Master's Thesis

Feasibility study on the biogas production from organic wastes generated at the University of Jyväskylä

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TIIVISTELMÄ

Tutkielman tarkoituksena on tehdä kannattavuusanalyysi Jyväskylän yliopiston tuottamien biohajoavien jätteiden mädätykselle, joka tuottaisi biokaasua. Tavoitteena on arvioida Jyväskylän yliopiston jätehuollon tämän hetkistä tilannetta, suorittaa kannattavuusanalyysi biokaasulaitokselle ja tutkia eri vaihtoehtojen energiataseita, kasvihuonekaasupäästöjä ja mahdollisuutta vähentää päästöjä. Perustuen orgaanisten jätteiden kemiallisiin koostumuksiin ja metaanintuottopotentiaaleihin biokaasulaitos mallinnettiin erilaisilla vaihtoehdoilla. Ensimmäisessä vaihtoehdossa ainoa jätelajike on biojäte sekä yliopistolta että Kortepohjan ylioppilaskylästä. Toisessa vaihtoehdossa lisätään yliopistolla muodostunut puutarhajäte. Kolmannessa vaihtoehdossa hyödynnetään kaikki biohajoava jäte (eli bio- ja puutarhajäte, paperi ja kartonki) sekä biojäte Kortepohjasta.

Tällä hetkellä yliopistolla muodostuva biojäte kuljetetaan Mustankorkean kaatopaikalle kompostoitavaksi. Suurin osa yliopistolla muodostuvasta biojätteestä on ruokajätettä Sonaatti Oy:stä, joka omistaa yliopiston alueella olevat ravintolat ja kahvilat. Mädätykseen soveltuvaa jätettä muodostuu yliopistolla noin 491 tonnia vuodessa. Jätelajikkeista, jotka soveltuvat mädätykseen, suurin osa muodostuu paperista – noin 55%, seuraavaksi eniten muodostuu pahvia ja biojätettä (molempia noin 20 %) ja vähiten muodostuu puutarhajätettä – noin 5 % kokonaisjätemäärästä.

Vaihtoehdoista kolmas olisi kannattavin, jos mitta-asteikkona on energiantuotto, koska vaihtoehto tuottaa eniten biokaasua (211 173 m^3/vuosi). Ensimmäinen vaihtoehto hyödyntää vain biojätettä, jolla on suuri metaanintuottopotentiaali. Siksi vaihtoehdolla on suurin suhteellinen biokaasuntuotto, mutta määrällisesti ensimmäinen vaihtoehto tuottaa selvästi vähemmän biokaasua (noin 15 765-35 691 m^3/vuosi riippuen käytetäänkö Kortepohjassa muodostuvaa biojätettä) kuin kolmas vaihtoehto. Koska biojäte on ainoa jätelajike, joka vaatii pastoröinnin, ensimmäinen skenaario on hieman energiatehottomampi kuin muut. Kaikissa tutkituissa vaihtoehdoissa biokaasun tuottamat mahdolliset säästöt kasvihuonekaasupäästöissä ovat suuremmat kuin laitoksen aiheuttamat päästöt.

Biokaasulaitoksen tuottama sähkö- ja lämpöenergia ei pystyisi korvaamaan suuria osuuksia energian kokonaiskulutuksesta, koska Jyväskylän yliopisto kuluttaa suuren määrän energiaa suhteessa kohtuulliseen jätteentuottoon. Kolmannella vaihtoehdolla pystyttäisiin korvaamaan noin 1,3 % yliopiston energiatarpeesta verrattuna ensimmäiseen ja toiseen vaihtoehtoon, joiden korvausasteet jäisivät 0,07-0,2 %:iin.

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ABSTRACT

The aim of the study was to carry out feasibility study on the anaerobic digestion of organic wastes generated at the University of Jyväskylä for biogas production. The objectives of this study were to evaluate the current solid waste management at the University of Jyväskylä, to carry out the feasibility study for the biogas plant and to estimate the energy balance, greenhouse gas emissions and possible emission savings. Based on the chemical composition and methane potential of these organic wastes, biogas plant was designed with different Scenarios. In first Scenario, the only feedstock is biowaste produced in the University of Jyväskylä and Kortepohja Student Village. In second Scenario, the garden waste from the University premises is added. Third Scenario utilizes all biodegradable waste streams generated at the University of Jyväskylä and biowaste from Kortepohja Student Village.

At the moment the biowaste generated at the University is transported to Mustankorkea landfill to be composted. Most of the biowaste generated at the University is food waste from the Sonaatti Ltd, which owns the restaurants and cafeterias located in the University premises. The total amount of organic wastes in 2012 generated at the University of Jyväskylä was 491 tons per year. Among the waste streams suitable for anaerobic digestion, the paper waste has the biggest proportion – approximately 55 %, followed by cardboard and biowaste both with fraction of 20 % and garden waste with 5 %.

Scenario 3 would be the most feasible option if considering the energy production as the Scenario produced by far the most amount of biogas (211 173 m^3/year). As the Scenario 1 utilizes only biowaste with the highest methane potential, Scenario 1 has the highest biogas production per reactor size and per feedstock amount but volumetric amount (in Run 1 15 765 m^3/year and 35 691 m^3/year in Run 2) is much lower than in Scenario 3. As the biowaste is the only waste stream that requires pasteurization, the energy efficiency of the option is slightly lower than with those options that add other waste streams. All studied Scenarios have the potential to give higher greenhouse gas emission savings when biogas replaces fossil energy than the emissions the plant operations and transportations cause.

Since the University of Jyväskylä is a large institute with enormous energy consumption compared to moderate waste production, the energy produced by the biogas plant cannot reach high levels of replacement. The highest replacement level (1.3 %) could be reached with Scenario 3 in the University level while Scenarios 1 and 2 could reach from 0.07 % to 0.2 %.

Table of contents

ACRONYMS

ABP	Animal By-Product
AD	Anaerobic digestion
AHR	Anaerobic hybrid reactor
CHP	Combined heat and power
CSTR	Continuously stirred tank
EC	European Commission
EGSB	Expanded granular sludge bed
EU	European Union
EU-27	27 Member States of European Union by 30.06.2013 i.e. Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, United Kingdom, Austria, Finland, Sweden, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia, Bulgaria and Romania
GHG	Greenhouse gas
HRT	Hydraulic retention time
LCA	Life cycle analysis
MSW	Municipal solid waste
Mtoe	Million tons of oil equivalent
NCV	Net calorific value
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
SCOD	Soluble chemical oxygen demand
TS	Total solids
UASB	Up flow anaerobic sludge blanket
VAT	Value added tax
WEEE	Waste electric and electronic equipment
VFA	Volatile fatty acids
WHO	World Health Organization
VS	Volatile solids
VSS	Volatile suspended solids
WtE	Waste-to-Energy
WWF	World Wildlife Fund

GLOSSARY

Brown paper and cardboard	cardboard boxes, brown cardboard, kraft paper, paper bags and corrugated cardboard
Confidential material (paper)	paper waste that contains corporate secrets, such as contracts, memos, plans, invoices and vouchers
Energy waste	material that cannot be recycled but can be used in energy recovery such as plastic packaging, dirty papers and cardboards, wood packaging, plastic, Styrofoam, paper towels, clothes and textiles
Landfill waste	the rest of the waste after all recyclable and materials for utilization are separated away
Metal waste	metal scrap and packaging, tins, pipes, empty canisters, metal furniture, empty and pressure less aerosol containers and empty paint jars
Mixed glass	all empty and clean glass bottles and jars
Mixed paper	magazine and newspaper papers, commercials, brochures, colored paper, envelopes and recycled paper
Office paper	all white based papers produced in offices like prints and copies etc.
Recordings and films	include material with confidential contents such as personnel IDs, photos, DVDs, memory sticks, films, slides etc.

1 INTRODUCTION

Solid waste management system in Finland has been undergoing major changes during the last few decades. The obvious changes in the national legislation have been the requirement to comply with the European Union's (EU) legislation (Lohiniva et al. 2002) as the framework for waste legislation in EU is based on three Acts: waste framework directive (Directive 2008/98/EC) providing the general framework of waste management requirements, decision 2000/532/EC establishing the list of wastes and Regulation (EC) No 1013/2006 of the European Parliament and of the Council on shipments of waste (EU waste legislation, 2013). At the same time, Finland has implemented a renewable energy policy which aims to increase the use of biogas as a renewable energy source up to 0.7 TWh by year 2020 (Motiva, 2013). Thus, use of anaerobic digestion technology for simultaneous treatment of biowaste and production of renewable energy in the form of biogas would not only facilitate the waste management requirements but also enable achieving the renewable energy target in sustainable manner.

Application of anaerobic digestion (AD) process for treatment of organic fraction of municipal solid waste (OFMSW) has increased in Europe (Hartmann et al. 2004) from three plants in Europe with capacity of 87 000 tons per year in 1990 to 171 plants with digestion capacity more than 5 million tons per year in 2010 (European Bioplastics, 2010). The OFMSW is source separated and collected as a food waste and as a biowaste (Hartmann et al. 2004). Utilization of AD process is expected to grow due to several advantages of the process, for example recovery of energy and nutrients, but at the same time the performance of the process is highly dependent on the waste quality (Hartmann et al. 2004). The quality of the feedstock affects greatly the performance of the AD process, the technical feasibility as well as the possibility to use the effluent as a fertilizer (Hartmann et al. 2004).

In 27 Member States of European Union (EU-27), approximately 250 million tons of waste was generated in 2010 (Eurostat, 2013a) and in 2010 municipal waste generation was 507 kg per capita (Eurostat, 2013b). In EU area, the potential for separately collected biowaste is estimated up to 150 kg/inhabitant/year including kitchen and garden waste from households, park and garden waste from public estates and waste from food industry, from which 30 % is collected separately and treated biologically (Green Paper on the management of bio-waste in the European Union, 2008).

Waste management of biodegradable waste is important factor since biodegradable waste decomposes in landfills into a gas and if this gas is not collected, it will contribute considerably to greenhouse effect hence landfill gas mainly consists of methane (Green Paper on the management of bio-waste in the European Union, 2008) which is 21 times more powerful than carbon dioxide in terms of climate change effects in the 100-years' time horizon considered by the Intergovernmental Panel on Climate Change (IPCC, 2007). The methane releases from waste accounts for approximately half of the methane emissions from Finland and thus measures taken in this sector will have a strong effect on the total methane emissions (Lohiniva et al. 2002). Biological treatment, including AD, produces emissions, but from AD the emissions are lower than from composting and due to the energy recovery potential from biogas and soil improvement potential of digestate, AD may be the most environmentally and economically beneficial treatment technique (Green Paper on the management of bio-waste in the European Union, 2008).

In 2010, primary production of biogas in Europe was 10.9 Mtoe with an increase of 31 % compared to 2009 and from this biogas 27 % was produced in the landfill, 10 % from sewage sludge and 63 % in biogas plants (Foreest, 2012). According to Latvala (2009) approximately 130 million m^3 of biogas was produced in 2006 from landfills and biogas plants in Finland and from this 62 % was used in energy production. While the AD process is the most common in wastewater treatment plants in Finland, the centralized biogas plants seems to be getting more common in the future as they can utilize for example source separated biowaste, sludge from wastewater treatment and industrial processes, plant biomass and agricultural residues (Latvala, 2009). Even though institutes generate large amounts of organic wastes, AD plants are not installed for OFMSW treatment.

The aim of the study is to carry out feasibility study on the anaerobic digestion of organic wastes generated at the University of Jyväskylä for biogas production. Primary and secondary data on the amounts and characteristics of the biodegradable wastes such as foodwaste, garden waste and paper and cardboard generated on the campuses will be collected. Based on the chemical composition and methane potential of these organic wastes, biogas plant will be designed. Different scenarios on the use of biowaste alone or co-digestion with other substrates will be assessed. The potential of utilization of biogas for heat and electricity generation, the greenhouse gas (GHG) emissions as well as energy and mass balances will be estimated.

The main objectives of the thesis are:

- To evaluate the current solid waste management at the University of Jyväskylä.
- To carryout feasibility study to treat organic wastes generated at the University of Jyväskylä for biogas production.
- To estimate the potential energy balance and greenhouse gas emissions associated with the waste generation and biogas utilization.

2 BACKGROUND INFORMATION

In background information, the literature review regarding the three main themes of the thesis i.e., background theory about the waste management, composting and anaerobic digestion is presented. Composting is presented briefly as it is the current biowaste management method. Also in the background information, the University of Jyväskylä and Kortepohja Student Village are introduced.

2.1 Waste management

Costi et al. (2004) define waste management to be one of the priority issues concerning protection of the environment and conservation of natural resources. The main alternatives to treat collected municipal solid waste (MSW) are recycling, treatment in specific plants and landfill disposal, where within MSW management systems, several treatment plants and facilities can be found: separators, plants for production of refuse derived fuel, incinerators with or without energy recovery, plants for treatment of organic material and landfills (Costi et al. 2004). According to EU Directive on Waste (2008/98/EC) waste is defined as "any substance or object which the holder discards or intends or is required to discard". Waste management involves the collection, transport, recovery and disposal of waste and it includes the supervision of such operations and the after-care of disposal sites and waste management include actions taken as a dealer or broker (2008/98/EC).

EU Directive on Waste (2008/98/EC) has established waste hierarchy that the Member States must apply as a priority order in waste management. Hierarchy is as follows:

1. prevention;
2. preparing for re-use;
3. recycling;
4. other recovery, e.g. energy recovery and
5. disposal.

Biowaste is defined by the EU as: "biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants" (2008/98/EC). The total annual increase of biowaste in EU is estimated at 76.5-102 million tons food and garden waste included in mixed municipal solid waste and up to 37 million tons from food and drink industry (Green Paper on the management of bio-waste in the European Union, 2008). Waste management options for biowaste include prevention at source, collection, anaerobic digestion and composting, incineration and landfilling, where biowaste can be incinerated as part of MSW (Green Paper on the management of bio-waste in the European Union, 2008). Landfilling is the most common method for disposal of MSW in EU, while composting is the most common biological treatment option and may be classified as recycling when compost is used on land or for the production of growing media (Green Paper on the management of bio-waste in the European Union, 2008).

2.2 Composting

Tchobanoglous (2003) defines composting as the controlled biological degradation of organic matter in a warm, moist environment by bacteria, fungi and other organisms. Composting process usually occur in three basic steps: preprocessing, decomposition and stabilization of organic material and finally post-processing (Tchobanoglous, 2003). Hence composting is aerobic process, mixing is essential to prevent anaerobic conditions as odor problems in composting processes are often due to anaerobic conditions within the composting pile (Tchobanoglous, 2003).

In United States, there are three methods for composting: windrow, aerated static pile and in-vessel methods (Tchobanoglous, 2003) while in EU, the trend is to abandon open air windrow and to compost food waste and other fermentable feedstock using high technology systems which compost in-vessel (Eunomia, 2013). Most often composting is applied to garden waste, the organic fraction of MSW or the mixture of OFMSW and sewage sludge (Tchobanoglous, 2003). If the biowaste is composted, the methane release is avoided in the landfills (Lohiniva et al. 2002).

According to Tchobanoglous (2003) the end-product of composting is called compost, which is biologically stable and free of pathogens and plant seeds, and it improves soil moisture but unlike digestate from anaerobic digestion process, it is a poor fertilizer. So compost can be utilized in landscaping, landfill cover and animal litter or as an additive in fertilizer, as a fuel or in building materials (Tchobanoglous, 2003).

The main process parameters for composting are for example particle size, C/N-ratio, blending and seeding, moisture content, mixing/turning, temperature, control of pathogen, air requirements, pH, degree of decomposition and land requirement (Tchobanoglous, 2003). For pathogen control, The World Health Organisation (WHO) recommends that the compost attain a temperature of at least 60°C as most of the pathogens present cannot survive temperatures over 55-60 °C (Tchobanoglous, 2003).

2.3 Anaerobic digestion

AD is sustainable option for biowaste management and it produces valuable biogas to replace fossil fuels in various technical applications (Kymäläinen et al, 2012). AD can be classified as recycling when digestate is used same way as the compost, but anaerobic digestion can also be classified as energy recovery method i.e. waste-to-energy (WtE) technology (Green Paper on the management of bio-waste in the European Union, 2008).

AD is a complex process that requires completely anaerobic conditions and depends on the coordinated activity of a complex microbial association to transform organic material into biogas (Apples et al, 2008). AD process consists four phases (Figure 1): hydrolysis, acidogenesis, acetogenesis and methanogenesis (Apples et al, 2008). In hydrolysis step, both insoluble organic matter and high molecular weight compounds degrade into soluble organics substances, which is followed by acidogenesis in which the substrates formed during hydrolysis are further degraded (Apples et al, 2008). The third stage, acetogenesis, is where the higher organic acids and alcohols will be digested to produce acetic acid, carbon dioxide and H_2S, and finally the methanogenesis phase, which produces methane by two pathways: by splitting acetate into methane and carbon dioxide and by using hydrogen as electron donor and carbon dioxide as acceptor to produce methane (Apples et al, 2008).

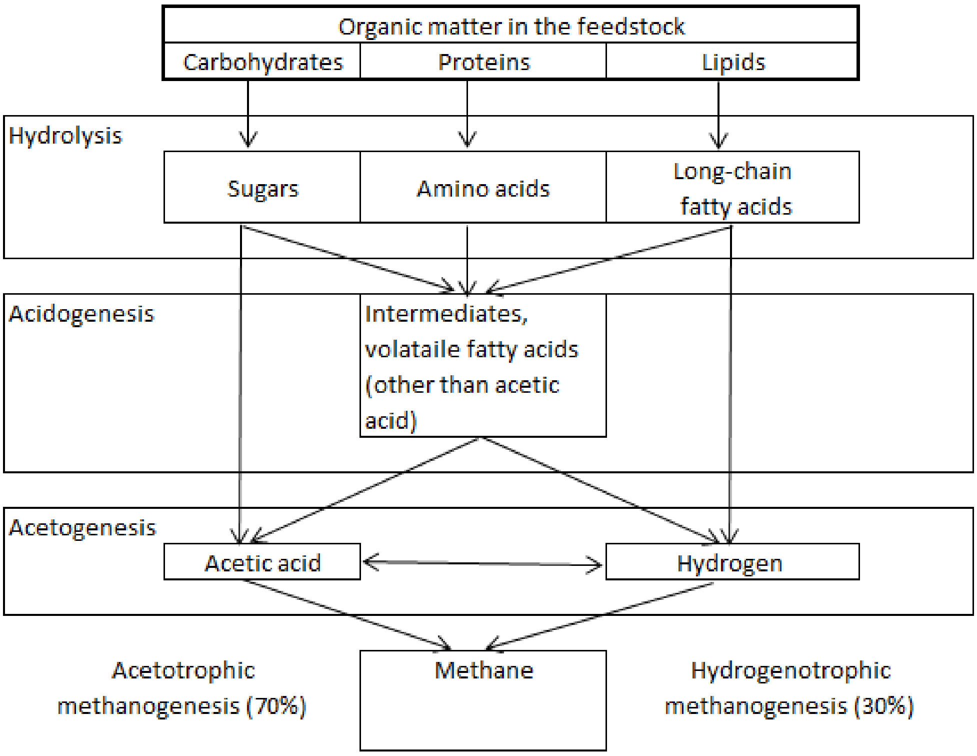

Figure 1: Anaerobic digestion and its four phases (Adapted from Latvala, 2009)

2.3.1 Factors affecting AD process

According to Apples et al. (2008), the main factors affecting the AD process are the pH, temperature, retention time, total solid and volatile solid content, dry matter content and organic loading rate. In every phase of AD process, there are different group of bacteria involved and each group of microorganisms have a different optimum pH range (Apples et al, 2008). Methanogenic bacteria are extremely sensitive to pH with optimum range of 6.5 and 7.2, whereas the fermentative bacteria are less sensitive for pH variations with optimum between 4.0 and 8.5 (Apples et al, 2008). The volatile fatty acids (VFAs) produced during the process decrease the pH level, but this reduction is normally countered by the activity of methanogenic bacteria producing carbon dioxide, ammonia and bicarbonate (Apples et al, 2008).

The process can be operated on different temperature ranges: from mesophilic conditions (approximately 35°C) to thermophilic conditions (ranging from 55°C to 60°C) (Kim et al. 2006). Temperature influences the growth rate and metabolism of microorganisms: increasing the temperature has several benefits including an increasing solubility of the organic compounds, enhanced biological and chemical reaction rates and in thermophilic conditions increasing death rate of pathogens (Apples et al. 2008). Thermophilic conditions may also lead to higher biogas yield but thermophilic process is more sensitive to environmental changes (Kim et al. 2006). Temperature also affects the moisture content of the biogas: the moisture content increases exponentially with temperature (Demirbas, 2004).

Organic loading rate (OLR) measures the biological conversion capacity of the process and it is an important parameter in continuous processes, since feeding the process above its sustainable OLR will lead to accumulation of inhibiting substances (Monnet, 2003). Maximum OLR depends on a number of parameters, such as reactor design, feedstock characteristics, activity etc. (Demirbas, 2009). For typical biogas plant the OLR is approximately 3-9 kgVS/m^3/d (Latvala, 2009).

The hydraulic retention time (HRT) refers to the average time the liquid sludge is held in the digester (Apples et al, 2008). The retention time depends on the process type, temperature and feedstock (Monnet, 2003). HRT varies between 15 to 30 days for mesophilic process and 12 to 14 days for thermophilic process (Monnet, 2003). Longer HRT results in higher degradation of the organic matter and higher yield of biogas, but it also increases the demand for heating and mixing and raises the investment costs due to increase in reactor size (Latvala, 2009). On the other hand, too short HRT may cause the process to overload and the biogas yield may decrease as the degradation of organic matter will not be in desirable levels (Latvala, 2009).

Gallert et al. (2003) defined the AD process by dry matter content as the process can either be a wet or dry fermentation system. For wet fermentation, the dry matter content is adjusted to 8-16 % by addition of process water (Gallert et al. 2003). If circulated process water is used to dilute the wet fermentation, salts and ammonia may accumulate to inhibitory levels (Gallert et al. 2003).

2.3.2 Feedstock

The biogas yield from the feedstock is dependent on the composition of the waste in terms of the biodegradable fractions: food waste will lead to high biogas yield but can also lead to ammonia toxicity whereas garden waste will have lower biogas yield due to higher lignin and hemicellulose content (Hartmann et al. 2004). Since the main feedstock in this study is biowaste (i.e. mainly food waste from catering and kitchens), its use is regulated by The European Commission (EC) Regulation No 1774/2002, also known as ABP-Regulation. According to Kirchmayr et al. (2003) ABP stands for Animal-By-Product, which means all bodies or parts of animals and products of animal origin not intended for human consumption, because either they are not fit for human consumption or there is no market for them as a foodstuff. Catering food waste belongs to the Category 3 in ABP-Regulation, so it can be processed in biogas plant equipped with a hygienisation unit which cannot be bypassed (Kirchmayr et al. 2003). Thermophilic process fulfills the hygienisation demands, but in mesophilic process the hygienisation is conducted with hygienisation unit with 70°C temperature with retention time of 1 hour (Latvala, 2009). If the digestate will be incinerated or it will be taken to landfill, the hygienisation may not be required (Latvala, 2009).

Thorin et al. (2012) suggests that in AD process a pre-treatment for the feedstock can be used in order to enhance the biogas yield by making the material more accessible to the microorganisms involved in the process. The possible increase in biogas production with pre-treatment is dependent on the pre-treatment method and material to be treated, but usually reduction of particle size has been found to enhance the biogas yield (Thorin et al. 2012).

Various compounds can inhibit the AD process and these inhibiting compounds can either be present in the feedstock or generated during the process (Apples et al, 2008). Ammonia is produced during degradation of nitrogenous matter (proteins and urea) and can be present as free ammonia and ammonium, and from the two, the free ammonia might be more toxic (Apples et al, 2008). Various cationic elements are found from the digester sludge and although those elements are required for microbial growth, they can be inhibitive in high concentrations (Apples et al, 2008).

2.3.3 Biogas

The end-product gas produced in the anaerobic process is called biogas and it mainly consist of methane, carbon dioxide and small amounts (less than 2 %) of oxygen, nitrogen, moisture, organic compounds and particles (Latvala, 2009). Biogas can be used basically in all applications that were developed for natural gas; hence the four basic ways of biogas utilization are production of heat and steam, electricity (co)generation, use as a vehicle fuel and production of chemicals (Apples et al, 2008).

In combined heat and power (CHP), the biogas will first go through moisture removal process and from there it goes to gas motor that rotates electricity producing generator as shown in the Figure 2 (Latvala, 2009). In this thesis, the main focus will be on utilization of CHP.

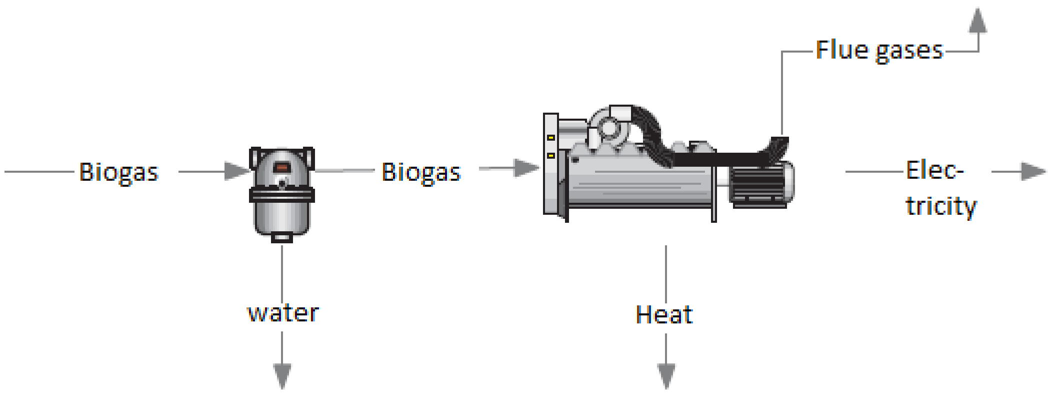

Figure 2: Working principle of combined heat and power (CHP) plant (adapted from Latvala, 2009)

Biogas losses occur at digesters, particularly in the gas storage. Murphy et al. (2004) estimate, that 6 % of the biogas is lost in the digester/biogas storage system. If there is methane (CH_4) upgrading system its losses would be 1.5 % (Murphy et al, 2004).

2.3.4 Digestate

Al Seadi & Lukehurst (2012) states that the digestate from biogas plants is rich in plant nutrients and it has excellent fertilizer qualities and thus has great potential to be used instead of mineral fertilizers, which have negative environmental impacts caused by use of fossil fuels, and as their natural reserves are declining. If digestate is intended as a biofertilizer, attention needs to be paid to the quality of digestate and the feedstock supplied to the plant (Al Seadi & Lukehurst, 2012). Utilization of digestate as a fertilizer is limited by the heavy metal content and organic pollutants in the digestate, as the digestion process is unable to degrade all chemical contaminants in the feedstock; hence the only way to produce high quality digestate is to use feedstocks which do not contain unwanted impurities (Al Seadi & Lukehurst, 2012). Digestate from food processing feedstocks is generally high quality product which can be used as a fertilizer as normally human food chain feedstock is low in chemical impurities but trace elements, which are necessary nutrients for healthy life, are present in food waste (Al Seadi & Lukehurst, 2012). However, these trace elements may become toxic when accumulated and reaching toxic levels (Al Seadi & Lukehurst, 2012).

The Finnish Act on nitrogen emissions from agriculture to water bodies (931/2000) regulates that if digestate is used as a fertilizer, the land application cannot exceed the rate of 170 kg of nitrogen per hectare per year and it cannot be spread between 15th of October and 15th of April or when there is a snow cover. Also fertilizer use is forbid in a distance of 5 m from water body (931/2000).

2.3.5 Plant design

Generally there are four basic components in an anaerobic digestion plant (Karellas et al. 2010):

1. a pretreatment module;
2. the digester;
3. the gas treatment and utilization; and
4. the solids-treatment line for the digestate.

According to Latvala (2009) pretreatment and feedstock receptions technical solutions are significant for the optimized operation of the plant as well as for the environmental issues since the possibility for odor emissions is increased in the reception phase. Pretreatment is required for the efficiency and optimization of the plant operation and to meet the demands of legislation (Latvala, 2009).

The reactor designs can be divided with many different ways: based on temperature, solid content or to single-stage, multi-stage and batch reactors (Monnet, 2003). The conventional method is to have the acid-forming and the methane-forming microorganisms in the same single reactor (Demirel & Yenigün, 2002). This causes the need for delicate balance because the different microorganism groups differ in their requirements for nutrients, in terms of physiology, growth kinetics, sensitivity and environmental requirements (Demirel & Yenigün, 2002). Thus one option is to physically separate acid-formers and methane-formers in two separate reactors (Demirel & Yenigün, 2002).

Demirbas (2009) states that the most widely used systems are granular sludge-based bioreactors, such as the up flow anaerobic sludge blanket (UASB), the expanded granular sludge bed (EGSB) and the anaerobic hybrid reactor (AHR). The UASB reactor has been widely used to treat wastewaters because it exhibits positive features such as high organic loadings, low energy demand, short HRT, long sludge retention time and little sludge production (Demirbas, 2009). The EGSB reactor is promising version of UASB operated at high superficial up flow velocities, obtained by means of high recycling rates, biogas production and elevated height/diameter ratios (Demirbas, 2009). Typical reactor type for single-stage low solids process is the continuously stirred tank reactor (CSTR) (Monnet, 2003). According to Demirbas (2009) stable CSTR operation requires HRTs of 15-30 days. Because of the slow growth rates of bacteria, reduction of HRT in CSTRs may cause washout of active biomass with consequent process failure i.e. short-circuiting (Demirbas, 2009).

2.3.6 Design parameters

Apples et al. (2008) suggests that the digestion tank can be designed based on certain volume (m^3) per capita, but this should only be used as a preliminary basis since it presumes constant values for different parameters such as solids removal efficiency. Common method for defining the digester volume is the volatile suspended solids (VSS) loading rate, but also the digester volume can be based on solids retention time thus the digestion process is a function of the time required by the micro-organisms to digest the organic matter and to reproduce (Apples et al, 2008).

According to Apples et al. (2008) most reactor designs acquire proper mixing to provide intimate contact between the feedstock and active biomass and to yield uniformity of temperature and of substrate concentration throughout the digester. Mixing also prevents both the formation of surface scum layers and the deposition of sludge on the bottom of the tank (Apples et al, 2008). Natural mixing is caused by rise of the gas bubbles and thermal convection currents created by addition of heated sludge (Apples et al, 2008). Natural mixing occurs always but usually is not sufficient alone for an optimum performance, hence auxiliary mixing is required in the form of external pumped recirculation, mechanical mixing or gas mixing (Apples et al, 2008).

2.3.7 Modelling of AD process

The optimization and modelling of AD process can estimate the retention time, reactor volume, gas production and composition for a requested system performance or investigate the sensitivity of the system performance or to provide cross-checking of simulation results and plant performance (Apples et al, 2008).

According to Apples et al. (2008) most simple models are based on a single rate-limiting step, which can be dependent on various parameters such as feedstock characteristics, hydraulic loading and temperature. Depending on the model, different phases of AD process can be considered as a limiting factor: some consider the acetogenic methanogenesis, other the conversion of fatty acids and some the hydrolysis of biodegradable suspended solids (Apples et al, 2008). By modelling the plant operations and the biogas production, it might be possible to increase the biogas yield since the controlling of the plant enhances and thus the plant operations are optimized (Thorin et al. 2012).

2.3.8 Emissions

According to Latvala (2009) the digestate is significantly more odor-free than untreated feedstock, especially if the feedstock in question is wastewater sludge. But if disturbances occur, there is a possibility for odor emissions, greenhouse gas (GHG) emissions and emissions of dangerous gases for human health from the biogas plant (Latvala, 2009).

Biogas plant itself as a process type is decreasing gaseous emissions to environment since untreated organic material will in uncontrolled degradation release GHG emission directly to atmosphere, but in biogas plants the gases are collected (Latvala, 2009). If biogas is used for energy production, the effect on emissions occurs in two pathways: it decreases greenhouse gas emissions itself but also it usually decreases the use of fossil fuels (Latvala, 2009).

Latvala (2009) states that especially the mechanical and thermal drying of the digestate has the potential to release odor emissions, thus the treatment should be done in closed spaces equipped with odor control systems. Odor emissions are also possible from transportation of the feedstock to the plant, transferring the feedstock into the process and during the storing and utilization of digestate (Latvala, 2009). Also the way how feedstock is transferred to the reactor affects the odor emissions: if there is turbulence in the feedstock, the higher the possibility for odor emissions (Latvala, 2009). The odor emissions can be treated with biofilter, active carbon filters, water scrubbing, ozone systems or combinations of these and one possibility is also direct the odor gases to CHP-unit as part of the intake air (Latvala, 2009).

2.4 University of Jyväskylä

University of Jyväskylä has approximately 15 000 students and 2 600 members of personnel (JYU, 2012). Located in Central Finland in the city of Jyväskylä, the University has seven faculties: The Faculty of Humanities, Information Technology, Education, Sport Sciences, Mathematics and Sciences, Social Sciences and the Jyväskylä School of Business and Economics, with three main campus (Seminaarinmäki, Mattilanniemi and Ylistönrinne) and services also at Ylistönmäki in Jyväskylä (JYU, 2012).

University of Jyväskylä signed with WWF (World Wildlife Fund) 18th of June 2012 Green Office agreement with the aim to achieve University of Jyväskylä the Green Office diploma. WWF's Green Office –environmental management system for offices is a managing tool for environmental issues that targets to lower the ecological footprint and decreasing the carbon emissions (JYU Green Office, 2013). The major environmental impacts of University of Jyväskylä involve the energy and water consumption in the campuses, waste production and recycling habits, transportation between and outside of the campuses and the investments the University does (JYU Green Office, 2013).

Among the three main campuses, Seminaarinmäki (Figure 3) is the biggest campus with an area of approximately 20 hectares; Mattilanniemi and Ylistönrinne both have an area of approximately 5 hectares (Tikkanen, 2012). The main vegetation in all campuses is grass, trees, bushes and flower plantings (Tikkanen, 2012). The buildings, where University of Jyväskylä operates, are rented mainly from the SYK Ltd (University Properties of Finland Ltd), and additionally University of Jyväskylä operates in building rented from the Student Union of the University of Jyväskylä, Technopolis Ltd, Capman RE II and Aberdeen (Vänttinen, 2012).

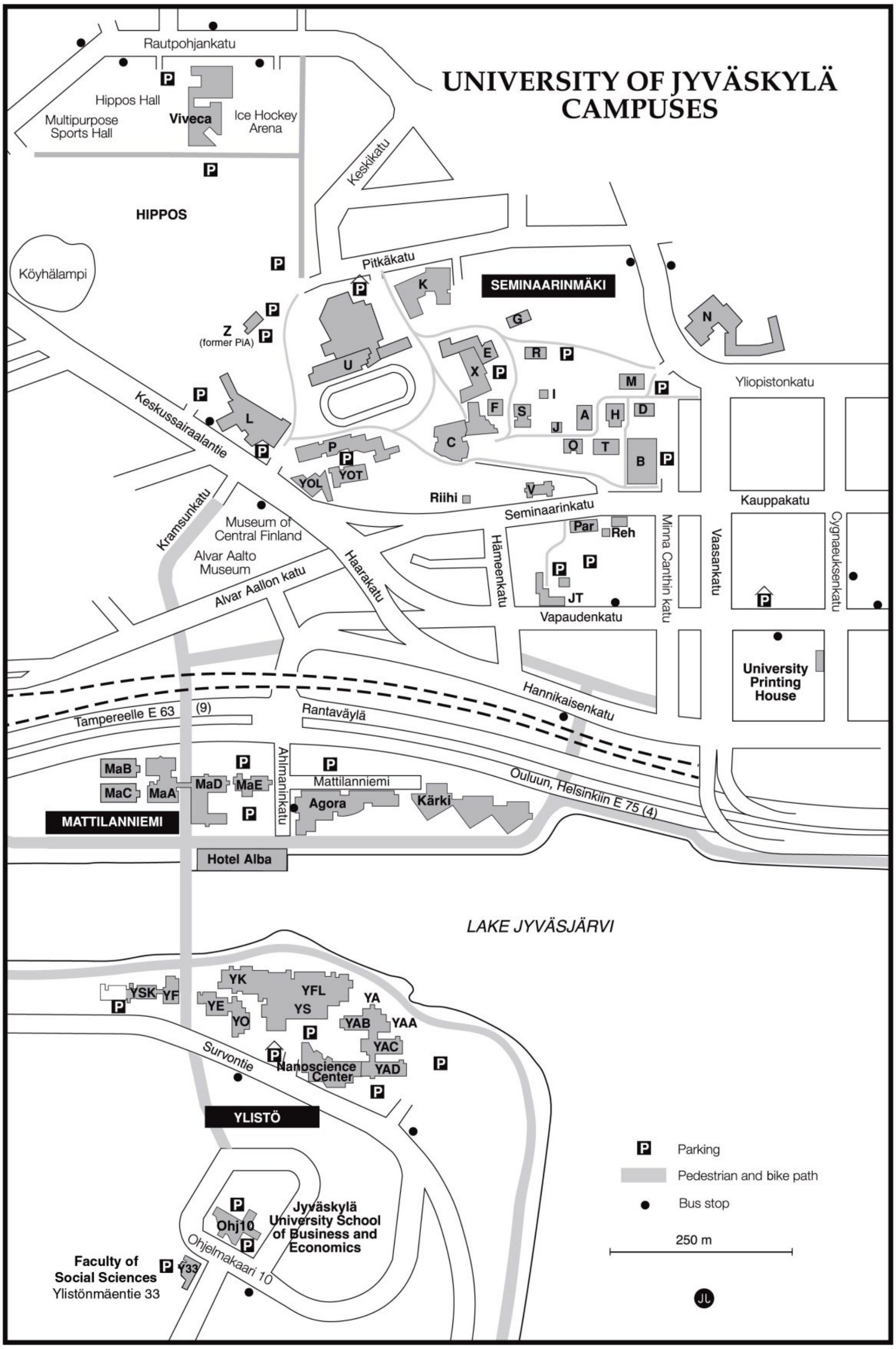

Figure 3: The campuses of University of Jyväskylä (www.jyu.fi)

2.4.1 Sonaatti Ltd

Established in 1997, Sonaatti Ltd offers restaurant and cafeteria services for the University of Jyväskylä and for its students, personnel and visitors and is owned by University of Jyväskylä, Student Union of University of Jyväskylä and Fazer Food Services Ltd

(Sonaatti Ltd, 2012). Sonaatti Ltd has six restaurants (Aallokko, Alvari, Lozzi, Café Libri, Musica and Syke) in Seminaarinmäki Campus, two restaurants (Piato and Wilhelmiina) in Mattilanniemi Campus and three restaurants (Ylistö, Kvarkki and Hestia) in Ylistönrinne and Ylistönmäki Campuses (Sonaatti Ltd, 2012). The locations of the restaurants and cafeterias are shown in Figure 4. So overall, there are five restaurants that prepare and sell food while other five cafeterias only sell food on the University campuses. For example, restaurant Ylistö served 127 120 lunch customers in the year 2012 (Table 1) (Vilppunen, 2013). Altogether the restaurants in the all campuses served 670 824 lunch customers in 2012 (Maijala, 2013).

Table 1: Monthly customers in Ylistö restaurant 2012 (Vilppunen, 2013)

Month	Number of lunch customers
January	11 520
February	12 434
March	12 108
April	10 002
May	10 792
June	7 407
July	6 132
August	7 742
September	12 519
October	14 764
November	14 550
December	7 159

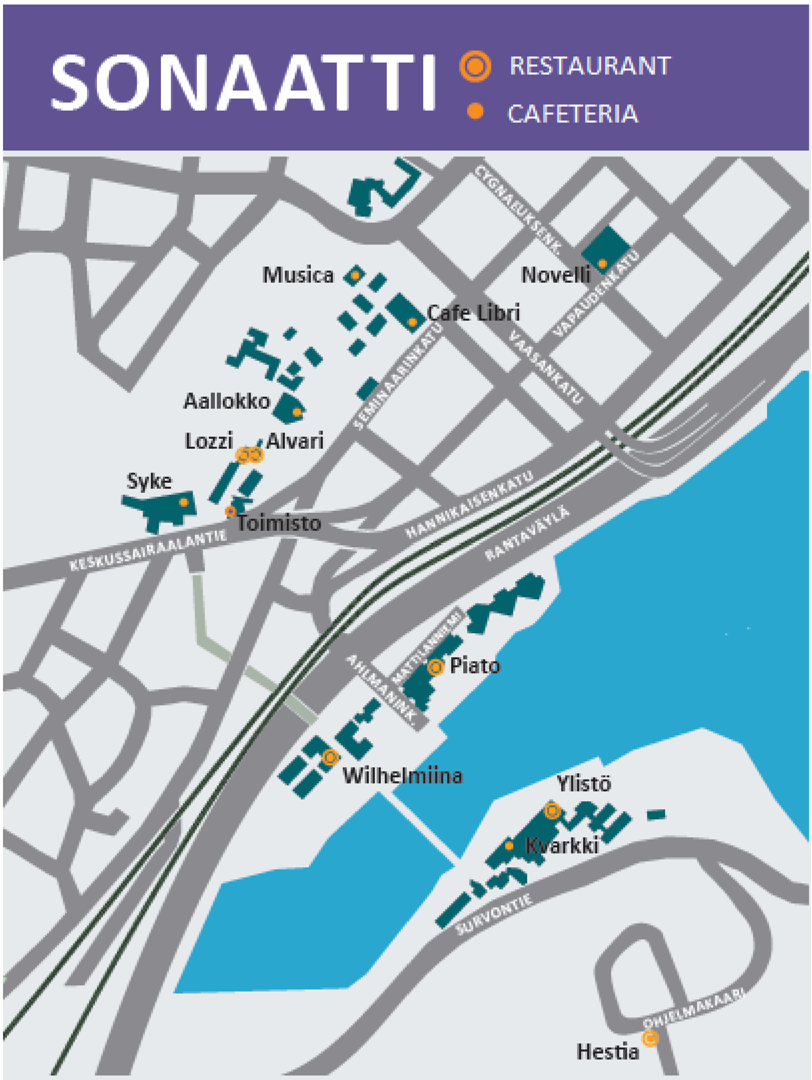

Figure 4: The locations of Sonaatti restaurants and cafeterias in University campuses (www.sonaatti.fi, altered)

2.5 Kortepohja Student Village

In the thesis, the source separated biowaste generated in Kortepohja Student Village was also utilized. The Kortepohja Student Village is owned by the Student Union of the University of Jyväskylä and its aim is to ensure that the students of the University of Jyväskylä could live close to the University, in an environment supporting their studies in a community formed by the students (Kortepohja, 2013). The official opening of the Student Village was at 1976 and it is situated in the Kortepohja district, approximately 2.5 kilometers from the city center (Kortepohja, 2013). The Student Village consists of 17 buildings and offers accommodation for 1 860 residents in 1 380 apartments (Pihlajasaari, 2013).

3 MATERIALS AND METHODS

In this section, information regarding the data collection, the baseline situation and the methods used to carry out the feasibility study are presented. In the baseline situation, the current waste management and waste generation are reviewed and energy consumption is presented. In the methods, both the basic and model calculations are presented. In addition, the anaerobic digestion modelling for the studied scenarios are presented. The data collection for this thesis can be divided into three sources: primary data, secondary data and literature review. The primary data means the data collected or obtained directly from the source, for example information about garden waste is directly from the company responsible (Total Ltd). The secondary data refers to the information obtained from the middleman. For example, information from the environmental coordinator of the University (Mr. Veli-Heikki Vänttinen) and the data on the chemical composition of food waste (Mr. Jari Koponen).

3.1 Baseline situation

3.1.1 Waste management in the University of Jyväskylä

The waste management of University of Jyväskylä is handled by several companies on contract basis, mainly by Lassila & Tikanoja Ltd. The waste management and recycling principles of Lassila & Tikanoja Ltd are presented in Figure 5. Lassila & Tikanoja Ltd handles the wastes generated in buildings rented from the University properties of Finland (SYK Ltd) (Vänttinen, 2012). Waste generated in buildings rented from other companies is difficult to estimate hence the buildings have additional companies operating in them and waste generated can only be estimated by the building level, not the company level (Vänttinen, 2012). Thus, those wastes are excluded from the scope of the thesis and only waste generated at the three main campuses are counted. Garden waste is handled by company called Total Ltd (responsible for the gardening in the University campuses).

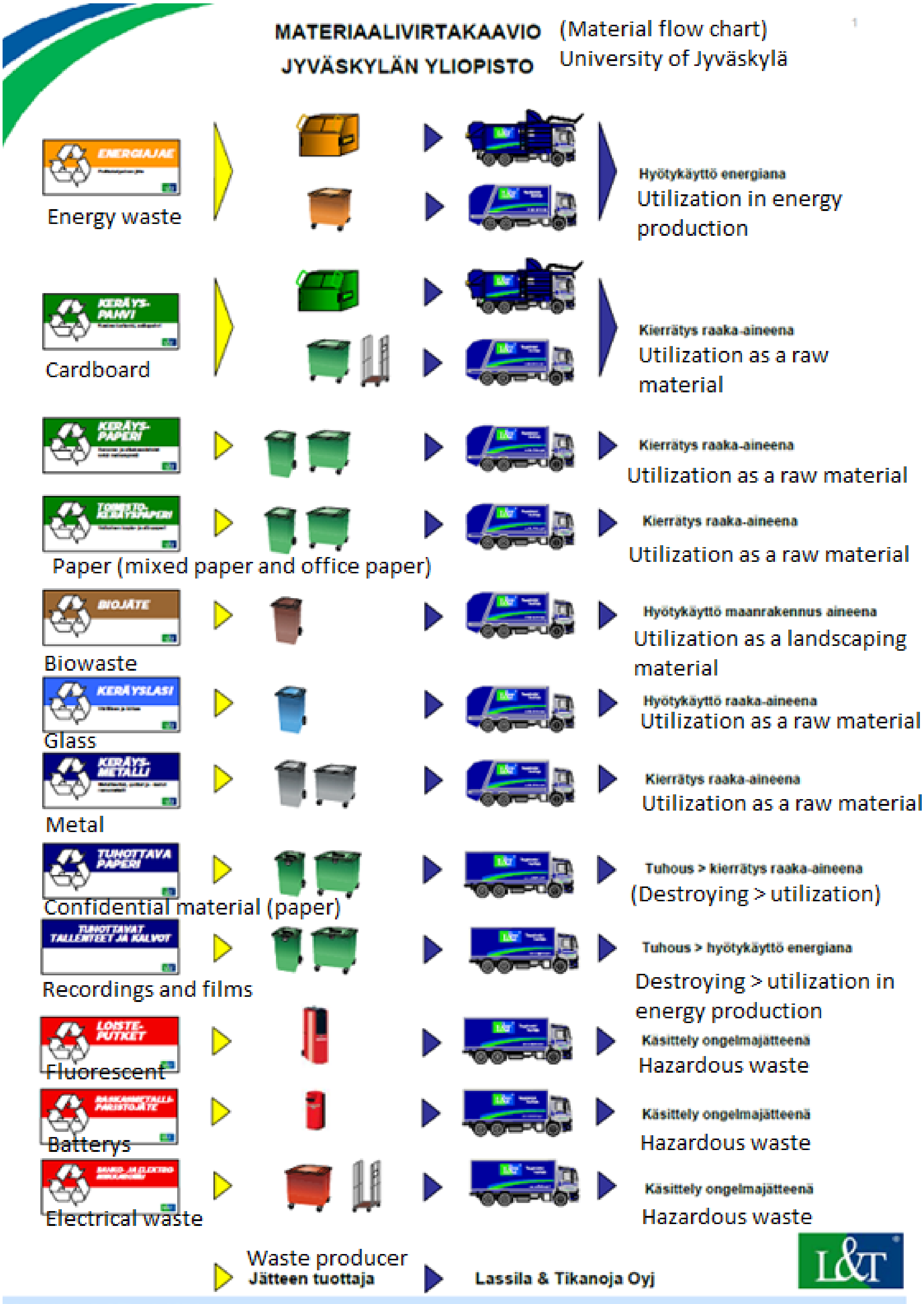

Figure 5: Lassila & Tikanoja Ltd waste management flowchart in the University of Jyväskylä (Joensuu, 2013. Altered)

3.1.2 Biowaste generation in the University of Jyväskylä

The biowaste produced in the University of Jyväskylä can be divided into three categories: the biowaste from offices, personnel break rooms, hallways, etc. and the biowaste from the Sonaatti restaurants which can be divided into kitchen and restaurant waste. Kitchen waste is the waste generated at the kitchen before and during food preparation and it mainly contains fruits and vegetables. On the hand, restaurant waste is the waste the customers through away after each meal (food remains, paper, bread etc.). During three weeks period, the amount of kitchen and restaurant waste generated and number of customers per day collected from a representative cafeteria in the University (Table 2).

Table 2: The daily amounts of restaurant and kitchen waste generated at the Ylistö restaurant along with the number of customers per day during 3 weeks period (Koponen, unpublished)

Date	Number of customers	Amount of kitchen waste (kg)	Amount of restaurant waste (kg)
Week 1			
24.9.2012	165	6	9
25.9.2012	231	11	15
26.9.2012	330	6	14
27.9.2012	310	14	24
28.9.2012	210	5	12
Week 2			
1.10.2012	261	16	16
2.10.2012	252	10	11
3.10.2012	390	9	21
4.10.2012	334	11	20
5.10.2012	204	17	14
Week 3			
8.10.2012	292	16	15
9.10.2012	48	12	10
10.10.2012	347	11	18
11.10.2012	335	14	17
12.10.2012	205	16	25
Week 4			
15.10.2012	72	16	14
16.10.2012	235	25	17
17.10.2012	313	6	13
18.10.2012	215	5	12
19.10.2012	230	6	10

Koponen (unpublished data) analyzed for his thesis the kitchen and restaurant wastes generated at the Ylistö restaurant (Table 3). In all parameters, clear difference can be noticed between the two waste streams.

Table 3: Ylistö food waste analysis (Koponen, unpublished data)

	Kitchen waste	Restaurant waste
pH	5.3	5.1
TS (w%)	16.6	28.6
VS (w%)	15.5	27.5
VS (% of TS)	93.4	96.1
SCOD (mg/l)	17.7	24.3

3.1.3 Biowaste management in Kortepohja Student Village

According to Pihlajasaari (2013), Kortepohja Student Village is divided to four waste management areas and the biowaste is collected once a week from three areas and fortnightly from one area. Biowaste amount is a rough estimate since it is not weighed and the emptying is based on predetermined schedule (Pihlajasaari, 2013). If the containers would be full every time they are emptied, the amount of biowaste would be 36.0 m^3 per month. In reality, the containers are probably about 70-80 % full when they are emptied and thus the amount of biowaste would be approximately 25.2-28.8 m^3 per month (Pihlajasaari, 2013). This would correspond to 302.4-345.6 m^3 per year. As there is no accurate data on the amount of biowaste generated, it is calculated based on the per capita biowaste generation of 67 kg in Finland during 2011. This per capita biowaste generation in Finland was calculated based on 362 764 tons of source separated biowaste generated (Statistics, 2011a) by 5 401 267 people (Statistics, 2011b) in Finland during 2011. Thus, with approximately 1 860 habitants, the biowaste generation in Kortepohja Student Village is approximately 124.6 tons per year.

In the Student Village, waste is collected in deep collection containers made by Molok Ltd (Figure 6). There are 13 containers for mixed waste (each one 5 m^3), 9 containers for biowaste (each one 1.3 m^3), 4 containers for glass (each one 1.3 m^3), 5 containers for metals (each one 1.3 m^3), 7 containers for paper (each one 5 m^3) and 3 containers for cardboard (each one 8 m^3) (Pihlajasaari, 2013).

Figure 6: Deep collection containers made by Molok Ltd (www.molok.com)

3.1.4 Waste disposal

The biowaste from the University of Jyväskylä goes to the Mustankorkea landfill owned by the cities of Jyväskylä, Laukaa and Muurame as well as the Vapo Ltd. The landfill was established in 1998 and in 2011 the utilization rate was 62 % (Mustankorkea, 2012). In the Mustankorkea landfill, the biowaste is composted to produce growth media used in landscaping at the landfill, and from 2011 onwards, the landfill has also produced growth media to be sold for gardening use with Kekkilä Ltd (Mustankorkea, 2012). The gate fee for biowaste is 76.1 €/ton without taxes and 94.4 €/ton with VAT (Mustankorkea, 2012). Similarly, gate fee for biowaste in packaging is 83.6 €/ton without taxes and 103.7 €/ton with VAT (Mustankorkea, 2012). Mustankorkea landfill is located approximately 7 kilometers away from the University campus area.

Other waste streams (such as paper, glass, metal etc.) generated at the University of Jyväskylä goes to Lassila & Tikanoja logistics center in Jyväskylä located approximately 8 kilometers away from the main campus (Joensuu, 2013). From there the waste streams are shipped to recycling and reuse purposes. Waste from the University of Jyväskylä is not collected separately from other locations, but it is part of logistic chain, thus it is nearly impossible to determine the distances the waste collecting trucks drive just for the University's wastes (Joensuu, 2013).

3.1.5 Energy consumption

In 2011, the electricity consumption in the University of Jyväskylä was approximately 24 991 MWh (Vänttinen, 2012). University of Jyväskylä acquires the electricity through

Hansel Ltd, which is the central procurement unit of the Finnish Government. The energy supplier is Vantaa Energy Ltd, whose primary energy sources in 2011 were as follows: renewables 22.4 %, fossil fuels 43.0 % and nuclear 34.6 % (Vänttinen, 2012). In addition, Hansel Ltd also acquires minimum 30 % of its energy manufactured with green certificates. In 2011, the electricity produced with green certificates was 100 % hydropower. So the primary energy sources for Hansel Ltd in 2011 were 46.9 % renewables, 29.4 % fossil fuels and 23.7 % nuclear (Vänttinen, 2012).

University of Jyväskylä is connected to the district heating and in 2011, the buildings owned by University Properties of Finland Ltd (which consist most of the places where University operates) consumed heat 25 500 MWh (Vänttinen, 2012). The average price for district heating in January 2012 was 68.6 €/MWh (Statistics, 2012).

The Department of Biological and Environmental Sciences operates in a building called Ambiotica located in Ylistönrinne campus. In 2011, Ambiotica consumed 2 600 MWh of electricity and 3 100 MWh of heat (Vänttinen, 2012).

3.2 Calculations

Calculations are used to design the biogas plant as well as for analyzing the results. Calculations used will give the basic parameters for the biogas plants but as well can be used to determine the energy balance, emissions and digestate use.

3.2.1 Reactor design

Amount of TS and VS are basic parameters in plant design are calculated with Equations 1 and 2, respectively.

$$Amount\ of\ TS\ (kg) = feedstock\ (kg) * TS\ (\%) \tag{1}$$

$$Amount\ of\ VS\ (kg) = amount\ of\ TS\ (kg) * VS\ (\%\ of\ TS) \tag{2}$$

The biogas production per reactor volume will reveal the waste stream with highest biogas yield and was calculated based on Equation 3.

$$Biogas\ per\ reactor\ volume\ \left(\frac{m^3}{m^3}\right) = \frac{biogas\ production\ per\ day\ (\frac{m^3}{d})}{reactor\ volume\ (m^3)} \tag{3}$$

Hence the methane is the valuable fraction of the biogas, it is important to calculate the methane production (Equation 4).

$$Methane\ production\ \left(\frac{m^3}{d}\right) = CH_4potential\ \left(\frac{m^3}{kgVS}\right) * amount\ of\ VS\ (\frac{kgVS}{d}) \qquad (4),$$

Hydraulic retention time (d) is the average time the sludge stays in the reactor and can be calculated as follows:

$$HRT\ (d) = \frac{Reactor\ volume\ (m^3)}{Daily\ feed\ rate\ (\frac{m^3}{d})} \quad (5),$$

where, daily feed rate is defined as amount of feedstock divided by the number of days. Working reactor volume can be calculated if organic loading rate is known (Equation 6).

$$Working\ reactor\ volume\ (m^3) = \frac{daily\ feed\ rate\ VS\ (\frac{kgVS}{d})}{OLR\ (\frac{\frac{kgVS}{m^3}}{d})} \quad (6)$$

The reactor must be designed to be approximately 20-30 % bigger than working volume to allow variations in feedstock amounts, possible foaming or gas build up in the reactor (Latvala, 2009). Thus, the total reactor volume is the working reactor volume with a 25 % headspace (Equation 7).

$$Total\ reactor\ volume\ (m^3) = 1.25 * working\ reactor\ volume\ (m^3) \quad (7)$$

3.2.2 Energy balance and emissions

Mainly the energy balance and emissions are calculated based on model developed by Salter & Banks (2009) and Salter et al. (2011) and is described in more detail in chapter "Anaerobic digestion and energy model".

To evaluate the energy balances for different scenarios and energy efficiency, an energy input/output ratio must be defined (Equation 8). Energy input is the sum of primary energy (energy demand in the collection of waste including the transportation, operation of the biogas plant) into biogas system while the energy output is the energy content in the biogas produced. The higher the input/output ratio is, the less energy efficient is the biogas system (Berglund & Börjesson, 2006).

$$Energy\ ratio = \frac{Total\ energy\ input\ (GJ)}{Total\ energy\ output\ (GJ)} \quad (8)$$

3.2.3 Digestate use

If produced digestate is used as a fertilizer, the required land area can be calculated as follows:

$$Required\ land\ area\ (ha) = \frac{amount\ of\ N\ (kgN)}{application\ rate\ (\frac{kgN}{ha})} \quad (9),$$

where application rate is 170 kgN/ha in Finland.

3.3 Anaerobic digestion and energy model

Many of the results presented in this thesis are based on calculation model developed by Salter & Banks (2009) and Salter et al. (2011) (Figure 7), which is based on various assumptions. With the calculation model the biogas production, digester parameters, digestate amount and values, electricity and heat production as well as their consumption and greenhouse gas emissions are calculated. Also the emissions for transportation are estimated for different scenarios. Energy requirements for biogas process and digestate use were conducted based on the information of feedstock and digestate characteristics, reactor design and process conditions and biogas use. The used global warming potentials are 20 year potentials according to IPCC and are as follows: for carbon dioxide (CO_2) the potential is 1, for methane (CH_4) 25 and for nitrous oxide (N_2O) 298 (IPCC, 2007).

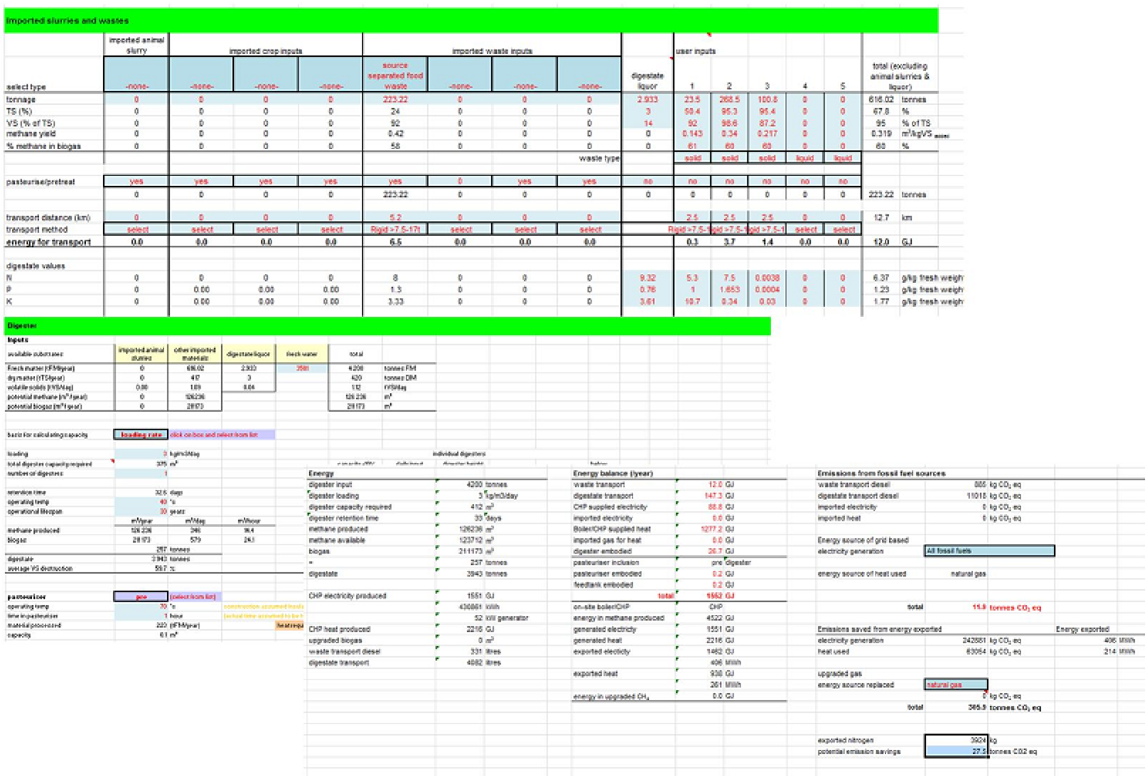

Figure 7: Illustration of the calculation model used in the thesis developed by Salter & Banks (2009) and Salter et al. (2011)

The estimated CO_2 emissions from electricity generation from all fossil fuels were 598 ton/GWh, from all fuels (including nuclear and renewables) 452 ton/GWh, from coal 915 ton/GWh, from natural gas 405 ton/GWh and from oil 633 ton/GWh (default values in calculation model). Assumed energy use for fertilizer production in N, P_2O_5 and K_2O were

40.3 MJ/ kg of product, 3.4 MJ/ kg of product and 7.3 MJ/ kg of product, respectively. Energy use in packing and transport was assumed to be 2.595 MJ/ kg for all nutrients (default values in calculation model). Emissions from fertilizer manufacture are in Table 4. The emissions (kg/kg) from average pesticide manufacture and transport for CO_2, CH_4, N_2O and total are 4.921, 0.004, 0.47 and 5.395, respectively (default values in calculation model).

Table 4: Emissions from fertilizer manufacturing (Default values in calculation model)

	N	P_2O_5	K_2O
CO_2 (kg/kg)	2.24	1.59	1.66
CH_4 (kg/kg)	0.012	0.003	0.003
N_2O (kg/kg)	0.015	0	0
kg/kg CO_2 eq.	7.01	1.665	1.735

The energy calculations are based on calorific values and following values are used (default values in calculation model): calorific value of methane is 35.82 MJ/m^3, natural gas 39.1 MJ/m^3 and diesel 35.7 MJ/m^3. The gas weight i.e. density of CH_4 is 0.717 kg/m^3 and CO_2 1.965 kg/m^3. Generator efficiencies are expected to be as follows: overall 0.85, electrical 0.35, heat 0.5 and the boiler efficiency assumed to be 0.85 (default values in calculation model). The fuel uses in different types of vehicles used in transportations are presented in Table 5.

Table 5: Fuel uses in different vehicles used in transportations (Default values in calculation model)

	MJ/ t km
Artic <33t	2.09
Artic >33t	1.21
Rigid <7.5t	9.01
Rigid >17t	2.73
Rigid 7.5-17t	5.64
Tractor & trailer	1.91

The used values and assumptions concerning fossil fuels are in Table 6.

Table 6: Emissions and other assumptions for fossil fuels (Default values in calculation model)

	kgCO2 eq/MJ	kgCO2 eq/unit	NCV MJ/l		direct GHG kg CO2eq/ unit		NCV GJ/t	density l/t	indirect energy ratio MJ/MJ	indirect GHG kg CO2eq/l
Diesel oil	0.07477	2.6720	35.73	l	3201.1	kg/t	42.8	1198	0.11	0.507
LPG	0.06396	1.4920	23.33	l	1.492	kg/l	45.9	1968	0.11	0.187
Natural gas	0.05711	2.0272	35.50	m^3	2.0272	kg/ m^3	47.6	1 340 651	0.11	
Petrol	0.07069	2.3220	32.85	l	3162.6	kg/t	44.7	1362	0.11	0.411

Note: NCV = Net Calorific Value

3.4.1 Feedstock amounts and its characteristics

The amount of waste to be digested and its characteristics (total and volatile solids content, methane potential, N, P and K content), the amount collected and transport distance from the collection point to the reactor were included in this section of calculation model. Default values for a number of pre-characterized waste streams were available. However, tool also allows the user to input waste characteristics for different waste streams e.g. food waste and garden waste. The default values were used for biowaste and for other waste streams values were input. The energy requirements associated with the waste collection and transport to the reactor is in the form of fossil fuel e.g. diesel. The vehicle used in transport was selected from a range of options including rigid with associated fuel consumption, and GHG emissions for those were based on standard values (Hill, 2010). In all scenarios and in all transports rigid witch capacity 7.5-17 t was used, as the waste amounts seemed to make it sensible and it is not realistic that the plant would have many different vehicles.

3.4.2 Reactor design and operating conditions

The required reactor capacity was calculated based on the amount of waste or feedstock to be digested and based on the user-specified loading rate (maximum of 4 $kgVS/m^3/d$) or retention time (d). Reactor is also designed with an assumption that the produced biogas is stored in the reactor and an additional 10% of the working volume was allowed for this purpose. The model allows for a maximum reactor size of 3500 m^3 and capacity higher than this would be distributed between numbers of equal-sized reactors. Parasitic energy requirements for reactor includes: the heat loss from the reactor and energy required for heating the feedstock. Heat loss from the reactor is calculated from the reactor size, based on heat loss through the walls, roof and floor and on the energy required to heat the feedstock to the user-specified reactor operating temperature. Ambient temperatures for heat loss calculations are user-specified in the form of average monthly air and soil temperatures. Parasitic electrical requirement was calculated based on the amount and nature of the feedstock.

3.4.3 Digestate production and use

The amount of digestate produced was calculated by converting the amount of biogas produced in volume to mass basis and then subtracting the mass of biogas produced from mass of feedstock, assuming no losses occur. The nutrient composition of the digestate was based on the N, P, and K values of the feedstock and assuming that all the nutrients in the feedstock were conserved during the biogas process. The transport distance for the digestate was calculated based on a user-specified distance from the reactor to the location where the digestate would be used either for agriculture or composting. The vehicle used for transporting digestate was selected from a range of vehicle options and were dependent on the associated fuel consumption and GHG emissions (Hill, 2010). Rigid with capacity 7.5 – 17 t was selected. The nutrient values of the waste streams are presented at Table 7.

Table 7: The nutrient contents of waste streams suitable for anaerobic digestion

	Biowaste (a	Garden waste (b	Paper (c	Cardboard (d
N [g/kg]	8.1	5.3	7.5	0.0038
P [g/kg]	1.3	1.0	1.65	0.0004
K [g/kg]	3.4	10.7	0.34	0.03

a) default value for food waste in the model, b) Boldrin et al. 2009, c) Defra, 2010, d) Chong & Hamersma, 1995

3.4.4 Biogas use

The parasitic energy requirement of the biogas plant was assumed to be supplied by on-site CHP plant where available. When a CHP unit was not selected or the output energy was insufficient it was assumed that the electricity demand was met by importing electricity from the national grid, and heat was provided from a user-specified range of fuel sources including natural gas, petrol or diesel oil. In thesis, the natural gas was chosen.

3.4.5 Energy balances and the avoided GHG emissions

The energy balances were calculated as direct energy only i.e. energy used in the form of fossil fuels or to replace energy produced from fossil fuels in the waste transport, biogas production and digestate transport and do not include the indirect or embodied energy in vehicles and biogas plant. Energy balances were calculated as the difference between the input energy required for collection and processing of the waste and the potential energy output from the biogas. The energy output of the system was taken as the energy obtained as electricity, heat or biomethane available for export. The energy input was taken as the energy required to collect and transport the waste to the reactor and to transport the digestate to the disposal point. Parasitic energy was not included here unless it is provided by external sources i.e. grid-based electricity or gas for heat. The obtained energy balance was expressed as absolute number and per ton of waste collected.

The possible GHG emission savings were also calculated as the energy used in the process was based on the use or replacement of fossil fuels. The main source of GHG emissions include the diesel consumed in transport and any electricity or heat provided from grid sources. GHG emissions from the CHP were not considered as it was assumed that these are part of the short-term carbon cycle. Emissions savings were calculated for the use biogas as an energy source to replace energy derived using fossil fuels in transport and/or heat and electricity replacement. For example, electricity produced and exported 'saves' 126 kg CO2eq/GJ compared to grid electricity production (DECC, 2011). Similarly, heat exported replaces heat produced using natural gas and saves 57 kg CO2eq/GJ (Hill, 2010). GHG emissions produced from the use of diesel in transport can therefore be off-set against emissions saved through the replacement of fossil fuel derived energy sources.

3.4.6 Parameters and assumptions made in modelling

Unless otherwise noted the following assumptions were applied in the studied scenarios. The specific heat capacity of the wastes is 4.19 kJ kg^{-1} K^{-1} (equal to that of water). Process losses are estimated at 1% of biogas produced. The reactor capacity was calculated based on a loading rate of 3 kg VS m^{-3} day^{-1} (Latvala, 2009). The maximum volume for a single digester was set at 3500 m^3 in the model (Slater and Banks, 2009). Thus, the number of reactors and the reactor size were determined by dividing the total waste available and the obtained reactor size. Parasitic electrical requirement was based on a value of 40 kWh t^{-1} of food waste (Slater and Banks, 2009). On the other hand, parasitic heat requirement was calculated based on the average monthly temperatures of Jyväskylä, the reactor operating temperature (37 °C) and the reactor thermal conductivity (insulation). In order to comply with the ABP regulation, feedstock was pre-pasteurized at 70 °C for 1 hour. The size of the pasteurizer tank was determined by dividing the daily amount of feedstock by 12, allowing

1 hour for heating and cooling. Heat loss from the pasteurizer tank was calculated similar to that of the reactor.

The produced biogas was used to provide the energy input to a CHP unit. In this study, the electrical and heat capture efficiencies of CHP unit were 35% and 50% of input energy, respectively. Both the parasitic electricity and heat for the reactor and pasteurizer tank were provided by the CHP unit. The net energy balance was calculated by subtracting the energy inputs (waste collection, transport to the AD plant and digestate transport to the composting or agricultural fields) from the energy available for export produced in the form of electricity and heat (total energy produced in the CHP minus the energy required for parasitic uses). The reported energy balances do not include allowances for embodied energy for the reactor or any ancillary units. Thus, the energy balance represents the net operating energy balance for the studied system boundary i.e. from collection to application.

The temperature of the surrounding air affects the heat losses and thus the overall efficiency of the system. The monthly mean air temperature values for 2012 are shown in Figure 9 (FMI, 2013).

Figure 8: The monthly temperature averages in Jyväskylä airport 2012 (FMI, 2013)

As part of the digester is underground, the soil temperature affects the heat losses. The used soil temperatures (Table 8) were measured by the Finnish Meteorological Institute from 1971 to 1990 and the mean is used for every month (Heikinheimo & Fougstedt, 1992). The measurements were carried out in Maaninka, a town located 130 km north-east from Jyväskylä (MapSite, 2013).

Table 8: Mean soil temperatures (°C) in Maaninka between 1971-1990 in varying depth (Heikinheimo & Fougstedt, 1992)

	Depth (cm)			
	20	50	100	200
January	-1	0.4	2.2	4.3
February	-1.1	0.1	1.8	3.7
March	-0.7	0.1	1.4	3.2
April	-0.2	0.3	1.2	2.9
May	5.7	4.2	2.8	2.8
June	13.1	11.3	7.8	4.7
July	16.2	14.6	11.0	7.0
August	14.9	14.3	12.1	8.6
September	9.9	10.4	10.3	8.9
October	4.6	5.9	7.3	8.1
November	1.1	2.4	4.4	6.5
December	-0.2	1.2	3	5.2

3.5 AD modelling scenarios

As the aim of this study is to investigate the biogas production potential from the waste streams of the University of Jyväskylä, in all scenarios the reactor design and affecting parameters are the same, only the feedstock composition varies with every scenario. This way the scenarios are comparable. The reactor design is basic CSTR reactor with mesophilic conditions. The size of the reactor and the retention times will vary depending on the waste amounts and the degradability of the waste streams. In all scenarios, water is added so that the total solids content will be approximately 10 %. Also in all scenarios, organic loading rate will be 3 kg/m^3/day. Basis for calculating the reactor capacity is in all scenarios the organic loading rate.

In all scenarios, the biogas plant is situated in Mattilanniemi campus (Figure 10). This will cause transportation distance from Seminaarinmäki campus to be 800 meters and from Ylistönrinne campus 1.7 kilometers. These distances are by road. The biowaste collected from Kortepohja Student Village is transported 2.7 km to the reactor. For calculations, it is assumed that the transportation of waste is from single point (from Ylistö in Survontie 9 address and in Seminaarinmäki from Seminaarinkatu 15). In reality, the wastes are produced in multiple places and there are several collection points in every campus. Same assumption is done for Kortepohja Student Village.

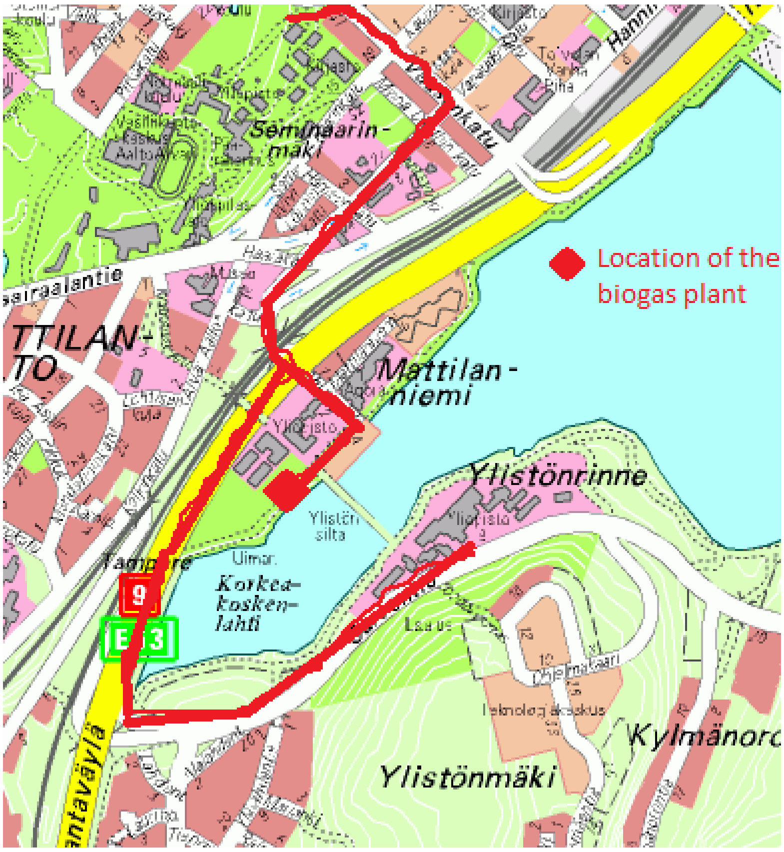

Figure 9: Location of the biogas plant and possible waste transportation routes from other campuses

The digestate is either transported to Mustankorkea landfill to be composted in their composting process or to Kalmari farm for digestate application on the fields. The distance between Mustankorkea landfill and the reactor is 6.7 kilometers. The Kalmari farm is located in Laukaa; the distance between the farm and the reactor is 17.9 km. The distances are gained by using Mattilanniemi 2 as an address for the biogas plant and for Mustankorkea the address is Ronsuntaipaleentie 204 and for Kalmari farm Vaajakoskentie 104. The digestate was transported from the reactor with a rigid truck. If the digestate is transported to composting, the solid and liquid fractions are separated and the solid fraction is composted and liquid fraction used in the process to dilute the feedstock. If used as a fertilizer, the digestate is transported as whole – no separation to liquid and solid fraction.

The area required for distribution of digestate was calculated based on the amount of digestate, nitrogen content of the digestate and by using application rate of 170 kgN/ha. The energy required for spreading the digestate was excluded from the energy balances as it forms part of the farms energy balance and is thus outside the current system boundaries. Similarly, the energy required for the composting in the landfill was not considered in the energy balance as it was outside the system boundaries of the present study.

As the aim of the study is to determine the feasibility of AD plant with the main feedstock being the biowaste collected from the University of Jyväskylä, the system boundaries for energy balances are defined so that the system is imagined to start from the waste collection and the plant located on the premises of the University so that the transportation distances are minimal. Both are expected to be same with every scenario. The main primary energy is the electricity and heating required for the operation of the plant. System boundaries (Figure 8) illustrate what factors are included in the calculations and which are not.

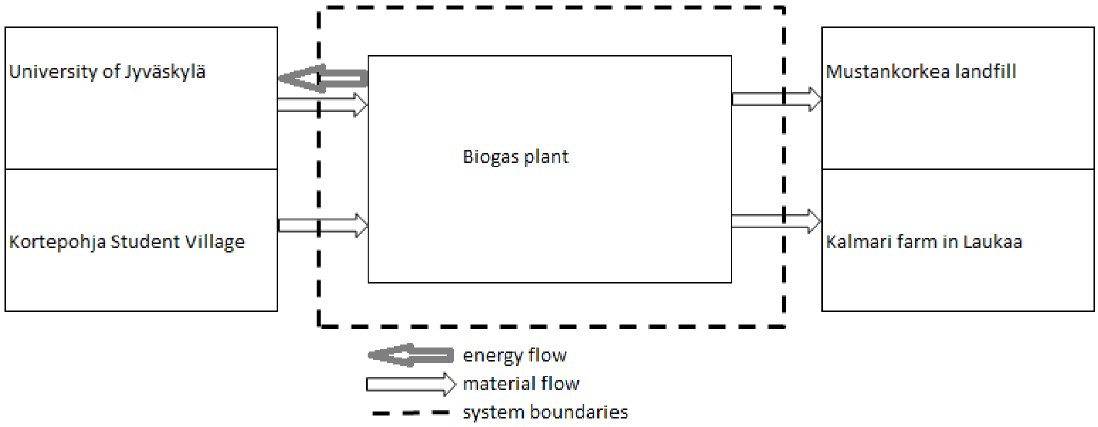

Figure 10: System boundaries used in the thesis and the material flows

3.5.1 Reference Scenario

The Reference Scenario i.e. baseline situation is that the waste management in the University of Jyväskylä continues as it is currently and no biogas plant is built.

3.5.2 Scenario 1

In the first Scenario, the only feedstock of the AD plant is the biowaste (mainly the foodwaste) generated at the University of Jyväskylä and in Kortepohja Student Village. In Scenario 1, the following Runs are carried out:

- Run 1: Biowaste from the University of Jyväskylä, biogas utilization in CHP, solid fraction of the digestate to landfill for composting and liquid fraction circulated back to the process for diluting the feedstock.
- Run 2: Biowaste from both the University of Jyväskylä and from the Kortepohja Student Village, biogas utilization in CHP, solid fraction of the digestate to landfill for composting and liquid fraction circulated back to the process for diluting the feedstock.

3.5.3 Scenario 2

In the second Scenario, the feedstock is the biowaste and the garden waste. Only the following Run is carried out in Scenario 2:

- Run: Biowaste from University and Student Village, garden waste from the University, biogas utilization in CHP, solid fraction of the digestate to landfill for composting and liquid fraction is circulated back to process for diluting the feedstock.

3.5.4 Scenario 3

In Scenario 3, all biodegradable waste streams generated at the University of Jyväskylä in addition with the biowaste generated at the Kortepohja Student Village are used as a feedstock. The following Runs are carried out:

- Run 1: Biowaste, garden waste, paper and cardboard from the University and biowaste from the Student Village, CHP, solid fraction of the digestate to landfill for composting and liquid fraction is circulated back to the process for diluting the feedstock.
- Run 2: Biowaste, garden waste, paper and cardboard from the University and biowaste from the Student Village, CHP, digestate as a whole is transported to Kalmari farm in Laukaa for land application.
- Run 3: Biowaste, garden waste, paper and cardboard from the University and biowaste from the Student Village, biogas upgrading, solid fraction of the digestate to landfill for composting and liquid fraction is circulated back to the process for diluting the feedstock.

4 RESULTS

In this section, the key findings about waste generation and composition at the University of Jyväskylä are presented. The type and amounts of wastes suitable for anaerobic digestion, the different biogas production scenarios and their process parameters, energy and mass balances as well as emissions are also presented. Finally, a basic economic analysis and sensitivity analysis are also carried out.

4.1 Waste generation

The annual waste streams generated at the University of Jyväskylä in 2012 is presented in Table 9. Waste collection and management at the University of Jyväskylä is being handled by Lassila & Tikanoja Ltd. Waste collection is based on predefined drain intervals for every waste stream. Waste amount is estimated based on drain intervals and on an average filling rate, which is estimated to be 80 % (Vänttinen, 2012). Thus, the waste amount presented in Table 9 is an estimated average weight.

Table 9: Annual waste streams from the University of Jyväskylä collected by Lassila & Tikanoja Ltd in 2012 (Vänttinen, 2012)

Waste	tons	Percentage of total waste stream
Energy waste	264.9	32.60 %
Mixed paper	123.3	15.20 %
Office paper	121.1	14.90 %
Brown paper and cardboard	100.8	12.40 %
Biowaste	98.6	12.10 %
Confidential material (paper)	24.10	3.00 %
Landfill waste	23.80	2.90 %
WEEE	22.40	2.80 %
Mixed glass	19.74	2.40 %
Metal	12.40	1.50 %
Food oil and fat	0.2	0.00 %
Recordings and films	0.1	0.00 %
Total	811.4	100 %

Note: WEEE = Waste Electric and Electrical Equipment

4.1.1 Biowaste

The biowaste collected by the Lassila & Tikanoja Ltd includes both the cafeteria waste (kitchen waste and restaurant waste) from campus restaurants and the source separated biowaste from offices, personnel break rooms etc.

In Ylistö restaurant of the Ylistönrinne campus (see Figure 4), the average customer throws away 74.3 grams of waste per day. The total number of customers in all Sonaatti restaurants 2012 was 670 824. If assumed that customers behave the same way in all restaurants, the amount of restaurant wastes in 2012 was 49 822 kilos (49.8 tons). This is approximately 51 % of the total biowaste generated at the University.

4.1.2 Garden waste

According to Tikkanen (2012), the garden waste mainly consists of grass, weeding waste, waste from format cutting and leaf waste. Grass waste is not generated on the University campuses as the lawn mowers used for mowing the lawn shred the grass to a small size and the shredded grass clippings are left on the lawn as a source of organic fertilizer. Weeding waste consists of mainly weed vegetation that is regularly removed in order to able the intended vegetation to succeed. The format cutting for the trees and bushes varies yearly based on the need for the cutting but the rough estimate for this waste is 1 500 kg from all campuses in the University. Leaf waste generates the largest portion (20 tons) from the garden wastes and is collected in the autumn. All garden wastes are transported to Mustankorkea landfill (Tikkanen, 2012). The garden waste amounts are presented in Table 10. The total amount of garden waste is 23.5 tons per year. This corresponds to an average of 1.96 tons per month. In reality, the month-to-month amounts of garden waste vary greatly due to changes in growing seasons, but the average is used to simplify the calculations.

Table 10: The annual garden waste generated in the University of Jyväskylä (Tikkanen, 2012)

Garden waste	Seminaarinmäki	Mattilanniemi	Ylistönrinne	Total
Weeding waste [kg/growing season]	1 000	500	500	2 000
Format cutting [kg/year]	--	--	--	1 500
Leaf waste [kg/year]	10 000	5 000	5 000	20 000
[kg/year]	--	--	--	23 500

4.1.4 Waste streams suitable for anaerobic digestion

The total waste amounts of biowaste, paper waste, cardboard and garden waste that could be used in AD process are presented in Figure 11. On a daily basis, the University of Jyväskylä produces approximately 1.37 tons of waste suitable for AD. This corresponds to an average of 40.95 tons per month.

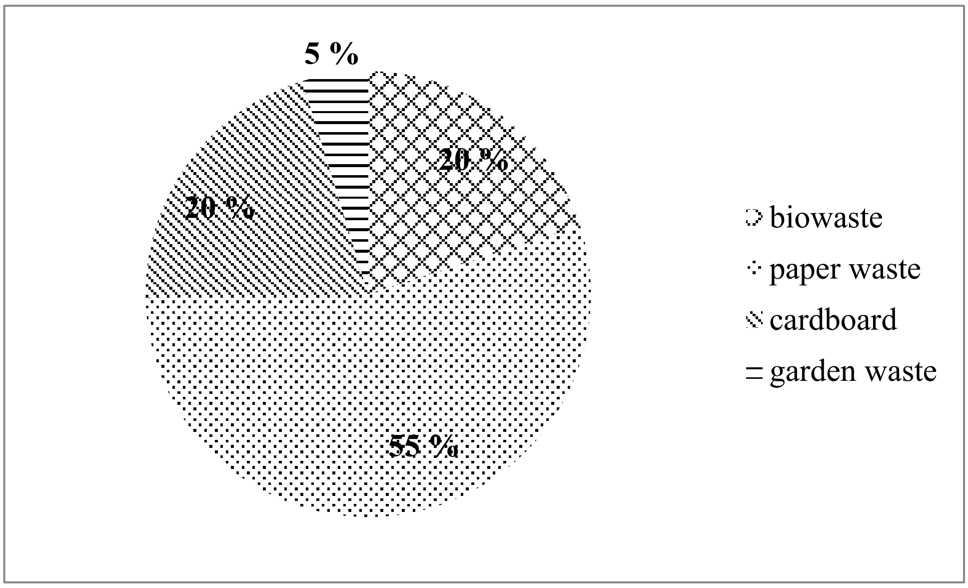

Figure 11: Annual waste streams from the University of Jyväskylä suitable for AD process and their percentage of total suitable waste amount

Characteristics and the methane potential of the waste streams generated at the University campuses that could be used for biogas production are presented in Table 11.

Table 11: Characteristics and methane potential of waste streams suitable for biogas production

Waste stream	Amount (t/a)	Amount (kg/d)	TS (%)	TS (kg/d)	VS (% of TS)	VS (kg/d)	CH_4-potential (m^3/kgVS$_{added}$)	CH_4 yield (m^3/d)
Bio-waste	99	270	22.6 [a]	61	94.8 [a]	58	0.550[b]	32
Garden waste	24	64	50.4 [c]	32	92.0 [c]	30	0.143 [c]	4
Paper	269	736	95.3 [d]	701	98.6 [d]	691	0.340 [e]	235
Card-board	101	276	95.4 [d]	263	87.2 [d]	230	0.217 [e]	50
Overall	491	1346		1058		1009		321

Note: a) Koponen (unpublished data), b) Latvala, 2009, c) Owens & Chynoweth, 1993, d) Yuan et al. 2012, e) Jokela et al. 2004

4.2 Design parameters for biogas production at the University of Jyväskylä

The feasibility of different biogas production Scenarios from the organic wastes generated at the University of Jyväskylä is investigated. The basic biogas production process is presented in the Figure 12 and in all the Scenarios the same process diagram is used.

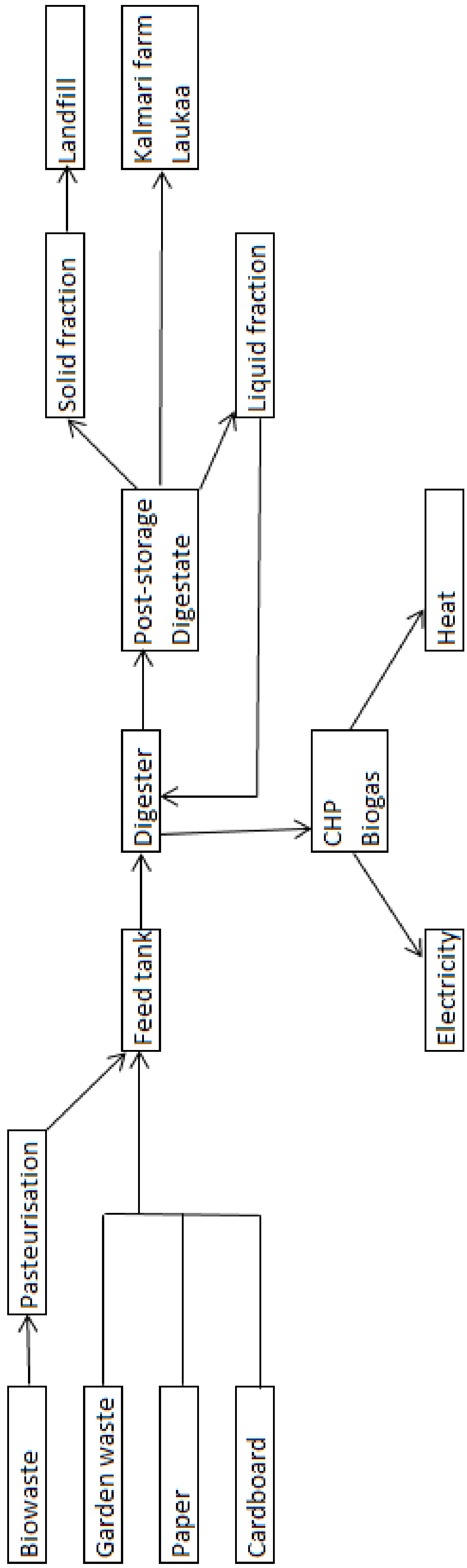

Figure 12: General process diagram for all Scenarios

4.2.1 Reference Scenario

In the Reference Scenario (current waste management practice), the biowaste from the University of Jyväskylä is collected by Lassila & Tikanoja Ltd and is transported to Mustankorkea landfill. The gate fee for the 98.6 tons of biowaste is 10 220 € per year. The source separated biowaste is treated by composting and the end-product is sold by the Mustankorkea as a landscaping material. The paper and cardboard collected from the University goes to Lassila & Tikanoja Ltd collection terminal from where they are transported to be utilized as a raw material for paper production.

4.2.2 Scenario 1

In Scenario 1, two different Runs were modeled and the basic parameters for the Runs are presented in Table 12. In Run 1, only biowaste from the University of Jyväskylä was used for biogas production while in Run 2 the biowaste from the Kortepohja Student Village is also included in the model. The biowaste is assumed to have same characteristics whether is comes from the University or Kortepohja Student Village.

Table 12: Basic parameters for the Scenario 1 calculated with the calculation model

	Run 1	Run 2
Energy and material outputs (/year)		
Digester input [ton]	270	570
Digester capacity required [m^3]	36	64
Digester retention time [d]	44	37
Methane produced [m^3]	9 144	20 701
Methane available [m^3]	8 961	20 287
Biogas (volume) [m^3]	15 765	35 691
Biogas (mass) [ton]	20	44
Digestate [ton]	250	526
Electricity produced [GJ]	112	254
[kWh]	31 209	70 653
kW generator	4	8
Heat produced [GJ]	160	363
Waste transport diesel [l]	38	179
Total energy output [GJ]	272	617
Energy inputs required (/year)		
Waste transport [GJ]	1	6
Digestate transport [GJ]	9	20
CHP supplied electricity [GJ]	20	37
Imported electricity [GJ]	0	0
CHP supplied heat [GJ]	130	237
Imported gas for heat [GJ]	0	0
Digester embodied [GJ]	5	7
Pasteurizer inclusion	pre	pre
Pasteurizer embodied [GJ]	0	0
Feedtank embodied [GJ]	0	0
Total energy input [GJ]	160	303
Energy exports		
Energy in methane produced [GJ]	328	741
Generated electricity [GJ]	112	254
Generated heat [GJ]	160	363
Exported electricity [GJ]	92	217
[MWh]	26	60
Exported heat [GJ]	31	126
[MWh]	9	35
Exported energy [GJ]	123	343
Energy balance [GJ]	112	314
[GJ/ton]	0.4	0.6
Energy ratio	0.6	0.5

In Run 1, use of 99 tons of biowaste from the University alone and 171 tons of water produced 15 765 m^3 of biogas and 250 tons of digestate. On a mass basis, 7.4 % of the feedstock converted into biogas while the remaining amount converted into digestate. The total energy output in Run 1 from CHP plant was 272 GJ, from which 112 GJ was electricity and 160 GJ was heat. The total energy input was 166 GJ. Heat requirement for biogas plant and pasteurization of biowaste accounted for 78 % of total energy input. The surplus energy (123 GJ) was exported. The final energy balance shows that 0.4 GJ of energy could be produced from 1 ton of biowaste produced from the University.

Use of biowaste from the Kortepohja Student Village in Run 2 resulted 2.25 times more biogas (35 691 m^3) with a slightly higher energy balance of 0.6 GJ/ton. However, the energy ratios would be slightly lower (0.5) in Run 2.

4.2.3 Scenario 2

The basic parameters for Scenario 2 are presented in Table 13. In this Scenario, in addition to biowaste from both the University of Jyväskylä and from the Kortepohja Student Village, garden waste from the University was also included.

Table 13: Basic parameters for Scenario 2 calculated with the calculation model

	Run 1
Energy and material outputs (/year)	
Digester input [ton]	680
Digester capacity required [m^3]	75
Digester retention time [d]	36
Methane produced [m^3]	22 259
Methane available [m^3]	21 814
Biogas (volume) [m^3]	38 021
Biogas (mass) [ton]	47
Digestate [ton]	633
Electricity produced [GJ]	273
[kWh]	75 972
kW generator	9
Heat produced [GJ]	391
Waste transport diesel [l]	188
Total energy output [GJ]	664
Energy inputs required (/year)	
Waste transport [GJ]	7
Digestate transport [GJ]	24
CHP supplied electricity [GJ]	36
Imported electricity [GJ]	0
CHP supplied heat [GJ]	272
Imported gas for heat [GJ]	0
Digester embodied [GJ]	8
Pasteurizer inclusion	pre
Pasteurizer embodied [GJ]	0
Feedtank embodied [GJ]	0
Total energy input [GJ]	346
Energy exports	
Energy in methane produced [GJ]	797
Generated electricity [GJ]	273
Generated heat [GJ]	391
Exported electricity [GJ]	238
[MWh]	66
Exported heat [GJ]	119
[MWh]	33
Exported energy [GJ]	357
Energy balance [GJ]	318
[GJ/ton]	0.5
Energy ratio	0.5

Codigestion of 24 tons of garden waste along with biowaste from the University and Kortepohja Student Village produced 38 021 m^3 of biogas and 633 tons of digestate. Thus, the mass balance for Scenario 2 shows that from the feedstock 6.9 % converts into biogas. Cogeneration of electricity and heat in CHP plant produced 273 GJ of electricity and 391 GJ of heat from the produced biogas. The total energy input was 346 GJ. The surplus heat and electricity production were 119 GJ and 238 GJ, respectively. The final energy balance was 0.5 GJ per ton of feedstock with and energy ratio of 0.5.

4.2.4 Scenario 3

The results of model for Scenario 3 are presented in Table 14. In all the three Runs, the amount of feedstock used is the same and contained all the biodegradable waste streams generated at the University of Jyväskylä and the biowaste produced at the Kortepohja Student Village. In Run 1 and 2, biogas is used for heat and electricity production in a CHP plant. The main difference between Run 1 and 2 is that in Run 2 the whole digestate is transported to Kalmari farm in Laukaa while the digestate in Run 1 was sent to the Mustankorkea landfill for composting. In Run 3, the biogas is upgraded to biomethane for vehicle use while the digestate was transported for composting in landfill.

Table 14: Basic parameters for Scenario 3 calculated with the calculation model

	Run 1	Run 2	Run 3
Energy and material outputs (/year)			
Digester input [ton]	4 200	4 200	4 200
Digester capacity required [m^3]	412	412	412
Digester retention time [d]	33	33	33
Methane produced [m^3]	126 236	126 236	126 236
Methane available [m^3]	123 712	123 712	123 712
Biogas (volume) [m^3]	211 173	211 173	211 173
Biogas (mass) [ton]	257	257	257
Digestate [ton]	3 943	3 943	3 943
Electricity produced [GJ]	1 551	1 551	0
[kWh]	430 861	430 861	0
kW generator	52	52	0
Heat produced [GJ]	2 216	2 216	0
Upgraded biogas [m^3]	0	0	121 238
Waste transport diesel [l]	331	331	331
Total energy output [GJ]	3 767	3 767	4 522
Energy inputs required (/year)			
Waste transport [GJ]	12	12	12
Digestate transport [GJ]	147	394	147
CHP supplied electricity [GJ]	89	89	0
Imported electricity [GJ]	0	0	312
CHP supplied heat [GJ]	1 277	1 277	0
Imported gas for heat [GJ]	0	0	1 503
Digester embodied [GJ]	27	27	27
Pasteurizer inclusion	pre	pre	pre
Pasteurizer embodied [GJ]	0	0	0
Feedtank embodied [GJ]	0	0	0
Total energy input [GJ]	1 552	1 799	2 001
Energy exports			
Energy in methane produced [GJ]	4 522	4 522	4 522
Generated electricity [GJ]	1 551	1 551	0
Generated heat [GJ]	2 216	2 216	0
Exported electricity [GJ]	1 462	1 462	0
[MWh]	406	406	0
Exported heat [GJ]	938	938	0
[MWh]	261	261	0
Energy in upgraded methane [GJ]	0	0	4 343
Exported energy [GJ]	2 401	2 401	4 343
Energy balance [GJ]	2 215	1 968	2 342
[GJ/ton]	0.5	0.5	0.6
Energy ratio	0.4	0.5	0.5

Total volumetric biogas production in all three Runs in Scenario 3 was 211 173 m^3 with total energy output of 4 082 GJ. On mass basis, 6.1 % of the feedstock converted into biogas in all three Scenarios while rest converted into digestate. Total energy input varied depending upon the energy required for digestate treatment and transport as well as biogas utilization. In Run 1, the total energy input was 1 552 GJ per year, from which energy required for digestate transport to landfill accounted for 9.5 %. On the other hand, 21.9 % of the total energy input (1 799 GJ per year) in Run 2 was used for digestate transport. The digestate would require approximately 23 ha for land application. The energy input for Run 3 was 2 001 GJ per year with imported natural gas and electricity accounting for 75 % and 16 %, respectively. In Run 1 and 2, utilization of biogas in CHP plant produced 1 551 GJ of electricity and 2 216 GJ of heat. The surplus heat and electricity production were 938 GJ and 1 462 GJ, respectively. The final energy balance was 0.5 GJ/ton of waste in both Runs while the energy ratio in Run 1 was slightly lower (0.4) than in Run 2 (0.5). On the other hand, biomethane production and utilization as a vehicle fuel resulted in a surplus energy of 4 343 GJ per year and energy balance of 0.6 GJ per ton of waste with an energy ratio of 0.5.

4.3 Comparing the Scenarios

In this section, the differences in the design parameters, energy savings and GHG emissions from the studied scenario were compared with each other and also with the Reference Scenario.

4.3.1 Comparing Scenario 1 to reference Scenario

Energy produced in Scenario 1 and the possible energy savings compared to Reference Scenario are presented in Table 15. The potential energy savings in Scenario 1 with both possible Runs at the University level would be from 0.07 to 0.19 % of the total energy consumption if utilizing the energy produced in the biogas plant upon AD of biowaste generated at the University of Jyväskylä and Kortepohja Student Village. A larger proportion of electricity consumption (0.1-0.24 %) compared to heat (0.03-0.14 %) could be replaced with the produced energy. On the other hand, the total energy savings for Ambiotica building is much higher (0.6-1.67 %) compared to the University level as 0.99-2.32 % of electricity and 0.28-1.13 % of heat consumption could be replaced with the produced biogas.

Table 15: Possible energy savings in Scenario 1 both at the University level and Ambiotica level

	Run 1	Run 2
Exported electricity [kWh]	25 634	60 384
Exported heat [kWh]	8 546	34 977
Possible energy savings		
University level (electricity)	0.10 %	0.24 %
University level (heat)	0.03 %	0.14 %
Total savings (University level)	0.07 %	0.19 %
Ambiotica level (electricity)	0.99 %	2.32 %
Ambiotica level (heat)	0.28 %	1.13 %
Total savings (Ambiotica level)	0.60 %	1.67 %

4.3.2 Comparing Scenario 2 to reference Scenario

The energy production in Scenario 2 and the possible energy savings compared to the Reference Scenario are presented in Table 16. As the produced biogas in Scenario 2 was used to cogenerate heat and electricity in CHP plant, 0.20 % of the energy consumed in the University of Jyväskylä could be replaced. In University level, from the electricity consumption 0.26 % could be replaced and from heat consumption 0.13 %. In Ambiotica level, the replacement level would be higher as 1.74 % of the total energy consumption could be replaced by the energy produced from the biogas.

Table 16: Possible energy savings in Scenario 2 both the University level and Ambiotica level

	Run 1
Exported electricity [kWh]	66 098
Exported heat [kWh]	33 105
Possible energy savings	
University level (electricity)	0.26 %
University level (heat)	0.13 %
Total savings (University level)	0.20 %
Ambiotica level (electricity)	2.54 %
Ambiotica level (heat)	1.07 %
Total savings (Ambiotica level)	1.74 %

4.3.3 Comparing Scenario 3 to reference Scenario

As the exported energy amounts in Runs 1 and 2 in the Scenario 3 are same, the possible energy savings are the same and are presented in Table 17. In the Run 3, the biogas is upgraded to biomethane and cannot be utilized in replacing electricity and heat, thus possible savings in University and Ambiotica level cannot be calculated. The potential energy savings in Scenario 3 could reach 1.3 % in University level and 12 % in Ambiotica level, when produced biogas is utilized in cogeneration in CHP plant. Higher proportion of electricity consumption could be replaced compared to heat at both the University and Ambiotica levels.

Table 17: Possible energy savings in Scenario 3 both the University and Ambiotica level

	Run 1 & 2
Exported electricity [kWh]	406 189
Exported heat [kWh]	260 674
Possible energy savings	
University level (electricity)	1.6 %
University level (heat)	1.0 %
Total savings (University level)	1.3 %
Ambiotica level (electricity)	16 %
Ambiotica level (heat)	8.4 %
Total savings (Ambiotica level)	12 %

4.3.4 Comparison of the 3 studied Scenarios

The scenarios and all the runs are compared to each other in various parameters such as biogas production, energy production, energy balance etc. and the results are presented in Table 18. When the biogas production is divided either by feedstock amount or digester size, it reveals that the Run 2 of Scenario 1 has the highest biogas production. But the Scenario 3 has the highest volume of biogas production due to the highest amount of volatile solids in the feedstock. The energy ratios (energy input divided by the output), which indicates the energy efficiency, shows that the Run 1 of Scenario 3 would be the most energy efficient options. At the same time, the energy ratio for Scenario 2 (0.5) would indicate this option to be more energy efficient than the Run 1 in Scenario 1 with an energy ratio of 0.6.

Table 18: Comparing the Scenarios to each other in key parameters

	Scenario 1		Scenario 2	Scenario 3		
	Run 1	Run 2	Run 1	Run 1	Run 2	Run 3
Digester input [ton]	270	570	680	4 200	4 200	4 200
Digester capacity required [m^3]	36	64	75	412	412	412
Biogas (volume) [m^3]	15 765	35 691	38 021	211 173	211173	211 173
Biogas per reactor volume [m^3/m^3]	439	561	510	512	512	512
Biogas per feedstock [m^3/ton]	58	63	56	50	50	50
Digestate [ton]	250	526	633	3 943	3 943	3 943
Electricity produced [GJ]	112	254	273	1 551	1 551	0
Heat produced [GJ]	160	363	391	2 216	2 216	0
Total energy output [GJ]	272	617	664	3 767	3 767	4 343
Total energy input [GJ]	160	318	346	1 552	1 799	2 001
Exported energy [GJ]	123	343	357	2 401	2 401	4 343
Energy balance [GJ]	112	314	318	2 215	1 968	2 342
[GJ/ton]	0.4	0.6	0.5	0.5	0.5	0.6
Energy ratio	0.6	0.5	0.5	0.4	0.5	0.5

In Figure 13, the exported energy and the energy balance are compared for each Scenario. Among the studied Scenarios, Run 3 of the Scenario 3 had the highest amount of the exported energy (4 343 GJ) while Run 1 of Scenario 1 had the lowest exported energy (123 GJ). The highest amount of surplus energy in Run 3 of Scenario 3 was obvious as all the produced biogas is upgraded and biogas was not used for the energy requirements of the biogas plant. While in other Runs, a part of the produced heat and electricity was used for the energy demands of the biogas plant. On the other hand, Run 1 of Scenario 3 had the highest energy balance (2 529 GJ). This indicates that the option has the most "excess energy" i.e. when from the energy input the output is reduced, the option has the highest residue.

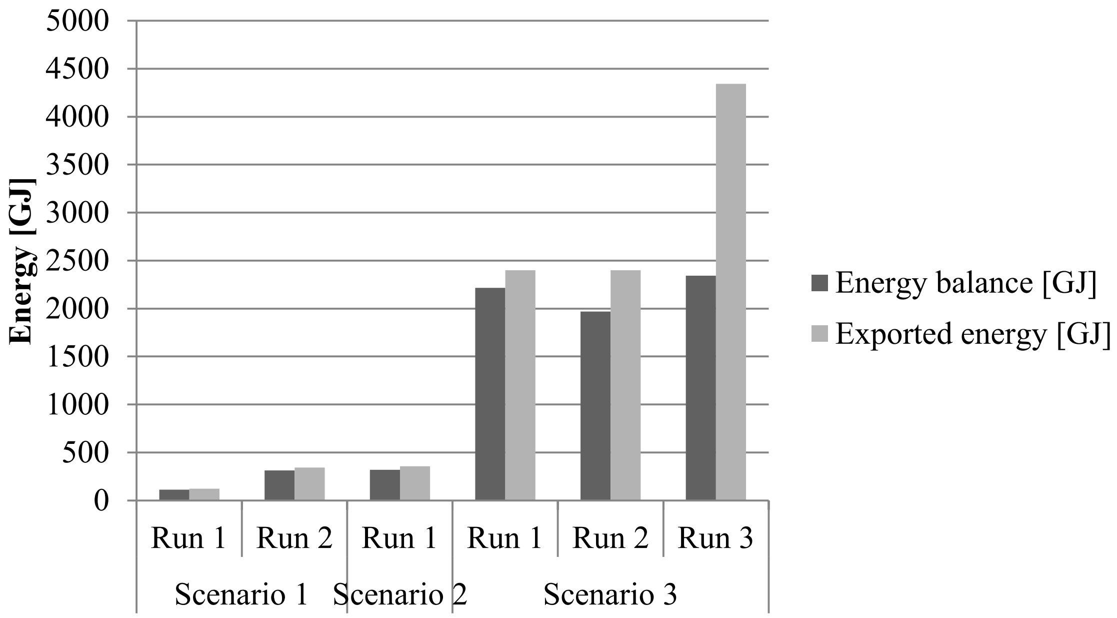

Figure 13: Comparison of the energy balance and exported energy the Scenarios

4.4 GHG emissions

The GHG emissions from fossil fuel consumption during transportation and plant operations, and possible GHG emission savings on the use of biogas replacing the fossil fuel are compared for the 3 studied Scenarios. The results are presented in Tables 19-21.

4.4.1 Reference Scenario

In 2011, the electricity and heat consumption by the University of Jyväskylä was approximately 24 991 MWh and 25 500 MWh, respectively. As the combined carbon dioxide coefficient (taking into account the mixture of different energy sources from which some are renewable) for the acquired electricity was 200 g/kWh in 2011, the electricity consumption by the University campuses caused approximately 4998 tonsCO_2eq emissions to the atmosphere.

4.4.2 Scenario 1

GHG emissions from fossil fuel consumption for transportation of waste and digestate and the emissions saved upon use of biogas to replace fossil fuel use in Scenario 1 are presented in Table 19. Results showed that GHG emissions increased with increase in transportation distance for the feedstock and/or digestate disposal. The higher GHG emission in Run 2 (1.9 tonsCO_2eq) than in Run 1 (0.8 tonsCO_2eq) was primarily due to the additional distance for the collection of biowaste from Kortepohja Student Village and the increase in the number of trips to landfill due to the increase in the amount of digestate to be transported to landfill. The total GHG emissions saved from the use of biogas were also higher for Run 2 (45 tonsCO_2eq) than for Run 1 (17 tonsCO_2eq). The benefit was much higher with respect to the electricity generation than with heat production (Table 19).

Table 19: The emissions in Scenario 1 from consumed fossil fuels and possible emission savings as the biogas replaces fossil fuels

	Run 1	Run 2
Emissions from fossil fuel sources		
Waste transport diesel [kgCO_2eq]	102	479
Digestate transport diesel [kgCO_2eq]	699	1 470
Total [tonsCO_2eq]	0.8	1.9
Emissions saved from energy exported		
Electricity generation [kgCO_2eq]	15 328	36 107
Heat used [kgCO_2eq]	2 067	8 459
Total [tonsCO_2eq]	17	45

4.4.3 Scenario 2

GHG emissions from fossil fuel consumption and possible emission savings when biogas replaces fossil fuel based energy sources are presented in Table 20. GHG emissions from fossil fuel consumption (2.3 tonCO_2eq) in Scenario 2 are mainly from digestate transportation (approximately 1.8 tonCO_2eq) to landfill for composting, so 22 % of the GHG emissions come from waste transportation (0.5 tonCO_2eq). Possible GHG emission savings would be 48 tonCO_2eq, from which major proportion comes from electricity (39.5 tonCO_2eq) and smaller fraction from heat utilization (8.0 tonCO_2eq).

Table 20: The emissions in Scenario 2 from consumed fossil fuels and possible emission savings as the biogas replaces fossil fuels

	Run 1
Emissions from fossil fuel sources	
Waste transport diesel [kgCO_2eq]	504
Digestate transport diesel [kgCO_2eq]	1 770
Total [tonsCO_2eq]	2.3
Emissions saved from energy exported	
Electricity generation [kgCO_2eq]	39 523
Heat used [kgCO_2eq]	8 006
Total [tonsCO_2eq]	48

4.4.4 Scenario 3

The GHG emissions from Scenario 3 due to fossil fuel consumption and the possible savings when energy produced by the biogas replaces exported energy are presented in Table 21. Run 3 has the highest GHG emissions (150 tonCO_2eq), which are mainly due to imported heat (86 tonCO_2eq) and electricity (52 tonCO_2eq). GHG emissions from waste transportation are same in all three Runs (0.9 tonCO_2eq), but Run 2 has the highest GHG emissions from digestate transportation (29 tonCO_2eq) as the digestate is transported to Laukaa for fertilizer use. In Runs 1 and 3 the digestate is transported to nearby landfill for composting and thus the GHG emissions are lower (11 tonCO_2eq) than in Run 2. Possible GHG emission savings is highest in Run 2 (334 tonCO_2eq) due to potential emission savings as the digestate is utilized as a fertilizer. Emission savings from energy exported are the same for Run 1 and 2 (306 tonCO_2eq) while for Run 3 they are lower (248 tonCO_2eq).

Table 21: The emissions in Scenario 3 from consumed fossil fuels and possible emission savings as the biogas replaces fossil fuels

	Run 1	Run 2	Run 3
Emissions from fossil fuel sources			
Waste transport diesel [kgCO_2eq]	885	885	885
Digestate transport diesel [kgCO_2eq]	11 018	29 436	11 018
Imported electricity [kgCO_2eq]	0	0	51 879
Imported heat [kgCO_2eq]	0	0	85 808
Total [tonsCO_2eq]	12	30	150
Emissions saved from energy exported			
Electricity generation [kgCO_2eq]	242 881	242 899	0
Heat used [kgCO_2eq]	63 044	63 043	0
Upgraded gas [kgCO_2eq]	0	0	24 8004
Total [tonsCO_2eq]	306	306	248
Emission savings from fertilizer use			
Exported nitrogen [kg]		3 924	
Potential emission savings [tonsCO_2eq]		28	

4.5 Economic analysis

A simple economic analysis with respect to the possible savings in electricity and heat among the studied 3 scenarios is presented in Tables 22-24. In 2011, the average price for electricity was 8 €cent/kWh for companies (Statistics Finland, 2013). The electricity and heat consumption in University in 2011 were approximately 24 991 MWh and 25 500 MWh, respectively, and for Ambiotica building the electricity and heat consumption were approximately 2 600 MWh and 3 100 MWh, respectively. Based on the above electricity price, the calculated electricity cost for the University would approximately be 1 999 292 €. Similarly, the average price of district heating is 68.6 €/MWh (Statistics Finland, 2012). The cost of heating is approximately 1 749 300 €. In Ambiotica building, the calculated electricity and heat expenses are 208 000 € and 212 660 €, respectively.

According to the Ministry of the Environment (2012) the carbon tax in Finland was 20€/tonCO_2 in 2010. As the general structure of energy taxation in Finland changed 1.1.2011 towards more LCA based and separating for example heating and transportation (Ministry of the Environment, 2012), the value 20€/tonCO_2 is used to simplify the calculations. As the electricity consumption caused emissions of 4998 tonsCO2eq in the University level, the estimated carbon tax would be 99 960€. The corresponding value for Ambiotica building would be 10 400 €.

If it would be possible to sell the digestate to outside party, according to Murphy & Power (2009) the selling price could be up to 40 € per ton. This would of course enhance the economic potential of all scenarios. As the biowaste is not transported to Mustankorkea landfill, the University will save 104 € per ton of waste, i.e. the savings would be 10 220 € per year. Most likely if the digestate is transported to landfill for composting, there will be a gate fee for the digestate. This would lower the economic feasibility of composting the digestate. The amount of gate fee would need to be separately negotiated with Mustankorkea landfill. If digestate would be utilized in land application as a fertilizer, there would not be a gate fee.

4.5.1 Scenario 1

The monetary value for the electricity and heat produced in Scenario 1 and the possible savings compared to Reference Scenario are presented in Table 22. Results showed that on an average 8 121 € will be saved for the generated electricity and heat from the Run 2 compared to 2 985 € from Run 1. The benefits are much higher for Ambiotica (0.69-1.88 %) than for the whole University level (0.08-0.21 %).

Table 22: Monetary value of produced energy and savings in carbon tax as well as possible savings both University and Ambiotica level in Scenario 1 per year

	Run 1	Run 2
Electricity [€]	2 051	4 831
Heat [€]	586	2 399
Emissions [€]	348	891
Total [€]	2 985	8 121
Possible savings (/year)		
University	0.08 %	0.21 %
Ambiotica	0.69 %	1.88 %

4.5.2 Scenario 2

The monetary value of energy produced in Scenario 2 and the possible savings compared to Reference Scenario are presented in Table 23. In Scenario 2, an average it would be possible to save 8 509 € per year. The savings would be higher in Ambiotica than for the whole University.

Table 23: Monetary value of produced energy and savings in carbon tax as well as possible savings both University and Ambiotica level in Scenario 2 per year

	Run 1
Electricity [€]	5 288
Heat [€]	2 271
Emissions [€]	951
Total [€]	8 509
Possible savings (/year)	
University	0.22 %
Ambiotica	1.97 %

4.5.3 Scenario 3

The values for electricity and heat produced in Scenario 3 and the possible savings compared to the Reference Scenario are presented in Table 24. Even though the Run 2 would have higher emission savings from using the digestate as a fertilizer, it is not taken into account in the economic analysis as the emission savings would occur outside the system boundaries (i.e. in the Kalmari farm). As Run 3 upgrades biogas to biomethane and it is not used for electricity and heat cogeneration, possible savings are not calculated here. With

Scenario 3, it would be possible to gain 59 496 € savings per year. In Ambiotica level, the savings would be approximately 13 % and for the whole University 1.5 %.

Table 24: Monetary value of produced energy and savings in carbon tax as well as possible savings both University and Ambiotica level in Scenario 3 per year

	Run 1& 2
Electricity [€]	32 495
Heat [€]	17 882
Emissions [€]	6 119
Total [€]	56 496
Possible savings (/year)	
University	1.47 %
Ambiotica	13.11 %

4.6 Sensitivity analysis

In sensitivity analysis, the effect the different amounts of waste streams on the biogas production was evaluated. For each scenario, the amount of each feedstock is doubled one at a time and key parameters are compared to the nominal level. The change (i.e. the increase) is presented as a percentage. Then, the first feedstock amount is brought back to nominal level and next feedstock is doubled. For each analysis, the amount of water was also increased in order to maintain the TS level at 10 %. All other parameters are kept the same.

Also the effect of doubling the amount of feedstock one at the time has on the value of exported energy and possible savings in energy expenses are studied. The energy expenses are kept in baseline level i.e. the same as in the economic analysis. Also the energy prices are assumed to remain the same as in the Reference Scenario.

4.6.1 Scenario 1

For Scenario 1, the amount of biowaste in Run 1 was doubled and the changes in some key parameters are presented in Table 25. When the change is 50 %, the value is purely dependent on the amount of feedstock. If the change is different than 50 %, other factors affect the parameter. It would seem that the amount of exported heat is least dependent on the amount of feedstock as the amount of exported heat increases approximately by 71 % if the amount of biowaste increases by 50 %. As in Scenario 1 the only feedstock is biowaste, which is assumed to have same characteristics whether it comes from the University or from Kortepohja, the changes should be similar for Run 2.

Table 25: Illustration of the effect the feedstock has in Scenario 1, i.e. the amount of bio-waste is doubled and the change in key parameters is shown

	Run 1	Altered	Change
Energy and material outputs (/year)			
Digester input [ton]	270	500	46 %
Digester capacity required [m^3]	36	58	38 %
Digester retention time [d]	44	38	
Biogas (volume) [m^3]	15765	31530	50 %
Digestate [ton]	250	461	46 %
Electricity produced [GJ]	112	225	50 %
Heat produced [GJ]	160	321	50 %
Total energy output [GJ]	272	546	50 %
Energy inputs required (/year)			
Waste transport [GJ]	1	3	50 %
Digestate transport [GJ]	9	17	46 %
Total energy input [GJ]	160	270	41 %
Energy exports			
Generated electricity [GJ]	112	225	50 %
Generated heat [GJ]	160	321	50 %
Exported electricity [GJ]	92	196	53 %
Exported heat [GJ]	31	107	71 %
Exported energy [GJ]	123	303	59 %
Energy balance [GJ]	112	276	59 %
[GJ/ton]	0.4	0.6	
Energy ratio	0.6	0.5	

If the amount of feedstock is changed, the economics of the process will also be affected and this is presented in Table 26. In Scenario 1, the increasing of amount of biowaste would affect the value of exported heat the most as it would increase by 72 %. Possible savings in energy expenses would rise from 0.08 % to 0.19 % in University level and from 0.69 % to 1.68 % in Ambiotica level.

Table 26: Effect of doubling the feedstock amount has on the economic aspects in Run 1 of the Scenario 1

	Run 1	Altered	Change
Electricity [€]	2 051	4 400	53 %
Heat [€]	586	2 058	72 %
Emissions [€]	348	796	56 %
Total [€]	2 985	7 254	59 %
Possible savings			
University	0.08 %	0.19 %	
Ambiotica	0.69 %	1.68 %	

4.6.2 Scenario 2

The results for Scenario 2 sensitivity analysis are presented in Table 27. Doubling the amount of biowaste has much greater effect on the biogas production (48 %) as increasing the amount of garden waste (6 %). Adding garden waste would have negative effect on exported heat as the amount would decrease by 7 % while adding biowaste would increase the amount of exported heat by 60 %.

Table 27: Illustration of the effect the feedstock has in Scenario 2

	Run 1	Biowaste x2	Change	Garden waste x2	Change
Energy and material outputs (/year)					
Digester input [ton]	680	1220	44 %	800	15 %
Digester capacity required [m^3]	75	124	40 %	85	13 %
Digester retention time [d]	36	34	-8 %	35	-3 %
Biogas (volume) [m^3]	38 021	73 688	48 %	40423	6 %
Digestate [ton]	633	1 129	44 %	750	16 %
Electricity produced [GJ]	273	528	48 %	293	7 %
Heat produced [GJ]	391	754	48 %	418	7 %
Total energy output [GJ]	664	1 282	48 %	711	7 %
Energy inputs required (/year)					
Waste transport [GJ]	7	13	49 %	7	5 %
Digestate transport [GJ]	24	42	44 %	28	16 %
Total energy input [GJ]	346	593	42 %	390	11 %
Energy exports					
Generated electricity [GJ]	273	528	48 %	293	7 %
Generated heat [GJ]	391	754	48 %	418	7 %
Exported electricity [GJ]	238	460	48 %	254	6 %
Exported heat [GJ]	119	297	60 %	111	-7 %
Exported energy [GJ]	357	757	53 %	365	2 %
Energy balance [GJ]	318	689	54 %	321	1 %
[GJ/ton]	0.5	0.6		0.4	
Energy ratio	0.5	0.5		0.5	

When the amounts of feedstocks are doubled one at the time, the effects to the economic aspects in Scenario 2 are presented in Table 28. Doubling of biowaste amount would increase the possible savings from 0.22 % to 0.46 % in University level and from 1.97 % to 4.13 % in Ambiotica level while the doubling of garden waste has a smaller effect as the possible savings would only increase from 0.22 % to 0.23 % in University level and from 1.97 % to 2.02 % in Ambiotica level. Noteworthy is also that the value of exported heat would decrease by 7 % if the amount of garden waste is doubled.

Table 28: Sensitivity analysis for economic aspects in Scenario 2

	Run 1	Biowaste x2	Change	Garden waste x2	Change
Electricity [€]	5288	10240	48 %	5600	6 %
Heat [€]	2271	5625	60 %	2127	-7 %
Emissions [€]	951	1928	51 %	992	4 %
Total [€]	8509	17793	52 %	8719	2 %
Possible savings					
University	0.22 %	0.46 %		0.23 %	
Ambiotica	1.97 %	4.13 %		2.02 %	

4.6.3 Scenario 3

For Scenario 3 the changes in key parameters are presented in Table 29. Noteworthy is that, doubling of garden waste may lead in increase of only 1 % in total energy production and decrease in exported heat (by 1 %), while the energy balance would remain the same. Thus, increasing the amount of garden waste should be avoided. Highest increase in exported energy would be gained by increasing the amount of paper (43 %). Doubling the amount of cardboard would increase the energy balance by 9 % while doubling the amount of biowaste would increase the energy balance by 15 %. Doubling the amount of paper would increase the energy balance by 43 %.

Table 29: The increase in key parameters when feedstocks are doubled one at the time

	Run 1	Change (biowaste x2)	Change (garden waste x2)	Change (paper x2)	Change (cardboard x2)
Energy and material outputs (/year)					
Digester input [ton]	4 200	11 %	3 %	38 %	19 %
Digester capacity required [m^3]	412	11 %	3 %	38 %	17 %
Digester retention time [d]	33	-1 %	0 %	0 %	-2 %
Biogas (volume) [m^3]	211 173	14 %	1 %	40 %	13 %
Digestate [ton]	3 943	11 %	3 %	38 %	19 %
Electricity produced [GJ]	1 551	14 %	1 %	40 %	13 %
Heat produced [GJ]	2 216	14 %	1 %	40 %	13 %
Total energy output [GJ]	3 767	14 %	1 %	40 %	13 %
Energy inputs required (/year)					
Waste transport [GJ]	12	35 %	3 %	24 %	11 %
Digestate transport [GJ]	147	11 %	3 %	38 %	19 %
Total energy input [GJ]	1 552	13 %	3 %	36 %	17 %
Energy exports					
Generated electricity [GJ]	1 551	14 %	1 %	40 %	13 %
Generated heat [GJ]	2 216	14 %	1 %	40 %	13 %
Exported electricity [GJ]	1 462	13 %	1 %	41 %	13 %
Exported heat [GJ]	938	17 %	-1 %	46 %	6 %
Exported energy [GJ]	2 401	15 %	0 %	43 %	10 %
Energy balance [GJ]	2 215	15 %	0 %	43 %	9 %

The effect the doubling of feedstocks one at the time has on the economic in Scenario 3 is presented in Table 30. Smallest increase in value of energy is gained by doubling the amount of garden waste (increase of 0.6 %) while the highest increase would be gained by doubling the amount of paper (increase of 43 %). The possible savings could increase in University level from 1.5 % to 1.7 % if doubling the biowaste, stay the same if doubling the garden waste, rise to 2.6 % if doubling the paper and to 1.6 % if doubling the cardboard amount.

Table 30: Sensitivity analysis for economic aspects in Scenario 3

	Run 1 & 2	BW x2 [€]	(BW x2) [%]	GW x2 [€]	(GW x2) [%]	Paper x2 [€]	(Paper x2) [%]	CB x2 [€]	(CB x2) [%]
Electricity	32495	37440	13	32880	1.2	55040	41	37120	12
Heat	17882	21472	17	17767	-0.6	32997	46	19071	6
Emissions	6119	7110	14	6164	0.7	10556	42	6896	11
Total	56496	66022	14	56811	0.6	98593	43	63087	10
Possible savings									
University	1.5 %	1.7 %		1.5 %		2.6 %		1.6 %	
Ambiotica	13.1 %	15.3 %		13.2 %		22.9 %		14.6 %	

Note: BW=Biowaste, GW=Garden waste, CB=Cardboard

5 DISCUSSION

The study shows that the University of Jyväskylä is a large institute with enormous energy consumption compared to moderate waste production. The energy produced by the organic wastes generated at the University of Jyväskylä using a biogas plant cannot be sufficient to meet the energy demand of either University of Jyväskylä or Ambiotica building. The Scenarios 1 and 2 could replace at the most 1.7 % in Ambiotica's energy consumption. The Scenario 3 would have slightly better replacement level (12 % in Ambiotica level) but still the level is low. As the energy consumption is high so is the GHG emissions from the energy production. The emission savings from the Scenarios are moderate and the biogas plant and its operations cause GHG emissions. In all cases, though, the possible savings are higher than the emissions caused by the fossil fuel use in plant operations. In Run 2 in Scenario 3, the emission savings would be higher than in other cases as the digestate is utilized as fertilizer and assumed to replace mineral fertilizer. Upgrading the biogas to biomethane causes the highest emissions as it relies solely on fossil fuels in biogas plant operation and transportation. On the other hand, use of biogas for heat and electricity generation would utilize renewable energy (biogas) and the emissions are mainly associated from transportation and not from biogas plant operations.

To determine the full feasibility of the biogas plant utilizing the biodegradable waste from the University of Jyväskylä further studies are required: full economic analysis including payback time etc. and the LCA to determine whether it is sustainable to utilize the paper in the biogas plant instead of recycling it. Whether the biogas production from the waste generated at the University of Jyväskylä is feasible waste management option, depends on the definition of feasibility, the aim of the biogas plant (i.e. energy production, waste management or both) and which factors are used in the decision making. The biogas plant may have advantages that cannot be measured in money: research use, green image, utilization in teaching etc. Economic feasibility cannot be determined based on this thesis but in the energy production the feasibility remains unanswered: the biogas plant is self-sufficient as it can produce the energy it requires (except transport fuels) and still has energy for exporting, but the exported energy could only replace small amounts of energy consumption in the University. In the Run 3 of Scenario 3, the biogas is upgraded to biomethane but this is not studied in more detail. Further studies would be needed whether it would be more feasible to utilize the biogas as a biomethane instead using it to heat and electricity production. The feasibility would depend on how the biomethane is utilized: as a vehicle use, sold to outside party, used to replace natural gas in the University etc.

There are factors that could affect the biogas plant operations and the feasibility of the biogas plant. Pretreatment could enhance the biogas yield but also demand more energy, which is suggested for example by Thorin et al. (2012). The waste amounts from the University can differ. In this thesis only statistic of one year was available and thus it cannot be stated whether the waste amount would increase or decrease in the future. The method used for determining the waste amount also causes certain uncertainty: the waste amount is not measured but estimated based on the volume of the collection containers, drain intervals and the assumption the containers are 80 % full in every emptying. Also the energy consumption of the University could differ in the future. In order to the emission savings to be “real” i.e. lower the emissions from the fossil fuels, the replaced energy would have to be produced from fossil sources. As part of the energy the University consumes is already renewable, it would be difficult to ensure that the biogas does not replace other renewable energy.

5.1 Waste management

Currently the waste management of the University of Jyväskylä is mainly handled by the waste management company called Lassila & Tikanoja Ltd. The biowaste generated at the University is transported to Mustankorkea landfill to be composted. Other waste streams are transported to Lassila & Tikanoja logistics center. Most of the biowaste generated at the University is food waste (kitchen and restaurant waste) from the Sonaatti Ltd, which owns the restaurants and cafeterias located in the University premises. Rest of the biowaste is generated at the offices, personnel break rooms etc. In the calculations and modelling, it was assumed that the biowaste from the University and from Kortepohja Student Village has the same characteristics. In reality, there might be a big difference: the biowaste from Kortepohja should have similar properties as an average household waste whereas the biowaste from the University could have higher amounts of paper napkins from the restaurants and lower amounts of pure food waste as customers throw away only 74.3 grams of waste per day and there is little food making as most of the served food is prepared from semi-finished products. Also the biowaste from break rooms might mainly be coffee grounds and tea bags.

If evaluated based on the waste management hierarchy, currently the paper waste management is according to EU Directive on Waste Management (2008/98/EC) in level 2 as the paper is prepared for re-use or in level 3 as the paper can be recycled. Utilizing the paper waste stream in the biogas plant would lower the waste management hierarchy level to 4 into energy recover or to level 3 if the digestate is utilized as a fertilizer. Thus the utilization of pure biowaste could be seen to be the best option when considering solely the waste management aspect as according to the directive (2008/98/EC) Member States must apply the hierarchy as a priority in waste management. The classification of proposed biogas plant is dependent on the digestate use as according to the Green Paper on the management of bio-waste in the European Union (2008), AD can be classified as an energy recovery (level 4) or recycling (level 3), when digestate is used as a fertilizer. As Mustankorkea landfill sells the compost to be used on land, the biowaste management of the University is at the moment in level 3 according to the Green Paper on the management of bio-waste in the European Union (2008).

In addition that the digestate utilization affects the waste management category, it has practical issues in studied biogas plant. In scenarios, where the digestate was transported for composting, the solid and liquid fractions were separated by centrifuge. The solid fraction was composted and liquid fraction was circulated back to the process. According to Gallert et al. (2003) this may lead to accumulation of salts and ammonia causing inhibition of the process. Also according to Latvala (2009) the mechanical and thermal drying of the digestate has the potential to release odor emissions, and as the plant is planned to locate in the middle of University campus, odor control needs to be taken into account in plant design and in plant operations.

5.2 Comparison of the studied scenarios

As the Scenario 1 utilizes only biowaste with the highest methane potential, Scenario 1 has the highest proportionate biogas production when the biogas yield is divided either by the feedstock amount or the volume of the reactor. Utilization of only biowaste raises the question of process stability, as according to Hartmann et al. (2004) foodwaste may lead to ammonia toxicity. During the break down of the organic matter in the feedstock, the biowaste may produce high levels of VFAs, which according to Apples et al. (2008) decrease the pH level. This could affect the methane production, since methanogenic bacteria are sensitive to pH changes (Apples et al., 2008). Thus adding other feedstocks may balance the process.

The feedstock in Scenario 2 is the biowaste from the University and from Kortepohja Student Village and the garden waste collected from the University campuses. According to Hartmann et al. (2004) reason why garden waste has the worst methane potential is the high lignin content. Garden waste also covers only 5 % of the wastes suitable for AD. Utilizing garden waste has its advantages and disadvantages: with the garden waste (Scenario 2) the energy efficiency is slightly better than without it (Scenario 1) as more of the waste is generated closer proximity of the biogas plant, but at the same time it has low methane potential, it requires heating (i.e. consumes energy) and it increases the volume of the reactor without adding the biogas production significantly.

Scenario 3 would be the most feasible option if considering the energy production as the Scenario produced by far the most amount biogas. In Scenario 3, the feedstock was same in all Runs (i.e. all biodegradable waste streams from the University and the biowaste generated at the Kortepohja Student Village) but the Runs still varied: first Run separated the liquid and solid fraction of the digestate and circulated the liquid fraction back to the process while solid fraction is transported to landfill for composting, second Run transported the whole digestate to farm to be utilized as a fertilizer and third Run upgraded the biogas to biomethane to replace natural gas. The Run 3 has by far the largest amount exported energy but this is explained by the fact that other Runs are self-sufficient utilizing the produced biogas for energy demand and Run 3 utilizes solely imported energy. In terms of energy balance, upgrading the biogas to biomethane is better option than CHP as in the Run 3 it is assumed that the total energy output is the same as the energy in upgraded methane while in Runs 1 and 2 the energy output is the sum of heat and electricity produced. Thus the energy output of Runs 1 and 2 are affected by the generator efficiency and Run 3 is not affected by generator efficiency. The feasibility of upgrading biogas is determined by the utilization of biomethane and that is not considered in this thesis. The main emphasis was given to the combined heat and power production.

5.3 Energy and mass balances

For the biogas plant to be feasible, the energy balance should be positive i.e. the energy in the produced biogas should be higher than the energy input. According to Berglund & Börjesson (2006) the primary energy input usually corresponds to 20-40 % of the energy content in the biogas, while the variations in the energy output can be explained by system designs, properties of chosen raw materials and allocations. In the studied Scenarios, the energy input was for Run 1 approximately 59 % and for Run 2 approximately 49 % in Scenario 1, 52 % in Scenario 2, for Run 1 41 %, Run 2 48 % and for Run 3 46 % in Scenario 3 out of the output. It would seem that the assumptions done by Berglund & Börjesson (2006) and their conclusions are similar to the Run 1 of Scenario 3 but other runs in the thesis differ from their assumptions. They also state that the plant operations is the most energy demanding process requiring 40-80 % of the energy demand but if the feedstock requires lot of handling, considerable part of the energy input may be used in these operations. This assumption seems to be in line with the findings in studied Scenarios as for example in Run 1 of the Scenario 1 the CHP supplied electricity and heat covers approximately 90 % of the total energy input while the energy required for transportation (both waste and digestate) covers only 6 % of the input energy. Even in the Run 2 of the Scenario 3, in which the digestate transportation requires most of the energy, the transportation energy demand is 22.5 % of the total input compared that the CHP supplied heat and electricity covers 75.9 % of the energy input.

One factor in the energy balances of the Scenarios are the transportation distances both the waste streams and the digestate. Thus when more of the waste is generated close to the biogas plant i.e. at the University, it requires less energy than to transport is from the Kortepohja, which is located 2.7 km away. From the main campus the distance to the biogas plant is 800 m and from Ylistönrinne campus (figure 3) the distance is 1.7 km making the combined waste transportation distance 2.5 km. As the Mustankorkea landfill is located 6.7 km from the biogas plant compared to the Kalmari farm in Laukaa, which is located 17.9 km away, the energy required for transporting the digestate to composting is much less. Also the amount is less as only solid fraction is composted.

According to Kirchmayr et al. (2003) use of biowaste in the biogas plant requires a hygienisation unit for pasteurization of the waste based on the European Commission Regulation No 1774/2002. In the hygienisation unit, the feedstock is heated up to 70° C for 1 hour which requires lot of energy and thus affects the energy balances of the Scenarios. The Scenarios were major fraction of the feedstock is the biowaste (Scenarios 1 and 2) has lower energy balance as Scenario 3 in which smaller proportion of the total feedstock requires the pasteurization. In the Runs, where the digestate is taken to composting, it might be possible to plan the plant without the hygienisation unit according to Latvala (2009). But this would need to be negotiated with the Mustankorkea landfill.

All the Scenarios have similar mass balances but in the Scenario 1 higher fraction of the feedstock (7.4 %) is converted into biogas compared to Scenario 2 (6.9 %) or Scenario 3 (6.1 %). And as the aim of the process is to produce biogas, the higher the conversion rates, the better. As the methane is produced when VS breaks down (Latvala, 2009), the biowaste with the highest VS content produces most of the methane and thus the Scenario with highest proportion of biowaste has the highest conversion rate, i.e. the Scenario 1.

5.4 GHG emissions and possible savings

On the GHG emission point of view both the current and the proposed (i.e. AD process) waste management systems are advantageous compared to dumping the biodegradable waste to landfill untreated, as they release methane, which according to IPCC (2007) is 21 times more powerful GHG than CO_2. In addition, that utilizing AD process in biowaste management avoids methane emissions from landfills, it is according to Kymäläinen et al. (2012) a sustainable option as it produces biogas to replace fossil fuels in various technical applications.

Main cause for GHG emissions from the operation of the biogas plants is the transportation, which utilizes fossil diesel. That is why Run 2 in Scenario 3 has the highest emissions from transportation (approximately 30 tonCO_2eq) as the digestate is transported the longest distance (17.9 km) compared to Run 1 in same Scenario (with same amount of feedstock) that had transportation emissions of 12 tonCO_2eq with transportation distance of 6.7 km for the digestate. All other studied options are self-sufficient in energy demand (excluding transportation) except Run 3 in Scenario 3 in which the biogas is upgraded for biomethane and all demanded energy is exported. Thus the Run 3 has clearly the highest emissions (150 tonCo_2eq) from fossil fuel consumption compared to other options, for example Run 2 of Scenario 3 had the second highest emissions with 30 tonsCO_2eq.

In all studied Scenarios, the possible GHG emission savings when biogas replaces fossil fuel are bigger than the GHG emissions caused by the fossil fuel consumption in plant operations. The smallest margin is in the Run 3 of Scenario 3, where the possible savings are

248 tonsCO_2eq and total emissions from fossil fuel consumption 150 tonsCO_2eq, so when taking into account the emissions the real savings are 98 tonsCO_2eq. In all studied scenarios, more of the possible emission savings comes from the electricity generation than from the heat used. As the biogas plant requires lot of heat for pasteurization and maintaining mesophilic conditions, there is less heat available for exporting and thus electricity enables higher savings.

As discussed earlier, the digestate has major role in categorizing the process as well as factoring to the energy balance and the GHG emissions from fossil fuel consumption. But digestate also affects the possible savings, since if the digestate is used as a fertilizer to replace mineral fertilizer, it would increase the savings. In Run 2 for Scenario 3, this possibility was calculated and possible savings would be 28 tonsCO_2eq. Thus the total savings would be 334 tonsCO2eq minus the emissions from transportation (30 tonsCO_2eq) making it 304 tonsCO_2eq. For Run 1 in Scenario 3 (which is otherwise same as the Run 2, but the digestate is composted) the emission savings would be 294 tonsCO_2eq when from the total savings (306 tonsCO_2eq) is reduced the emissions from fossil fuel consumption (12 tonsCO_2eq). So even though the transportation distance is longer in Run 2 than in Run 1, it has higher emission savings do to the fertilizer use.

5.5 Economic analysis

The economic aspect in this thesis is not covered in such detail that the economic feasibility of the project could be determined. Solely based on the energy value and carbon tax, the Scenario 3 could give at the most monetary savings of 13 % in Ambiotica level. This value is only for one year and it does not take into account for example the changes in energy prices. Thus based on this value it cannot be assumed that the savings would be 13 % every year. Also the energy consumption of the Ambiotica could change and thus affect the savings level. The building, maintenance, operation, payback time and other costs and expenses of the biogas plant are not evaluated at this thesis - hence the savings most likely are smaller in reality.

The possible economic savings are compared to calculated expenses based on approximate energy consumption and an average energy prices. In all Scenarios, there is more electricity to be exported than heat and thus most savings are from the electricity. As the Scenario 3 has the higher volumetric biogas production and thus highest energy production from all the studied Scenarios, it also has the highest savings reaching approximately 13 % in Ambiotica level. As the garden waste added in Scenario 2 requires lot of heating without producing much biogas, the monetary value of heat produced is 2 271 €, which is less than the monetary value of heat produced in Scenario 1. But as the Scenario 2 produced more biogas than Scenario 1, the total savings from Scenario 2 are 388 € higher. Taking into account the need for transportation and energy when adding garden waste, it most likely is not economically feasible to add garden waste to the AD process.

5.6 Sensitivity analysis

Sensitivity analysis in this thesis tries to demonstrate how much the operations of the biogas plant are dependent on single waste stream in the different Scenarios. In the sensitivity analysis, if the change is close to 50 % when the feedstock is doubled, the parameter is dependent mostly on the amount of feedstock. But as for example, the biogas production is also dependent on the VS content and methane potential, doubling the amount of feedstock might give change different from 50 %. Noteworthy is that for example adding of garden waste in Scenario 3 by 50 %, would not seem to have an effect on the energy balance as the change is 0 %. The highest increase in energy balance could be reached by adding paper in Scenario 3. As there are different amounts of feedstocks in Scenario 3, doubling the amounts one by one does not give the whole picture of the effects the increase might have. For example, if in the beginning there would be same amount of biowaste and paper, doubling the amount of biowaste would increase the biogas yield more than doubling the amount of paper. This is due to the higher methane potential and VS content of the biowaste. But as the University generates over 2.7 times more paper than biowaste, doubling the amount of paper has more advantages in the sensitivity analysis.

Changing the major variable i.e. the amount of feedstock affects most of the key parameters studied in the sensitivity analysis. Only parameters not affected are the retention time when amounts of garden waste and paper are doubled in Scenario 3 and the amount of exported energy when amount of garden waste was increased in Scenario 3. These parameters are neither affected by the amount of feedstock or the affect cannot be noticed due to other factors, for example the retention time is dependent on the reactor size and organic loading rate, which is kept as the same. The energy required for transportation changes linearly i.e. approximately 50 % in Scenario 1 as biowaste is the only feedstock and there is assumed to be only one collection point in every location. In Scenario 3, on the other hand, the energy required for transportation changes differently than in Scenario 1 depending on which waste stream is increased and the proportion of that waste stream. So in Scenario 3, the logistics are more complex than in Scenario 1 making the total energy required for transportation less dependent on one waste stream. The energy production parameters (energy input, output, exported energy, energy balance etc.) change in the sensitivity analysis as both the energy production and energy demand are dependent on the feedstock amount but the change is not necessarily around 50 % as the energy production is dependent on other factors (methane potential, VS content etc.) and the energy demand about for example the heat requirements. For example, adding biowaste requires more heat than adding of paper as the biowaste needs to be pasteurized and paper does not.

6 CONCLUSIONS

Currently the biowaste generated at the University of Jyväskylä is composted and sold as a landscaping material by Mustankorkea landfill. Other waste streams are transported to Lassila & Tikanoja Ltd logistics center to processing. At the moment the rate for recycling and reuse are high which is the target of EU Waste Directive. But composting is not waste-to-energy technology i.e. possible energy is lost.

The University produces 2.7 times more paper than biowaste, thus biowaste from the Kortepohja Student Village was added. From the possible waste streams, biowaste is the "best" feedstock in terms of biogas production due to its high methane potential and VS content. But using purely biowaste may lead to unstable process. As the amount of paper is much bigger than biowaste, in the end it produces more biogas than biowaste.

Three possible biogas plants i.e. Scenarios were studied. From these, the Scenario 3 produced by far the most volumetric amount of biogas and thus most amount of energy, both heat and electricity. The Scenario 3 was thus the most feasible based on the studied parameters. Scenario 2 was questionable due to the adding of garden waste as it did not add much to the energy output but increased the energy demand of the plant. So adding of garden waste can make the process less efficient and thus less feasible.

All Scenarios produced more energy than they consumed during plant operations making them self-sufficient and they all produced energy also for exporting. This makes it possible to cover some of the University energy demand by the energy from the biogas plant. The only exception, where all Scenarios require imported energy, is the diesel oil used in transportation. This is also the source of GHG emissions from fossil fuel consumption. All Scenarios though enable higher emission savings when renewable energy (biogas) replaces energy from fossil sources than the caused emissions from fossil fuel consumption.

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