekka 2008. Erilliskerätyn biojätteen soveltuvuus biokaasun tuotantoon. Bachelor's thesis. PDF-document.

https://publications.theseus.fi/bitstream/handle/10024/12092/2008-05-13-08.pdf?sequence=1 No update information. Read 24.11.2011.

Tervahartiala, Hannu, 2007. Maatilan biokaasulaitoksen kannattavuus. Jyväskylä University. The Faculty of Economics. PDF-document. http://www.sentre.fi/mp/db/file_library/x/IMG/15719/file/Maatilanbiokaasulaitoksenkannattavuus_ILMES.pdf No update information. Read 5.12.2010.

Theunissen, Jos 2010, Docent milieutechnologie. Hogeschool Van Hall Larenstein, personal e-mails etc.

Verma, Shefali 2002. Anaerobic digestion of biodegradable organics in municipal solid wastes. Thesis. USA : Columbia University. PDF-document. http://www.seas.columbia.edu/earth/vermathesis.pdf No update information. Read 24.11.2011.

Wal, van der P., Shacklady, C. A., Barreveld, W.H., Burgers, A. C. J. , DaSilva, E., Hedén, C.-G., Scrimshaw, N.S. & Seshadn, C. V. 1979. Bioconversion of Organic Residues for Rural Communities. Japan: The United Nations University. WWW-document. http://unu.edu/unupress/unupbooks/80434e/80434E00.htm No update information. Read 24.11.2010.

Wall, J., Harwood, C. S. & Demain, A. L. 2008. Bioenergy. ASM Press.

Ward, A.J., Hobbs, P. J., Holliman, P. J. & Jones, D. L. 2008. Optimisation of the anaerobic digestion of agricultural resources: review. Bioresource Technology. Volume 99. Issue 17, 11/2008.

APPENDIX 1(1).

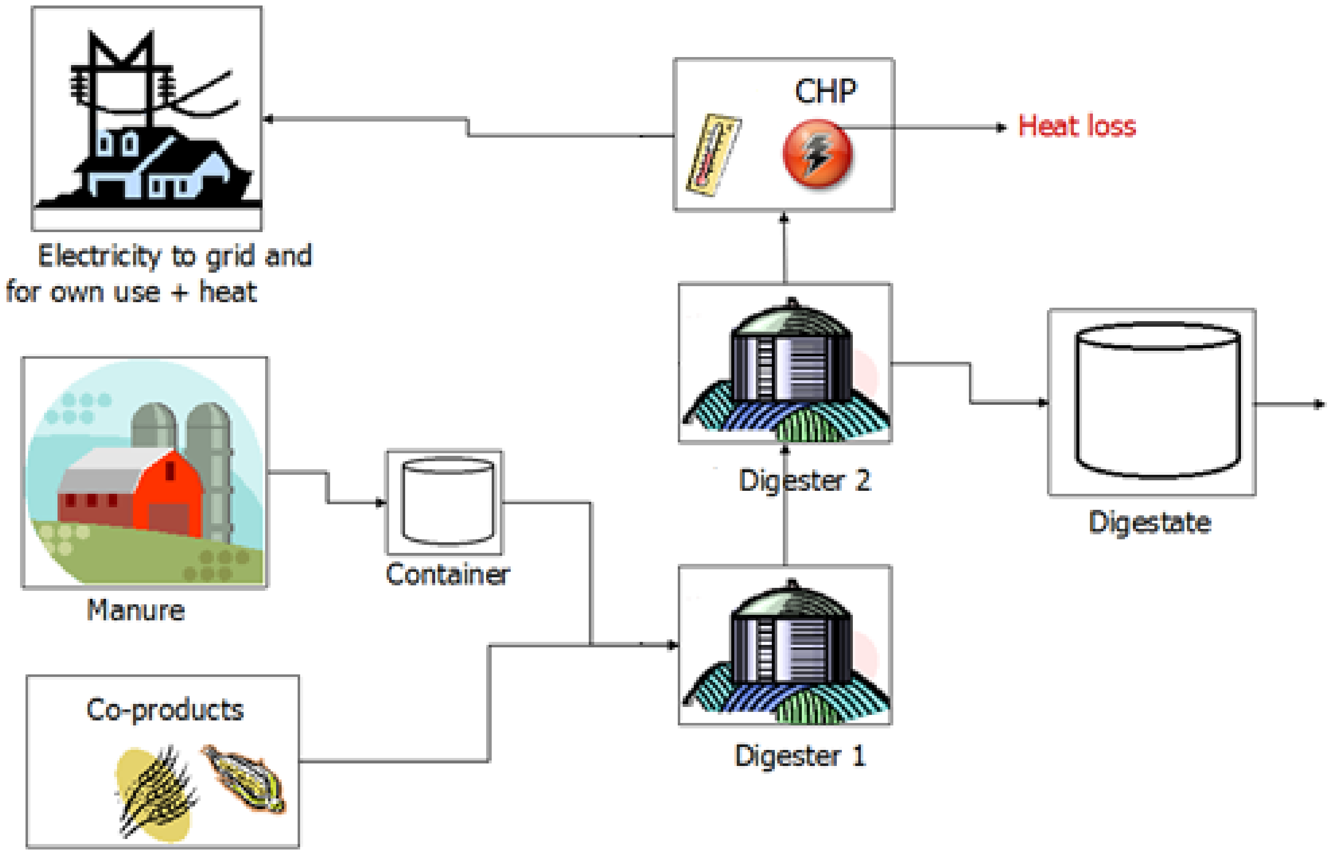
Monitoring table

General data

	Picture	Farm 1/ January		Farm 1/ February		Farm 2/ January		Farm 2/ February	
Name of the farm									
Date of start									
CHP									
CHP1	6	215	kW_{el}	215	kW_{el}	150	kW_{el}	150	kW_{el}
CHP2	6	175	kW_{el}	175	kW_{el}	150	kW_{el}	150	kW_{el}
Farm's own electricity and heat usage									
Direct electricity use in farm	7	2020	kWh/month	2120	kWh/month	1628	kWh/month	1180	kWh/month
Electricity used for digester	3,4	18230	kWh/month	18622	kWh/month	14250	kWh/month	13924	kWh/month
Direct electricity use in farm	7	7272	MJ/month	7632	MJ/month	5860,8	MJ/month	4248	MJ/month
Electricity for digester	7	65628	MJ/month	67039	MJ/month	51300	MJ/month	50126,4	MJ/month
Heat used in farm	7	26375	MJ/month	25430	MJ/month	16380	MJ/month	16730	MJ/month
Heat used for digester	3,4	324000	MJ/month	314650	MJ/month	224050	MJ/month	214570	MJ/month
Sold heat	7	0	MJ/month	0	MJ/month	0	MJ/month	0	MJ/month

APPENDIX 1(2).

Monitoring table



Overview of technical and measured information

	Limit/ optimum range	Farm 1/ January					Farm 1/ February			
Overview of used manure		Ton/d	Price [€/ton]	Price [€]	%	Picture	Ton/d	Price [€/ton]	Price [€]	%
Manure 1		19,8	0	0	50,4	1	22,5	0	0	50,2
Manure 2		0	0	0		1	0	0	0	
Total		19,8		0		1	22,5		0	
Overview of co-products		Ton/d	Price [€/ton]	Price [€]	%	2	Ton/d	Price [€/ton]	Price [€]	%
Substrate 1		15,5	29,5	456,8	39,3	2	18,2	29,5	537,3	40,6
Substrate 2		4,1	12	48,8	10,3	2	4,1	12,5	51,8	9,2
Substrate 3		0	0	0		2	0	0	0	
Substrate 4		0	0	0		2	0	0	0	
Total		19,5		505,5			22,4		589,1	
Total feedstock		39,4	ton/d			1+2	44,9	ton/d		

Farm 1		DIGESTER 1		DIGESTER 2			DIGESTER 1		DIGESTER 2	
Technical aspects		**January**	**Unit**	**January**	**Unit**		**February**	**Unit**	**February**	**Unit**
pH	6.0-8.0	6,5		7,2		3,4	6,5		7,2	
Temperature in digester	30°C-40 °C	38,6	°C	39	°C	3,4	38,8	°C	39,1	°C
Hydraulic retention time	25-40 days	31,7	d	31,7	d	3,4	27,8	d	27,8	d
Reactor volume		1250	m^3	1250	m^3	3,4	1250	m^3	1250	m^3
Flow rate		39,4	m^3/d	39,4	m^3/d	3,4	44,9	m^3/d	44,9	m^3/d
VFA/TIC	<0.3	0,37		0,14		3,4	0,33		0,12	
Organic dry matter (ODM)		6,2	ton/d	6,2	ton/d	3,4	7,0	ton/d	7,0	ton/d
Dry matter DM		7,2	ton/d	7,2	ton/d	3,4	8,3	ton/d	8,3	ton/d
Dry matter DM (% of total)		18 %		18 %		3,4	18 %		18 %	
Organic dry matter ODM (% of DM)		86 %		86 %			85 %		85 %	
Organic dry matter ODM (% of to-tal)		16 %		16 %			16 %		16 %	
Organic loading rate (OLR)	0.5-5$kg_{OM}/m^3/d$	4,93	$kg_{OM}/m^3/d$	4,93	$kg_{OM}/m^3/d$		5,63	$kg_{OM}/m^3/d$	5,63	$kg_{OM}/m^3/d$

APPENDIX 1(5).

Monitoring table

		Farm 1 /January					Farm 1/ February			
Overview of output										
Biogas production		3649	m^3/d			3,4	4178	m^3/d		
Gas composition						3,4				
- methane content		53 %				3,1	51 %			
Total electricity per month		217463	kWh/month	782867	MJ/month	6	226668	kWh/month	816005	MJ/month
Average electricity per day		7015	KWh/d	25254	MJ/d	6	8095	KWh/d	29143	MJ/d
"Unavoidable" heat losses	10 %	6923	MJ/d			6	7657	MJ/d		
Potentially useful heat per day		37054	MJ/d				39773	MJ/d		
Potentially useful heat per day [%]		54 %					52 %			
Digestate										
Digestate production		1060	ton/month			5	1075	ton/month		
Digestate production per day		34,2	ton/d			5	38,4	ton/d		
Dry matter (% of total)		7 %				5	7 %			
Organic dry matter (% of DM)		57 %				5	54 %			
DM		2,2	ton/d			5	2,6	ton/d		
ODM		1,3	ton/d				1,4	ton/d		
Nitrogen		4,8	g/kg				5,0	g/kg		
Phosphate		1,0	g/kg			5	0,9	g/kg		

Monitoring table

	Farm 2/ January				Farm 2/ February				
Overview of used manure	**Ton/d**	**Price [€/ton]**	**Price [€]**	**%**	**Ton/d**	**Price [€/ton]**	**Price [€]**	**%**	**Picture**
Manure 1	26,0	0	0	50,3	27,9	0	0	49,8	1
Manure 2	0	0	0		0	0	0		1
Total	26,0		0		27,9		0		1
Overview of co-products	**Ton/d**	**Price [€/ton]**	**Price [€]**	**%**	**Ton/d**	**Price [€/ton]**	**Price [€]**	**%**	2
Substrate 1	10,3	7,75	80	20	17,1	7,75	132,9	30,7	2
Substrate 2	15,3	40	612,9	29,7	10,9	40	435,7	19,5	2
Substrate 3	0	0	0		0	0	0		2
Substrate 4	0	0	0		0	0	0		2
Total	25,6		692,9		28,0		568,6		
Total feedstock	51,6	ton/d			55,9	ton/d			1+2

Farm 2 Technical aspects	DIGESTER 1 January	Unit	DIGESTER 1 February	Unit	
pH	7		6,3		3
Temperature in digester	39,1	°C	39	°C	3
Hydraulic retention time	57,2	d	52,8	d	3
Reactor volume	2950	m^3	2950	m^3	3
Flow rate	51,6	m^3/d	55,9	m^3/d	3
VFA/TIC	0,28		1,14		3
Organic dry matter (ODM)	6,8	ton/d	6,1	ton/d	3
Dry matter DM	8,2	ton/d	7,4	ton/d	3
Dry matter DM (% of total)	16 %		13 %		3
Organic dry matter ODM (% of DM)	82 %		83 %		
Organic dry matter ODM (% of total)	13 %		11 %		
Organic loading rate (OLR)	2,30	$kg_{OM}/m^3/d$	2,08	$kg_{OM}/m^3/d$	

Monitoring table

Overview of output	Farm 2/ January				Farm 2/ February				
Biogas production	2901	m^3/d			2595	m^3/d			3
Gas composition									3
- methane content	52 %				48 %				3
Total electricity per month	179250	kWh/month	645300	MJ/month	144909	kWh/month	521672	MJ/month	6
Average electricity per day	5782	KWh/d	20816	MJ/d	5175	KWh/d	18631	MJ/d	6
"Unavoidable" heat losses	5400	MJ/d			4477	MJ/d			6
Potentially useful heat per day	27785	MJ/d			21663	MJ/d			
	51 %				48 %				
Digestate									
Digestate production	1393	ton/month			1355	ton/month			5
Digestate production per day	44,9	ton/d			48,4	ton/d			5
Dry matter (% of total)	9 %				8 %				5
Organic dry matter (% of DM)	66 %				69 %				5
DM	4,2	ton/d			4,0	ton/d			5
ODM	2,8	ton/d			2,7	ton/d			
Nitrogen	6,0	g/kg			5,8	g/kg			
Phosphate	0,9	g/kg			0,9	g/kg			5

Calculation model

General evaluation

	Farm 1/ January		Farm 1/ February		Farm 2/ January		Farm 2/ February	
Biogas production per $m^3_{reactor}$	1,5	$m^3/(m^3_{reactor}d)$	1,7	$m^3/(m^3_{reactor}d)$	1,0	$m^3/(m^3_{reactor}d)$	0,9	$m^3/(m^3_{reactor}d)$
CH_4 production	1934	m^3/d	2139	m^3/d	1508	m^3/d	1251	m^3/d
Electricity production per total feedstock	178	kWh/ton	180	kWh/ton	112	kWh/ton	93	kWh/ton
Electricity production per total feedstock	641	MJ/ton	650	MJ/ton	403	MJ/ton	333	MJ/ton
Heating value of biogas	19,0	MJ/m^3	18,3	MJ/m^3	18,6	MJ/m^3	17,3	MJ/m^3
Energy in the biogas (E)	69231	MJ/d	76573	MJ/d	54001	MJ/d	44771	MJ/d
Energy in the biogas (E)	2146168	MJ/month	2144050	MJ/month	1674044	MJ/month	1253585	MJ/month

Digester evaluation

	Farm 1/ January		Farm 1/ February		Farm 2/ January		Farm 2/ February	
ODM conversion efficiency	80 %		80 %		59 %		55 %	
Specific CH_4 production	314	m^3/ton	304	m^3/ton	223	m^3/ton	204	m^3/ton

Efficiency

	Farm 1/ January	Farm 1/ February	Farm 2/ January	Farm 2/ February
CHP η_{el}	36 %	38 %	39 %	42 %
Net electric efficiency	33 %	35 %	35 %	38 %
Net total energy efficiency	35 %	36 %	36 %	39 %

Constant

Heating value (H_{CH4})	35,8	MJ/m^3

APPENDIX 1(10).

Monitoring table

Comparison between farms

	Farm1				Farm 2			
	January		February		January		February	
Name of the farm								
Technical aspects	Digester 1	Digester 2	Digester 1	Digester 2				
pH	6,5	7,2	6,5	7,2	7		6,3	
Temperature in digester	38,6°C	39°C	38,8°C	39,1°C	39,1°C		39°C	
Hydraulic retention time	63,5	d	55,7	d	57,2	d	52,8	d
Reactor volume	2500	m^3	2500	m^3	2950	m^3	2950	m^3
Flow rate	39,4	m^3/ton	44,9	m^3/ton	51,6	m^3/ton	55,9	m^3/ton
Feedstock	39,4	ton/d	44,9	ton/d	51,6	ton/d	55,9	ton/d
Overview of output								
Biogas production per $m^3_{reactor}$	1,46	$m^3/(m^3_{reactor}d)$	1,67	$m^3/(m^3_{reactor}d)$	0,98	$m^3/(m^3_{reactor}d)$	0,88	$m^3/(m^3_{reactor}d)$
CH_4 production	1934	m^3/d	2139	m^3/d	1508	m^3/d	1251	m^3/d
Gas composition								
- methane content	53 %		51 %		52 %		48 %	
Biogas production per ton of feedstock	92,6	m^3/ton	93,1	m^3/ton	56,2	m^3/ton	46,4	m^3/ton
Energy amounts from CHP								
Average electricity per day	7015	kWh/d	8095	kWh/d	5782	kWh/d	5175	kWh/d
Total electricity per month	217463	kWh/month	226668	kWh/month	179250	kWh/month	144909	kWh/month
Potentially useful heat per day	37054	MJ/d	39773	MJ/d	27785	MJ/d	21663	MJ/d

Monitoring table

Digester evaluation	Farm 1/ January		Farm 1/ February		Farm 2/ January		Farm 2/ February	
ODM conversion efficiency	80 %		80 %		59 %		55 %	
Specific CH_4 production	314	m^3/ton	304	m^3/ton	223	m^3/ton	204	m^3/ton
Efficiency								
CHP η_{el}	36 %		38 %		39 %		42 %	
Net electric efficiency	33 %		35 %		35 %		38 %	
Net total energy efficiency	35 %		36 %		36 %		39 %	