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DEVELOPING THE ANAEROBIC DIGESTION PROCESS THROUGH TECHNOLOGY INTEGRATION

Johan Lindmark

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School of Business, Society and Engineering

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DEVELOPING THE ANAEROBIC DIGESTION PROCESS THROUGH TECHNOLOGY INTEGRATION

Johan Lindmark

Akademisk avhandling

som för avläggande av teknologie doktorsexamen i energi- och miljöteknik vid Akademin för ekonomi, samhälle och teknik kommer att offentligen försvaras onsdagen den 19 november 2014, 09.00 i rum R2-025, Mälardalens högskola, Västerås.

Fakultetsopponent: Dr. Renaud Escudié, INRA

Akademin för ekonomi, samhälle och teknik

Abstract

Process optimization is needed for the development and expansion of the biogas industry and to meet the ever growing demand for methane. This thesis explores process technologies for the development of the anaerobic digestion process and includes pre-treatments, studies on the effects of different mixing modes and evaluation of a water treatment technology.

Two pre-treatments were evaluated, mechanical and electroporation, for treatment of ley crop silage. Mechanical treatment included two milling machines designed for recycling of paper, Grubben deflaker and Krima disperser, and showed an increased biogas production of 59 % and 43 % respectively as well as a positive energy balance and economic results.. Electroporation increased the biogas production with 16 %, however, development is needed to increase its energy efficiency.

Digester mixing has an effect on the digestion result. The performed review and experiments show that the mixing demand increases with organic loading. Excessive mixing during process start up, instabilities and shock loads leads to increased volatile fatty acid concentrations and process inhibition. Reduction of mixing reduces the effects of process instabilities and periodical mixing with mixing breaks has been shown to be beneficial for biogas production.

A high temperature membrane filtration unit was evaluated at 70 °C, 90 °C and 110 °C to determine separation efficiencies, permeation speed when treating process water at a biogas plant. Improved separation can increase the capacity of the substrate pre-processing and reduce process related problems. The results show a total solids separation of 60 %, and an increasing filtration speed with temperature with fluxes of between 113 and 464 L/ h m^2. The substrate pre-processing could theoretically handle up to 29 % more substrate as a result.

Integration of these technologies in a biogas plant show that the pre-treatments studied exhibits a good performance when integrated and that mixing reduction has the potential to lower the process electricity demand by 23 % in the performed case study. However, even though the membrane filtration unit shows promising results it would demand a relatively high energy consumption and lead to limited benefits to a process already at it maximum organic loading.

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Dedicated to my family!

English summary

Process optimization is needed for the development and expansion of the biogas industry and to meet the ever growing demand for methane. This thesis explores a number of different process technologies and applications for the development of the anaerobic digestion process including pre-treatment, mixing modes and water treatment technology.

The evaluated pre-treatments were performed on ley crop silage as substrate, which is made up out of different types of grass and clover, which are usually planted in the crop rotation in ecological farming and are readily available in Swedish agriculture. The evaluation included two types of mechanical treatments with full scale machines originally designed for recycling of paper, the Krima disperser and the Grubben deflaker, and a pre-treatment method called electroporation which applies electric fields to break up the substrate. Both mechanical pre-treatments reduced the particle size of the ley crop silage - the deflaker and disperser treatments increased methane yields by 59 % and 43 % respectively. Energy calculations show that both disperser and deflaker have a positive energy balance and that the energy efficiency of the deflaker is greater due to its low energy demand and large treatment capacity. Electroporation was performed at laboratory scale to evaluate its potential for treatment of ley crop silage. The results show increased methane yields of up to 16 %, but also that the energy efficiency of the treatment needs to be improved further to compete with other treatments. The main drawback of mechanical treatments compared to electroporation is the amount of wear on the equipment during treatment.

Mixing in the anaerobic digestion process is seldom actively controlled and is mainly used to maintain the substrate in suspension and to improve mass transfer within the digester. Mixing experiments, comparison of different modes of mixing at different organic loadings, and a review of current literature on the subject were used to shed light on the effects of mixing on the process. The demand for mixing has been shown to increase with the organic loading. At low loadings low mixing is needed but at higher organic loadings insufficient mixing can reduce the biogas production rate. Negative effects of excessive mixing have been observed in several studies during process start up, as well as during instabilities and shock loads, with increased production of volatile fatty acids and process inhibition as a result. Reduction of mixing during process instabilities has also been shown to reduce the effects of overload and increase the rate of process recovery. The mixing experiments performed as part of this thesis also show that high intensity mixing can inhibit the anaerobic digestion process without affecting the level of volatile fatty acids and that high intensity mixing can have a negative effect on the biogas process at both low and high organic loadings. Reducing mixing intensity and mixing periodically with mixing breaks (intermittent mixing) has been shown

to be beneficial for biogas production in many studies, and in other cases biogas production is similar but with the benefit of a reduced energy demand for mixing.

During digestion, solid substrates are often diluted with recirculated process water produced by dewatering the already digested material. The quality of such process water can affect the capacity of the process when the recirculation leads to accumulation of suspended materials or inhibitory compounds. A study was performed to evaluate the use of a high temperature high rate compact membrane filtration unit for reduction of suspended solids in the process water of a co-digestion biogas plant. This was done to increase the capacity of the substrate pre-processing to produce a suitable feed for the process and to reduce process related problems in connection to an increasing dry solid content of the process water. The experiment was performed at 70 °C, 90 °C and 110 °C and shows increased fluxes with increasing temperatures, and maximum fluxes of between 113 to 464 L/ h m^2 and approximated steady state fluxes of 70, 100 and 190 L/ h m^2 for the respective temperatures tested. A total solids separation of around 60 % was attained at all the evaluated temperatures. This translates to a theoretical increase in capacity in the feed production of up to 29 %. The possibility to add more substrate to the digestion process is however limited by the organic loading rate. There is a positive energy balance for the filtration process and an evaluation of the capital and operational cost has been performed for four cases and installation sizes. The high cost of the installation makes the economic calculations very sensitive to the approximations and assumptions made about the operation of the membrane filtration unit.

To evaluate the possibility to integrate these technologies in a full scale biogas plant a case study was performed to theoretically calculate their impacts on the Växtkraft biogas plant in Västerås, Sweden. The case study shows a large energy demand of the water treatment and limited benefits to the gas production because of an already high organic loading rate. The mechanical pre-treatment and the electroporation show a substantial effect on the methane yield of the process of 2-6 %, even though ley crop silage only makes up for 12 % of the substrate. Reducing the mixing has the potential to save up to 23 % of the total electricity demand of the process, however, there is as of yet no possibility to determine the resulting biogas production in a full scale installation as an effect of a changed mixing regime.

Sammanfattning

För att kunna möta den ständigt ökande efterfrågan på metan, öka konkurrenskraften gentemot andra typer av förnybara energikällor samt att stödja utbyggnaden av biogasindustrin krävs det att biogasprocessen utvecklas och optimeras ytterligare. I denna avhandling utvärderas ett antal olika processteknologier och applikationer för utvecklingen av den anaeroba rötningsprocessen. Avhandlingen inkluderar två olika typer av förbehandlingar: en utvärdering av effekten av olika omrörningsintensiteter i rötkammaren och en utvärdering av en högtemperatursapplikation av membranfiltrering för att reducera partikulärt material i processvattnet.

Avhandlingen utforskar möjligheterna till ett förbättrat utnyttjande av ensilerad vallgröda, som används i växtföljden vid ekologisk odling, genom två olika typer av förbehandlingar: mekanisk förbehandling och elektroporation.

Förbehandling av ensilerad vallgröda utfördes och utvärderades i full skala med två olika maskiner för mekanisk sönderdelning som ursprungligen var avsedda för återvinning av papper, dispergeringsmaskinen Krima och Grubben deflaker. Resultaten av de två mekaniska förbehandlingarna visar på en bra storleksreduktion av vallgrödan samt ökade metanutbyten med 59 % för deflakern och 43 % för dispergeringsmaskinen. Energiberäkningarna visar att båda maskinerna har en positiv energibalans och då speciellt deflakern på grund av dess låga energiförbrukning och höga kapacitet.

Elektroporeringen utfördes i laboratorieskala för att utvärdera dess potential att förbehandla ensilerad vallgröda. Resultaten visar på 16 % högre metanproduktion än för det obehandlade materialet och en positiv energibalans. Energibalansen måste dock förbättras för att kunna konkurrera med andra typer av förbehandlingar. Den huvudsakliga nackdelen med mekanisk behandling jämfört med elektroporation är det stora slitaget som utrustningen utsätts för under förbehandlingen, vilket också återspeglas i driftkostnaden av förbehandlingen.

Omblandningen i rötkammaren är sällan aktivt kontrollerad och utförs i första hand för att hålla substratet i suspension och minska risken för sedimentering och flotation av materialet samt att förbättra transporten av olika näringsämnen. Litteraturstudien och de utförda experimenten har lett till att flera slutsatser angående effekten av omblandningen på biogasprocessen har kunnat göras. Under experimenten gjordes observationer som visar att en låg omblandningsgrad av rötkammare kan vara lämpliga vid låg organisk belastning men att omblandningens betydelse ökar med den organiska belastningen och att en intensiv omblandning kan resultera i ett minskat metanutbyte jämfört med lägre omblandningsintensiteter. Litteraturstudien

gav liknande slutsatser om effekterna av omblandningsintensiteten men visade även på att ett byte från kontinuerlig omblandning till periodisk omblandning är fördelaktigt för den anaeroba processen och gasutbytet. Den visar också på negativa effekter av för kraftig omblandning under uppstart av processen, en negativ påverkan på instabila processer samt negativa effekter vid tillfälliga överbelastningar med ökad produktion av flyktiga fettsyror och hämning av processen. Minskad omblandning under instabila förhållanden har också visat sig minska effekterna av överbelastningen, med snabbare processåterhämtning som följd.

Experiment för behandlingen av processvattnet på en biogasanläggning med hjälp av en kompakt högtemperatursapplikation av membranfiltrering har genomförts. Kvaliteten på processvattnet kan påverka kapaciteten hos processen då det återcirkulerade processvattnet leder till ansamling av suspenderat material eller inhiberande föreningar i rötkammaren. I denna studie utvärderades avskiljningen av det suspenderade materialet från processvattnet vid en biogasanläggning. Genom att avskilja suspenderat material kan kapaciteten i substratförbehandlingen öka genom att förändra blandningsförhållandet mellan processvatten och substrat för att producera en lämpligt tjock suspension att pumpa till rötkammaren. Genom att höja temperaturen på processvattnet innan filtrering ökar filtreringshastigheten och en kompaktare membranfiltreringsenhet kan utnyttjas för att producera större volymer. Experimenten utfördes vid 70 °C, 90 °C och 110 °C och visar på ökade flöden av permeat vid högre temperaturer och maximala flöden mellan 113 till 464 L / h m^2 och approximerade flöden runt 70 , 100 och 190 L / h m^2 för de olika temperaturerna under mer kontinuerliga driftförhållanden. En total separering av fasta partiklar uppnåddes under filtreringen, vilket innebar en torrsubstans reduktion runt 60 % för de utvärderade temperaturerna. Teoretiskt kan detta innebära en ökad kapacitet i substratförbehandlingen med upp till 29 %. Möjligheten att tillföra mer substrat till rötningsprocessen är dock begränsad av den organiska belastningen som rötkammaren kan hantera. Energibalansen för membranfiltreringen är positiv och en utvärdering av investeringskostnaden och driftskostnaderna för fyra olika process-vattenflöden och installationsstorlekar har utförts. De generellt höga kostnaderna för installationerna gör de ekonomiska beräkningarna mycket känsliga för de approximationer och antaganden som görs runt driften av membranfilteranläggningen.

Möjligheten att integrera de studerade teknikerna i en fullskalig biogas-anläggning utvärderade genom en fallstudie av samrötningsanläggningen Växtkraft i Västerås. Beräkningarna visar på en relativt hög energiförbrukning

för att rena processvattnet och att nyttan med en membrananläggning är begränsad av att den organiska belastningen i rötkammaren redan ligger på en hög nivå. Den mekaniska förbehandlingen och elektroporationen visar på ett ökat metanutbyte från processen med 2-6%. Detta trots att ensilerad vallgröda bara utgör 12 % av den totala substratmängen. Att minska omblandningen i rötkammaren har en potential att spara upp till 23 % av anläggningens totala elkonsumtion. Det finns dock ingen möjlighet att idag teoretiskt fastställa den resulterande biogasproduktionen i en fullskalig anläggning som en effekt av en förändrad omblandningsstrategi.

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Author's contribution

I. Participated in the planning and execution of the experiments. Performed the digestion experiment and most of the evaluation and writing.

II. Participated in the planning and execution of the experiment and startup of the digestion experiment. Performed most of the evaluation and writing.

III. Conducted the literature review and wrote most of the paper.

IV. Led the planning and participated in the execution of the experiments. Performed most of the evaluation and writing.

V. Participated in the planning and conducted the experiments. Performed most of the evaluation and writing.

Parts of this thesis were previously presented in the Licentiate thesis "The wet Fermentation Biogas Process – Limitations and possibilities for efficiency improvements".

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Abbreviations

BMP	Biochemical methane potential
CSTR	Continuously stirred tank reactor
OLR	Organic loading rate
SSOFMSW	Source-sorted organic fraction of municipal solid waste
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

1 Introduction

There is an urgent need for a shift towards renewable energy sources to combat the increasing release of greenhouse gases from human activities and to prepare for the unavoidable depletion of fossil fuels. Biogas production from waste fractions and from agricultural resources is a potentially important energy carrier in the future fuel mix of the transport sector. Biogas production in Sweden currently accounts for 1.6 TWh per year of energy use (Swedish Energy Agency, 2013) and the forecast for 2015 suggests an increase to 2.5 TWh based on currently planned expansions (Energy gas Sweden, 2013a). The total biogas potential in Sweden has been estimated at 15 TWh per year, with 70 % coming from the agricultural sector (Linné et al., 2008).

Swedish regulations prohibit landfilling of organic materials (SFS 2001:512). This has driven the adoption of the biogas process as a common treatment method for organic waste. The ban on landfilling and the European goal of 20 % renewable energy generation and 10 % renewable energy in the transport sector by the year 2020 (European commission, 2012) have strengthened the position of the biogas industry. Sweden aims to make the vehicle fleet independent of fossil fuels by 2030 (Swedish Ministry of Industry, 2008), and the expansion of the biogas industry is expected to be an important part of this transition. The biogas process has three different functions: (i) to treat organic waste streams to reduce the amount of solids; (ii) to produce biogas for conversion to heat, electricity, upgrading to transportation fuel or for injection into a natural gas grid; and (iii) to produce fertilizer, which will increase in importance as phosphorus becomes scarce.

Agricultural raw materials and waste fractions are abundant resources in our society. They have great potential as substrates for biogas production and the infrastructure for planting, harvesting and storing these materials is already in place. Weiland et al. (2010) and Ward et al. (2008) highlight the agricultural sector as an important source of substrates for the anaerobic digestion process. A survey conducted for the Swedish government (Swedish Ministry for Rural Affairs, 2007) also highlights energy crops such as sugar beet, ley crop, corn and straw for their wide availability and large potential for biogas production. However, energy crops account for a small proportion of present day biogas production (Swedish Energy Agency, 2013).

Biogas production is however not the only measure of efficiency improvement. The energy efficiency and economic efficiency of the biogas plant are equally important from a sustainability viewpoint. Lower energy

demands and higher profit margins are critical for the development and expansion of the biogas market. The economic efficiency is especially interesting since it summarizes the efficiency of the process by adding income and subtracting the costs, weighted by how the different inputs and outputs are valued by the society.

Ward et al. (2008) identified digester mixing, environmental conditions in the digester, monitoring and control and the need for pre-treatments to increase the biogas yield as some of the key factors in developing the anaerobic digestion. The research trends have followed a similar path and have included pre-treatments, microbial community dynamics, modeling as well as upgrading (Appels et al. 2011). This thesis considers measures to increase the efficiency of an anaerobic digestion system by studying and evaluating different technical solutions and issues regarding their integration. Studies to optimize the anaerobic digestion process were performed by evaluating two pre-treatment methods for ley crop silage (paper I and II), studying the effects of mixing on the process (paper III and IV) and studying how a high temperature high rate ultrafiltration membrane unit may increase process capacity by treating the plant's recirculated process water (paper V). The thesis focuses on ley crop silage substrate since it is a widely available agricultural substrate used for biogas production in present day Sweden and is a potentially important substrate for future expansion of the Swedish biogas industry (Swedish Ministry for Rural Affairs, 2007). Source sorted organic fraction of municipal solid waste (SSOFMSW) was used in the mixing studies, as it is more homogeneous and it is a likely co-digestion substrate along with ley crop silage. In the pre-treatment experiments, two conventional and commercial machines were evaluated for mechanical treatment alongside electroporation, which is a developing technology. In order to gain a system perspective the process was studied from both pre- and post-digestion perspectives.

1.1 Objective and research questions

Optimization of a biogas plant can be performed from the perspective of energy efficiency, economic efficiency, methane production, substrate utilization and the capacity of the anaerobic digestion. Even though some of the key factors for digestion optimization are known the impacts of these process improvements on the system as a whole are still undetermined. Where is the largest potential for improvement of the anaerobic digestion process to be found, and is it worth the investment of energy and capital? The system perspective is crucial, because each change in the system also affects downstream stages of the process in different ways. Changes in the environmental conditions affecting the microorganisms in the digester may also nullify any attempted improvements. Sub-optimal operation can result if

the process changes are viewed as isolated stages in the system. An overview of each of these aspects is needed to avoid sub-optimizing the process.

The objective of this thesis is to explore different technical solutions and issues concerning their integration to improve the overall efficiency of the anaerobic digestion process. The technologies studied in this thesis are adaptions and technology transfers from other industries and are carried out as experiments at laboratory, pilot and full scale, working with experimental setups built by industrial partners and experts in the respective field. Digester mixing regimes are also studied to improve digester performance and stability. The studied system focuses on digestion using ley crop silage and SSOFMSW as substrate. This work includes:

- An experimental evaluation of two pre-treatment methods to increase the production of biogas from ley crop silage. (paper I and II)
- A review of previous studies on the effects of mixing on the anaerobic digestion process. (paper III)
- An experimental evaluation of the effects of different mixing intensities during continuous mixing compared to minimally intermittently mixed anaerobic digesters. (paper IV)
- An experimental evaluation of process water treatment using a high temperature high flow membrane filtration technique, including an economic evaluation of a full scale installation. (paper V)

Each of the technical solutions studied has an effect on the process and gives an indication of the extent to which it is possible to affect the efficiency of the anaerobic digestion through retrofitting of individual process steps. The studies described in this thesis addresses the optimization of the anaerobic digestion process by evaluating the impact of different process changes and providing concrete answers to the stated research questions:

- What influence can mechanical and electroporation pre-treatment of the lignocellulosic material ley crop silage have on the biogas production during anaerobic digestion? (Q1)
- What effect does digester mixing have on the anaerobic digestion process and the production of biogas? (Q2)
- How can membrane filtration be used to treat large amounts of process water to improve the anaerobic digestion process? (Q3)

1.2 Thesis structure

The thesis is divided into the following six chapters:

Chapter 1 *Introduction*
Introduction to the subject and the research topic.

Chapter 2 *Literature review*
Previous research related to the studies in the thesis.

Chapter 3 *Materials and Methods*
Describes the methodologies, experiments and analyses performed in this thesis.

Chapter 4 *Results and Discussion*
Presents the results of the studies performed and discusses the significance of these results.

Chapter 5 *Conclusions*
Summarizes the main results of the thesis.

A graphical presentation of the different studies performed in this thesis work and the included papers is presented in Fig. 1, showing the experiments, the analyses performed, and the review, relating them to the individual research question (Q1–Q3). The technologies studied are connected to the three different stages of industrial biogas production, namely substrate preparation, digestion and digestate post treatment. For substrate preparation, mechanical pre-treatment and electroporation was performed on ley crop silage and analyzed through batch wise digestion. Digestion results during different mixing intensities and mixing regimes were studied through mixing experiments and literature review. Experiments on process water treatment by membrane filtration were evaluated in a high temperature application. The integration of the technical solutions studies in the biogas process is addressed further in Chapter 3 (materials and methods) and in the system perspective section (Chapter 4 and Section 4.3).

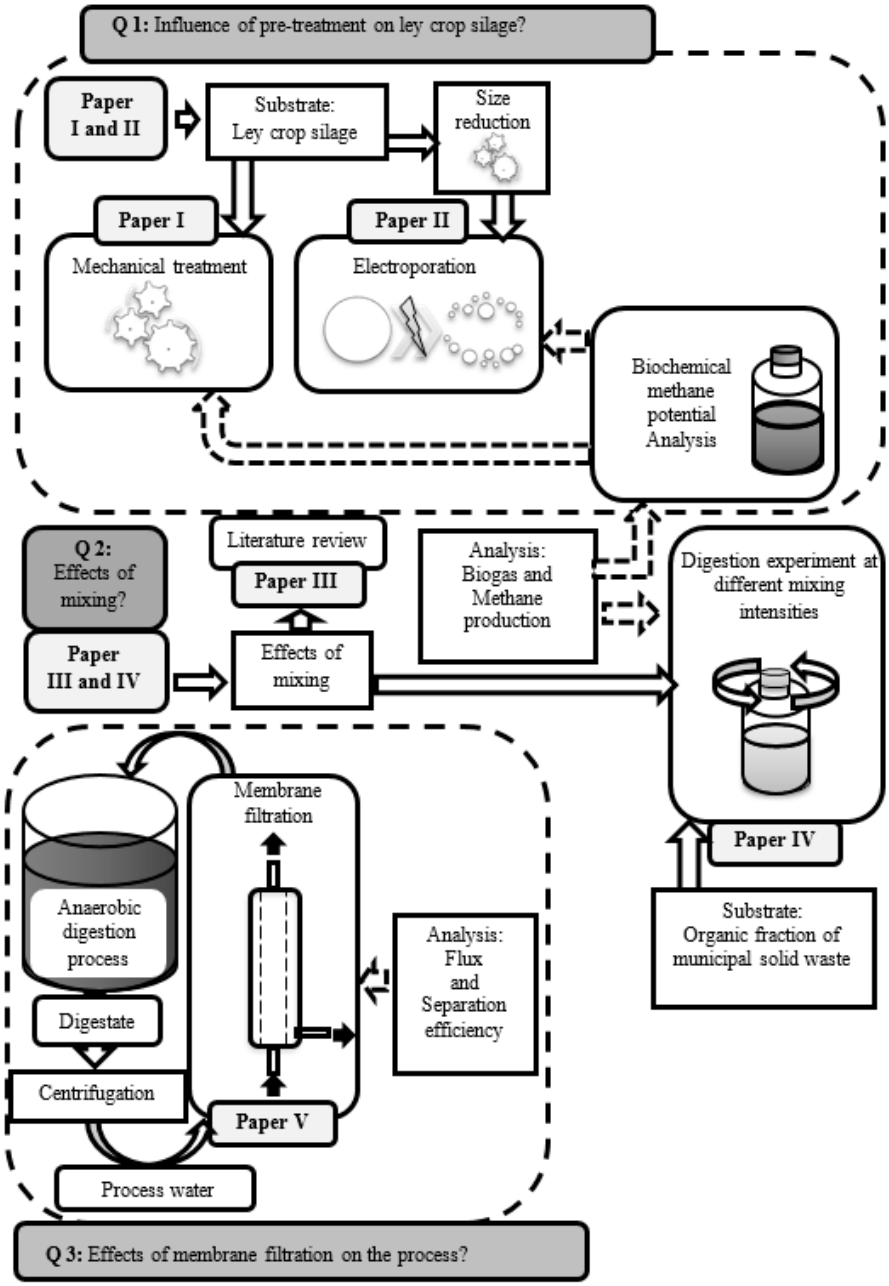

Figure 1. Graphical presentation of the thesis work and included papers
Shortened versions of the research questions are included to indicate the aim of the studies (Q1–Q3). The solid line arrows show the research performed and the dotted arrows show the main analysis.

2 Literature review

2.1 The anaerobic digestion process

Anaerobic digestion is a naturally occurring process in which organic material is broken down under anaerobic conditions, producing a mix of gases called biogas, which is mostly made up of energy rich methane (CH_4), and carbon dioxide (CO_2). Anaerobic digestion can be broken down into four distinct steps: (i) hydrolysis, where complex organic compounds like carbohydrates, proteins and fats are broken down to sugars, fatty acids and amino acids; (ii) acidogenesis, where these components are broken down further to fermentation products e.g. short-chain organic acids, alcohols, hydrogen and carbon dioxide; (iii) acetogenesis, where acetate, hydrogen and carbon dioxide are produced from the products of acidogenesis; and (iv) methanogenesis, where methane and carbon dioxide are formed (Deublein & Steinhauser, 2008).

The industrial process of biogas production can be divided into three different process steps: (i) substrate preparation; (ii) anaerobic digestion; and (iii) digestate post-treatment. The substrate preparation is dependent on the type of substrate, but can include contaminant removal (e.g. sand, rocks and different waste fractions like metal and plastics), feed production (producing a suspension by mixing substrate and water to obtain a suitable TS content), and pre-treatments that cause substrate disintegration and hygienisation. Anaerobic digestion is performed by microorganisms in the digester and control over this stage is limited to the environmental conditions created in the digester. Practical control measures in an anaerobic digester include the OLR and characteristics of the feed (substrate/feed composition and degree of disintegration), possible additives (e.g. trace elements or enzymes), hydraulic retention time (HRT), process temperature and mixing. Analysis of TS, VS, pH, alkalinity, ammonium and VFA are commonly performed at weekly or biweekly intervals in Swedish biogas plants to evaluate the status of the digestion process (Lindmark, 2012). Digestate post-treatment can include post digestion, dewatering and other types of water treatments, depending on the use or disposal method of the digestate.

2.2 Evaluating the methane potential

The biogas potential of a substrate can be determined by performing a batch digestion experiment called a biochemical methane potential (BMP) experiment. A BMP experiment is an anaerobic batch digestion setup where a known amount of substrate is digested in a 100–2 000 ml digester with a starter culture of microorganisms, usually taken from an active biogas process, and incubated in an air tight reaction flask at a fixed temperature (Angelidaki et al., 2009).

At startup all BMP digesters are flushed with nitrogen gas or a nitrogen/carbon dioxide gas mix to establish an anaerobic environment and the digester can be topped off with water to obtain a fixed liquid and headspace volume for easier gas volume determination (Hansen et al., 2004). Biogas production can be measured through pressure measurements and volumetric methods and samples can be extracted for gas composition analysis using a gas chromatograph (Angelidaki et al., 2009) or by gas separation through absorption (Raposo et al., 2011). Each substrate evaluated should be digested at least in triplicate to establish the variability and reliability of the measurements as well as statistical significance (Angelidaki et al., 2009). Control digesters containing a reference substrate such as cellulose can be used for quality control of the inoculum by comparing the results with digestion results of a standard substrate in previous studies, but also to determine the homogeneity of the inoculum by observing the variation between the control digesters (Hansen et al., 2004). Using a control substrate enables the BMP result to be standardized, making comparisons with other substrates and experiments easier and more reliable. The inoculum to substrate ratio is an important factor that can influence the rate of digestion and the digestion dynamics, but it only has a small effect on the total biogas yield (Raposo et al. 2006; Raposo et al., 2011). However, the inoculum to substrate ratio should be sufficient to avoid acidification of the process (Neves et al. 2004; Angelidaki et al., 2009). Evaluation of the effects of a pre-treatment can also be performed by setting up a batch digestion experiment (Bougrier et al., 2006;, Vlyssides & Karlis, 2004; Kim et al., 2003) similar to the BMP experiment. However, because all comparisons are made between different samples within the experiment, a control substrate is rarely used. The digestion experiments performed as part of this work are presented in detail in Chapter 3. Fig. 2 shows the batch digestion setup, the BMP flasks and the incubator used to perform the experiments in paper I and IV.

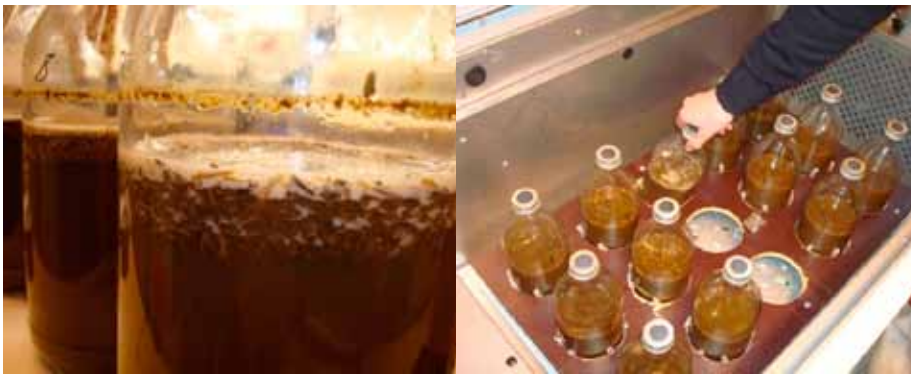

Figure 2. Biochemical methane potential experiment

2.3 Ley crop silage

Ley crop is composed of different types of grass, clover and other legumes that are used in crop rotation to naturally fertilize the soil with nitrogen. Ley crop silage is a lignocellulosic biomass mainly consisting of cellulose, hemicellulose and lignin that has been stored through an ensilaging process where the crop is fermented to keep the substrate from spoiling. The ensilaging process is used to store and make the ley crop available all year round. Ley crops have attracted attention as a potential substrate for biogas production in Sweden since before the turn of the last century (Lantz & Björnsson, 2011; Ström, 2010; Dalemo, 1993). The most recently opened biogas plant which uses ley crop as a co-substrate was inaugurated in Karlskoga, Sweden in January 2014. Fig.3 shows a ley crop sample and ensilaging tubes used for storage of the material. Ley crop silage can be used both as animal feed and as a substrate for anaerobic digestion.

Figure 3. Ley crop silage sample (scale in centimeters)

Hydrolysis and acidogenesis are the most difficult and time-consuming steps of anaerobic degradation of the lignocellulose rich ley crop silage, and thus the rate limiting step of the process (Zinder, 1984). Lignocellulosic biomass like ley crops can be difficult to break down completely during the relatively short retention time of most digesters, because of its complex structure, and as a result some of the bound nutrition and gas potential is necessarily lost (Monlau et al., 2013). Pre-treatments of the substrate may improve the digestion dynamics. Pre-treatments performed on ley crop silage include mechanical, thermal, ultrasound, extrusion and chemical treatments. However, of these only ultrasound and extrusion have been shown to increase biogas production (Nordberg & Edström, 1997; Bohman et al., 2011; Carlsson et al., 2013), and further studies to improve biogas yields are needed. Destruction of the crystalline structure of cellulose and the lignin structure are important for improving the methane yield when degrading lignocellulosic biomass (Chang & Holtzapple, 2000). Life cycle assessments of ley crop as a substrate for anaerobic digestion show that as much as 40 % of the total energy is used during cultivation and harvesting, which makes it important to utilize its full biogas potential (Berglund & Börjesson, 2006).

2.4 Pre-treatment

The quantities of proteins, carbohydrates and fats in the substrate determine the biogas yield (Carlsson & Uldal, 2009). However, the complexity of the substrate can affect its degradability by reducing the contact between the microorganisms and the substrate, effectively lowering the gas yield and the rate of digestion (Monlau et al., 2013). Pre-treatments of the substrate can

reduce this impediment by breaking up the material, giving the microorganisms and enzymes easier access to the material and the nutrients it contains (Hendriks & Zeeman, 2009). Pre-treatments can destroy the individual cells and compounds and make them more available for further degradation (Carlsson et al., 2012). However, pre-treatment can also lead to the formation of inhibitory substances such as furfural and phenolic compounds when lignocellulosic material is broken down (Hendriks & Zeeman, 2009). There is a wide range of pre-treatment types that can be used to improve the digestibility and gas production of the substrates and studies have been performed on an array of different substrates with varying results (Carlsson et al., 2012). Ley crop silage and other types of grass are abundant resources and developing pre-treatment methods are important for the efficiency of the digestion process for these types of substrates. Carlsson et al. (2012) and Hendriks & Zeeman (2009) have extensively reviewed the use and effects of different pre-treatments. Different pre-treatments are often combined and there is not always a clear division between treatments. Carlsson et al. (2012) subdivide the pre-treatments into the following categories: thermal, freeze/thaw, ultrasonic, other mechanical, chemical treatments, wet oxidation, microwave and pulsed electric fields. Most of the pre-treatments require energy input in the form of electricity or heat, except for the chemical treatment, which is based on the addition of a solvent, often an acid or alkali. The effects of the pre-treatments are often evaluated in a digestion experiment by observing the increased methane and biogas production, but they can also be identified by e.g. increased solubility or reduced particle size (Carlsson et al., 2012). Mechanical treatment and electroporation are two very different treatments which have shown promise from other applications as well as from the biogas industry, that could be used to further enhance the biogas production rate from ley crop silage.

2.4.1 Mechanical pre-treatment

Particle size and surface area of the substrate have been shown to affect the biogas yield of a substrate by altering the accessibility of biomass for microbial degradation (Jedrczak & Królik, 2007). A larger surface area enables a higher degree of contact between the microorganisms and the substrate, resulting in higher biogas yields. Following particle size reduction the rate and degree of degradation increases, especially for materials with high fiber content (Palmowski & Müller, 2003). Biomass with naturally low bioavailability and degradability shows the greatest improvement following particle size reduction (Palmowski et al., 2001). The biogas yield from some substrates can increase almost linearly with the increase in surface area (Jedrczak & Królik, 2007) and has been shown to be inversely proportional to the particle size (Mshandete et al., 2006; Hills & Nakano, 1984). There may also be a shearing effect that has no impact on fiber size (Hartmann et al.,

2000). Palmowski & Müller (2003) also identified a strong link between the gas yield and the surface area of the substrate particles but emphasized the importance of structural damage and cell rupture on the final result. Chang and Holtzapple (2000) observed improved degradation after lignin and crystalline structures in the material were destroyed, indicating that the lignin acts as a barrier around the hemicellulose and cellulose and protects it from enzymatic degradation, while the crystalline structure lowers the effectiveness of the enzyme. Particle size reduction has been shown to increase methane production from substrates such as food waste, sisal fibre, municipal wastewater treatment sludge, paper and tomato solids by 28 %, 23 %, 7 %, 60 % and over 100 % respectively after mechanical pre-treatments (Kouichi et al., 2010; Mshandete et al. 2006; Sundin et al, 2008; Jedrczak & Królik 2007; Hills & Nakano, 1984). Treating manure with a macerator and treating manure biofibers with a kitchen blender resulted in 25 % (Hartmann et al., 2000) and 8 % (Brunia et al., 2010) increases in biogas production respectively compared to untreated samples. The technical digestion time can also be reduced by 23–59 % according to Palmowski & Müller (1999). Equipment for mechanical pre-treatments including chopping, grinding, milling and crushing, is available for commercial applications, e.g. in the food industry, pulp and paper industry as well as in the biogas industry. The effects of mechanical pre-treatment are dependent on substrate characteristics and the equipment used. Further experimental data and data from large scale installations are needed for the treatment of ley crop silage, as well as for other substrates and grasses, to develop the application of mechanical pre-treatments of agricultural crops and residues in the biogas industry.

2.4.2 Electroporation

Electroporation is performed by exposing the substrate to an electric field, which increases cell permeability. Pores through the cell membrane have been identified indirectly by observation of increased permeability and conductance over the cell membrane following electroporation treatment (Weaver & Chizmadzhev, 1996). Cells without cell walls experience large deformations during treatment as cell walls offer structural support. The effect of the treatment, i.e. cell disintegration, can be verified by dye diffusion and through changes in conductivity (Janositz & Knorr, 2010). The pores formed can be either reversible or irreversible. Irreversible pores sometimes cause complete rupture of the cells. Electroporation has previously been studied for the treatment of waste activated sludge (Choi et al., 2006) and municipal solid waste (Carlsson & Lagerkvist, 2008; Uldal et al., 2009) before anaerobic digestion with good results. Electroporation has also been studied for its use in the food industry (Knorr et al., 2001; Bazhal et al., 2003; Lebovka et al., 2002) and in medical applications (Weaver, 2000; Tsong, 2001). The effect of the treatment depends on the development of the cell wall (Bazhal et al.,

2003), the cell type and its geometry and size (Lebovka et al., 2002), and the specific energy input per pulse has to be evaluated for the specific substrate (Ade-Omowaye et al., 2000). Electroporation has been studied for many applications, however its effect on biogas production from different substrates has not been studied to the same extent. The efficiency of the electroporation treatment and its effect on the biogas production from ley crop silage are important for the evaluation and further development of the technology on agricultural crops and residues.

2.5 Digester mixing and process water treatment

2.5.1 Effects of mixing

In order to enhance the utilization and degradation of the substrate, in addition to pre-treatment, there should also be a focus on the digester and the biological and chemical processes taking place inside it. It is important that the environmental conditions in the digester are optimal in order to reach a high biogas yield. Mixing is especially important in the continuously stirred tank reactor (CSTR) design, as it controls the environmental parameters by means of mass transfer of nutrients, metabolites and microorganisms within the digester (Deublein & Steinhauser, 2008). There are different types of mixing equipment used for digester mixing, including mechanical mixing with different types of agitators, hydraulic mixing using pumps and pneumatically by gas compression and injection at the bottom of the digester. Mixing design and configuration varies and can be run continuously or intermittently. Mixing can also vary in both duration and intensity. However, the mixing demand and the effects of mixing are not well characterized. The intensity and mode of mixing have a direct effect on the anaerobic digestion process and biogas production. This increases the complexity of the interaction between microorganisms and the substrate in the anaerobic digestion process. Knowledge of how digester mixing can be used to increase biogas production, improve process stability and energy efficiency of the anaerobic digestion process are needed for further development of the industry.

According to the research performed by Karim et al. (2005a, 2005b), continuous mixing with different types of mixing equipment has no effect on biogas production, compared to unmixed digesters at low organic loading rates (OLR), but it increases the biogas yield at higher OLR. Karim et al. (2005a, 2005b, 2005c) attributed the increased mixing demand to changes in viscosity and rheological properties caused by the increased total solids (TS) concentration. Unmixed digesters have also shown improved results compared to continuously mixed digesters under thermophilic (Kim et al., 2002) and mesophilic (Hamdi et al., 1991) conditions.

2.5.1.1 Mixing regime

Reducing the intensity of mixing from continuous to intermittent mixing (i.e. periodic mixing with breaks) can increase gas production (Kaparaju et al., 2008; Sung & Dague, 1995), alleviate process instabilities (Stroot et al., 2001; McMahon et al., 2001) and reduce the energy demand of the mixing (Rico et al., 2011; Gomez et al., 2006; Hashimoto, 1982). Hashimoto (1982) and Ong et al. (2002) obtained similar gas production from continuous and intermittent mixing. Sulaiman et al. (2009), Kaparaju et al. (2008) and Lin & Pearce (1991) observed higher gas production from intermittent mixing with shorter mixing periods. On the other hand, Kowalczyk et al. (2013) saw no changes in gas production when varying the mixing periods during intermittent mixing. Lin & Pearce (1991) also observed increased methane production with intermittent mixing compared to unmixed digesters. However, optimization of the anaerobic digestion process does not only involve increasing the methane yield. Reduction of maintenance costs and other operational costs like the energy demand are also important aspects. Kowalczyk et al. (2012) reported that that the two intermittent mixing regimes evaluated reduced energy demand by 12 % and 29 % respectively compared to continuous mixing, without reducing the biogas yield. Since the energy demand for mixing in a full-scale digester can be 29–54% of the total energy demand of an agricultural biogas plant (Dachs & Rehm, 2006), the energy savings can be substantial. In a co-digestion biogas plant the substrate preparation step and digestate post-treatment can account for a higher portion of the total energy demand, however mixing can still be the single most energy demanding process at the plant, accounting for 23 % of the total electric energy demand (Liljestam, 2011).

The literature review in paper III presents a wide range of experiments performed at different scales, using different substrates and mixing regimes. Parts of the review are summarized in Table 1, and show that intermittent mixing regimes can increase biogas production and the stability of the process compared to a continuously mixed system. Even though some of the intermittently mixed systems are only mixed for a few minutes each day, they still show better performance than a totally unmixed system. The data sets compiled and evaluated in the review are presented in the appendix of paper III.

Table 1. Comparison between the effects of different mixing regimes, summarized in paper III

					Intensity (x)		Mixing period (y)	
	Feed	Continuous	Unmixed	Intermittent	High	Low	Short	Long
Karim et al. (2005b)	A	1	0	-	-	-	-	-
Rico et al. (2011)	A	0	-	1	-	-	-	-
Kaparaju et al. (2008)	A	0	-	1	-	-	-	-
Kaparaju et al. (2008)	A	0x	-	1y	0	1	1	0
Stroot et al. (2001)	B	0	-	1	-	-	-	-
Sulaiman et al. (2009)	C	-	0	0x	-	-	1	0
Hoffman et al. (2008)	A	x	-	-	0	0	-	-
Karim et al. (2005a)	A	1	0	-	-	-	-	-
Karim et al. (2005c)	A	0x	0	-	0	0	-	-
Ong et al. (2002)	A	0x	-	0	0	0	-	-
Kim et al. (2002)	D	0	-	1	-	-	-	-
Rojas et al. (2010)	E	1	0	-	-	-	-	-
Lin & Pearce (1991)	F	-	0	1xy	0	0	1	0
Hamdi et al. (1991)	G	0x	1		0	1	-	-
Hamdi et al. (1991)	H	1x	0	-	1	0	-	-
Jiaja et al. (2011)	I	x	-	-	1	0	-	-
Kowalczyk et al. (2012 & 2013)	J	0	-	0x	-	-	0	0
Ghanimeh et al. (2012)	K	0	-	0	-	-	-	-

0 indicates the worst result, or the baseline, of the mixing experiment and 1 indicates an improvement over the baseline. Different mixing intensities (x) and mixing periods (y) were compared in some of these studies and are indicated by the letters x and y where they are applied. The different feeds used are; A: Cow manure; B: Primary sludge and waste activated sludge; C: Palm oil mill effluent; D: Dog food; E: Lipid-rich mix (kitchen, meat and milk-processing) and Corn silage; F: Primary clarifier influent (potato processing); G: Olive mill wastewater; H: Fermented olive mill wastewater (fermented by fungi); I: Rice straw; J: Maize silage, Corn Cob Mix and cow manure; K: Source-sorted organic fraction of municipal solid waste.

2.5.1.2 Mixing intensity

High mixing intensities have been shown to have negative effects on gas production during process startup and when shock loads have been applied (Karim et al., 2005b; Hoffman et al., 2008). High intensity mixing increases the volatile fatty acids (VFA) concentration (Stroot et al., 2001; Sulaiman et al., 2009), and this process instability seems to be elevated at higher OLR (Hoffman et al., 2008). However, Hoffman et al. (2008) and Ong et al. (2002) found no changes in gas production by varying the mixing intensity during

stable operation. Mixing during startup is thought to affect the balance between hydrolysis/fermentation and methanogenesis, resulting in VFA accumulation which inhibits the process (Stroot et al., 2001).

2.5.1.3 The microbial community

Shear stress can inhibit gas production and reduce flock formation (Whitmore et al., 1987; McMahon et al., 2001; Stroot et al., 2001; Kim et al., 2002) at least partly due to the effect of shear stress on the juxtapositioning of microorganisms and their syntrophic interactions, including interspecies hydrogen transfer (Conrad, 1985; Dolfing, 1992). Mixing intensities of 50–1500 RPM have been shown to almost completely eliminate flock formation (Hoffman et al., 2007). High mixing intensity also reduces the concentration of extracellular polymeric substances (EPS) (Ong et al., 2002).

High mixing intensity has been reported to increase the abundance of *Methanosarcina* spp. and *Methanobacteriacea* during destabilization of the process in the presence of high VFA concentrations (McMahon et al., 2001; Hoffman et al., 2007). *Syntrophobacter wolinii* has been shown to play an important role during digester stabilization by degrading propionate, and is abundant in digesters with a history of high VFA content (McMahon et al., 2001). Conversely, *Methanosaeta concilii* increase in abundance at low mixing intensities without VFA accumulation.

The methanogens are sensitive to acidification and uneven mixing can create initiation zones which allow the methanogen population to grow and seed the entire digester (Vavilin & Angelidaki, 2005). During startup, a high OLR and mixing intensity can lead to VFA dispersal and thus inhibition of the anaerobic digestion process if the methanogenic biomass concentration is too low (Vavilin et al., 2007). However, once the process has stabilized increased mixing intensities can improve digestion (Vavilin et al., 2002).

2.5.2 Membrane filtration

Conventional techniques for reducing suspended solids in waste water treatment include the use of belt-type presses, chamber filter presses, decanters, centrifuges and membrane filters (Deublein & Steinhauser, 2008). Many of these treatments can be improved by using polymers to precipitate the solids and in doing so improving their dewaterability. However, these types of additives may also limit the use of digestion residues as fertilizer. Membrane filtration is a technology with many industrial applications including processes such as desalination, drinking water treatment, oil and water separation and separation in dairy industries. Each application has different goals and requirements and membrane filters must be evaluated to determine their suitability for each process. Membrane filters have been used in the biogas industry for different applications (Pillay et al., 1994; Elmaleh and Abdelmoumni, 1997; Beaubien et al., 1996; Ince et al., 2001; Saddoud et

al., 2007; Zhang et al. 2008; Stamatelatou et al., 2008), with most of the focus on water treatment before emission. Klink & Salewski et al. (2008) performed a study with the aim of cleaning the process water of a biogas plant using a membrane filter but presented limited data and the effectiveness and economics of such an installation are still questioned. Another membrane filter experiment treating digestate at 30 °C showed a flux of 40 L h^{-1} m^{-2} (Waeger et al., 2010). Membrane filters can be very effective but they are able to treat a relatively small volume compared to those involved at a biogas plant. The rate of filtration, the flux, can be improved by increasing the temperature of the incoming liquid feed, thus favourably changing the viscosity (US EPA, 2005). Membrane filters with the ability to operate at temperatures well over 100 °C make it possible to construct compact high-rate filtration installations. The flux is also affected by the pressure and can be optimized (Wallberg & Jönsson, 2006). However, ultrafiltration membrane capacity is more dependent on the temperature than on the pressure, since such membranes have a maximum useful pressure of 300 to 500 kPa (Wagner, 2001). Ultrafiltration separates high molecular weight organic compounds like proteins as well as all suspended solids (Wagner, 2001), and experience from ultrafiltration on kraft black liquors in the pulp and paper industry has shown that high temperature applications can result in good solid separation and high flux even with TS values as high as 18% (Wallberg, 2003; Wallberg & Jönsson, 2006). However, lower temperatures are advantageous from an energy standpoint if the heat cannot be recovered and reused efficiently. To be able to implement a high temperature membrane filtration system to treat bulk volumes of process water in the biogas industry further evaluation on separation efficiency, filtration speed and economics is need.

3 Materials and Methods

Experimental approaches were used to evaluate the effects of the different technical solutions in paper I, II, IV and V. Paper III is a literature study and analysis of previously published theoretical and experimental results on the effects of mixing on the process. Energy balance, economy, capacity and biogas production increases have been evaluated for the experimental setups and findings are supported by a thorough literature review. This chapter describes the experimental methods used to evaluate the different technical solutions and process changes. Further details of the studies can be found in the appended papers.

3.1 Växtkraft

This research was performed partly in cooperation with the Växtkraft biogas plant in Västerås, Sweden, and is focused on subjects that are current and relevant to their and other biogas plants operation. The Växtkraft biogas plant is a mesophilic co-digestion biogas plant with a total digester volume of 4 000 m^3 and production capacity of 1.8 million cubic meters of upgraded vehicle fuel annually. The upgraded biogas is sold as vehicle fuel to public transportations and private vehicles. The substrates digested are mainly SSOFMSW (15 800 tones per year) from nearby cities but also ley crop silage (2 400 tones per year) from local farmers and fat removal sludge (2 100 tones per year) from restaurants (Swedish Växtkraft AB, 2013). The plant also produces solid and liquid fertilizer which is certified for ecological farming and sold to local farmers.

3.2 Pre-treatment

3.2.1 Mechanical pre-treatment

Machines for size reduction are used in many industries and could be used more extensively to improve biogas production as a pre-treatment of the feed, but there is a need for data on the effects of mechanical pre-treatment on biogas production from different substrates as well as the capacity and efficiency of such installations. Two different mechanical treatments are

evaluated in this thesis for their effect on biogas production from ley crop silage (paper I).

3.2.1.1 Substrate and inoculum

The ley crop silage substrate was collected at the Växtkraft biogas plant in Västerås, Sweden. It had a TS content of 34 % and a VS content of 84 % (VS of TS). The inoculum was collected at the same co-digestion biogas plant as the ley crop and had a TS content of 5 % and a VS content of 72 % (VS of TS) (Swedish standard, SS-28113).

3.2.1.2 Experiment setup

The Grubben deflaker (GLD 360 HW) and the Krima disperser (KD 450) are two devices that were built for recovery of fibers during paper recycling in the pulp and paper industry (Fig. 4). The devices were evaluated at the industrial scale pilot plant of Cellwood Machinery AB in Nässjö, Sweden. Both devices work on similar principles, i.e. the grinding was performed as the material passes through a narrow gap between two opposing rotor discs.

Figure 4. Grubben deflaker (left) and Krima disperser (right)

Before treatment in the Grubben deflaker, 474 kg of ley crop silage was premixed with water to 7 % TS. This TS was set according to its pumpability using the available pumps and pipe system of the full scale test plant. In the Grubben deflaker, the substrate passes eight treatment zones between the rotor discs, like a labyrinth with eight sharp turns, which disintegrate the ley crop. The Krima disperser is fed with ley crop through a screw and water is added before it reaches the grinding segments. The Krima disperser was supplied with 1.8 ton of ley crop silage per hour during the full scale experiment, which possibly underutilizes its full capacity, thereby potentially affecting the energy

balance calculation for the system. The contact surfaces between the substrate and the rotor discs are lined with interchangeable segments for treating different materials and for different treatment effects. A square pattern segment was used in the experiment with the Krima disperser (Fig. 5) to provide more of a cutting action than a shearing effect.

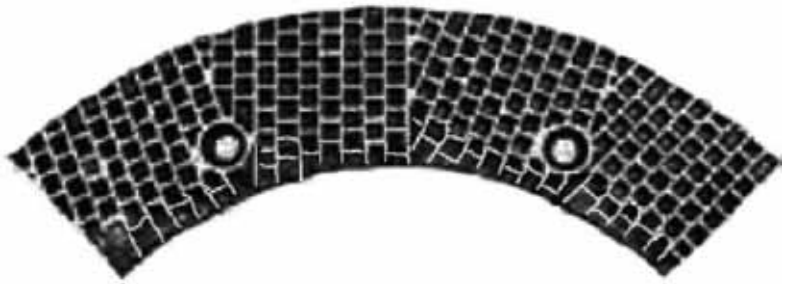

Figure 5. Square pattern segment of the Krima disperser (Cellwood Machinery AB)

A BMP experiment was set up to evaluate the effect of the mechanical pre-treatment on the biogas yield from ley crop silage in line with the description by Hansen et al. (2004). This experiment included twelve BMP flasks comprising three flasks each of the substrate pre-treated by the Gruben deflaker (Gd) and the Krima disperser (Kd), three flasks containing the untreated ley crop silage as control flasks, and further three flasks containing inoculum as a reference. 1 000 ml flasks were prepared containing 2 g VS of ley crop silage, 4 g VS of inoculum and topped up with tap water to 700 ml while flushing with nitrogen gas, and closed with butyl rubber stoppers and aluminium caps. The BMP experiments were incubated at 37 °C and mixed at 130 RPM (Orbital Shaker 4536, Forma Scientific) and gas production was measured with a differential pressure meter (GMH 3161-13, Greisinger). The methane content was determined using a gas chromatograph according to the method described by Westerholm et al. (2010). Ley crop silage is, however, a very heterogeneous substrate with many different plant materials and particles of different sizes which are problematic when evaluating its gas potential in a BMP experiment with a small substrate amount, which often leads to variations in the biogas production between replicates.

3.2.2 Pre-treatment using electroporation

Electroporation is a promising technology under development, and is evaluated here for its effect on biogas production from ley crop silage as an alternative to more conventional technologies (paper II). In these experiments,

two different field strengths and frequencies were compared to show the potential of applying electroporation as a pre-treatment for ley crop silage.

3.2.2.1 Substrate and inoculum

The ley crop silage used in the experiment was collected at the Växtkraft biogas plant in Västerås, Sweden, and had a TS content of 51 % and a VS content of 90 % (VS of TS). The inoculum was collected from an anaerobic digester at a municipal waste water treatment plant and had a TS of 4 % and VS of 75 %. The ley crop silage was shredded with a blender to reduce the particle size from approximately 0–0.1 m to under 0.03 m. The ley crop silage was than mixed with water to reach 8 % TS. This TS content was selected to make the slurry pumpable for a possible future continuous application and shredding was performed for practical reasons associated with the small size of the reaction container. The TS and VS were determined according to the Swedish standard (Swedish standard, SS-28113).

3.2.2.2 Experiment setup

The effects of the electroporation pre-treatment on ley crop silage are evaluated in paper II. The electroporation instrument used can be seen in Fig. 6 and it was made by KEA-TEC GmbH (Germany) for batch experiments of up to 1 000 ml with a maximum loading current and voltage of 40 mA and 40 kV per capacitor at a frequency of up to 10 Hz. A reaction container with a volume of 100 ml and variable electrode distances of 0.05 m and 0.025 m were used. The treatment volume was 100 ml or 65 ml depending on the distance between the electrodes.

Figure 6. Electroporation unit

The experiment was setup as shown in Table 2 with one pulse per ml of sample, each containing 67.2 Joules of energy, and alternating the frequency between 10 Hz and 5 Hz. The field strength is dependent on the electrode distance and is larger with smaller electrode distances. Three samples were treated at each setting. Untreated ley crop silage was also saved for use as a control sample. The results of the pre-treatment were evaluated in a batch digestion experiment by taking one sample from each of the three treatments at every setting.

Table 2. The different settings of the electroporation experiment

Test series	Sample Volume (ml)	Frequency (Hz)	Distance between electrodes (m)	Field strength (kV/cm)	Number of pulses
A	100	10	0.05	48	100
B	65	10	0.025	96	65
C	100	5	0.05	48	100
D	65	5	0.025	96	65

The effect of electroporation pre-treatment on the biogas yield from ley crop silage was evaluated in a BMP experiment. In this experiment 18 BMP flasks were used, 12 flasks with the treated ley crop samples, i.e. triplicates for each of the four electroporation settings, three flasks with the untreated control sample and three flasks with inoculum as a reference. The 100 ml flasks were prepared with 14 g of the ley crop silage water mix, 30 g of inoculum and topped up to 60 ml with water and closed with butyl rubber stoppers and aluminum caps. The flasks were incubated at 30 °C without mixing and the gas production was quantified twice per week initially, and then with decreasing frequency using a gas syringe as an expansion vessel for the pressure. The assessment of methane content was done indirectly by separation of carbon dioxide using alkaline solution.

3.3 Digester mixing and process water treatment

3.3.1 Effects of mixing

A review of literature on the effects of mixing was performed to identify gaps and advancements in this research field as well as common determinants for the observed results (paper III). In the review, data from anaerobic digestion experiments comparing different modes of mixing were gathered and compared to detect trends in the results that may indicate ways in which mixing in digesters should develop. In order to study the effects of mixing on the anaerobic digestion process further a batch mixing experiment was performed with continuous mixing at two different mixing intensities, 150 and 25 RPM, and with minimal intermittent mixing, at both minimal loading and after a shock load (paper IV).

3.3.1.1 Substrate and inoculum

The substrates used were fresh SSOFMSW to produce the shock load, and digestate containing SSOFMSW at different stages of degradation for a post-digestion setup. Both substrate and digestate were collected from the Växtkraft biogas plant using the SSOFMSW as the main substrate. The SSOFMSW used during the digestion experiment was made up from suspension that had been through the substrate preparation step of the co-digestion biogas plant, including size reduction, contaminant removal and hygienisation (70 ˚C for 1 hour). The digestate was stored at 33 ˚C for one week and filtered through a 2-mm sieve to remove larger particles in order to reduce organic material to a minimum before analysis and the start of the digestion process. The SSOFMSW had a TS content of 6 % and VS content of 82 % (VS of TS) and the digestate had a TS of 4 % and a VS of 63 % (VS of TS) (Swedish standard, SS-28113). The digestate was used both as a feed at minimal loading and as an inoculum when digesting the SSOFMSW. The organic content of the digestate would be expected to contain a large microbial biomass which may affect biogas yields compared to SSOFMSW.

3.3.1.2 Batch experiment setup

In order to study the effects of different mixing intensities on the anaerobic digestion process and gas yield, a batch digestion experiment was performed in 1 000-ml serum flasks with different mixing configurations. The digesters were set up in line with the BMP experiments (Angelidaki et al. 2009), however, the focus of the experiments was on digestion kinetics rather than methane potential. Half of the 24 batch digestion flasks were loaded with 7.1 g VS of digestate and 9.3 g VS of SSOFMSW, i.e. an inoculum to substrate

ratio of 0.8. The other 12 flasks were set up for post-digestion only, with 7.1 g VS of digestate. These also fulfilled the function of a blank test. In this way the digestate was used both as a starting culture and as a low organic content substrate for the post-digestion experiment containing a relatively high microbial concentration compared to the digestion of fresh substrate. SSOFMSW was added to create a high organic loading and shock load in the system. All flasks were topped up with tap water to 700 ml while flushing with nitrogen gas and sealed using butyl rubber stoppers and aluminum caps. The experimental setup is presented in Table 3.

The batch digesters were incubated at 37 ˚C for the first 20 hours and then lowered to 33 ˚C for the rest of the 31 day experiment to avoid issues with fluctuating temperatures as a result of a technical error with the incubator. Continuous mixing was performed by two orbital shaking incubators (Forma Scientific), with rotation of 25 mm in diameter, at 25 or 150 rotations per minute (RPM), and compared to a minimally intermittently mixed series of digesters which were mixed by inverting the flask briefly at each VFA sampling and incubated in a heating cabinet (Model 300, Memmert). The mixing regimes commenced after Day 7 of the experiment to allow the digestion and microbial biomass growth to start under similar unmixed conditions, and to reduce initial instabilities that could occur at high loadings, as indicated by paper III. Four flasks at each loading condition were incubated and mixed in the same incubator, allowing for triplicate flasks for monitoring of gas production kinetics and one flask for liquid sampling and chemical analysis.

Biogas production was monitored once daily with a differential pressure meter, and gas samples were also taken daily with a syringe for analysis of methane content during the first 16 days of digestion to indicate whether mixing had any effect on methane production during initiation of the mixing. Liquid samples were also taken with a syringe on every other day from Day 6 during initiation of the mixing and at 3–4 day intervals after the first week for determination of pH and VFA content.

Table 3. Anaerobic digestion experiment setup

Mixing	Digester	Organic loading (g VS/l)	Analysis
Minimally mixed	1 2 3 4	SSOFMSW (13.3) and digestate (10.1)	Biogas production and methane yield (Digester 1–3) VFA and pH (Digester 4)
	5 6 7 8	Digestate (10.1)	Biogas production and methane yield (Digester 5–7) VFA and pH (Digester 8)
25 RPM	9 10 11 12	SSOFMSW (13.3) and digestate (10.1)	Biogas production and methane yield (Digester 9–11) VFA and pH (Digester 12)
	13 14 15 16	Digestate (10.1)	Biogas production and methane yield (Digester 13–15) VFA and pH (Digester 16)
150 RPM	17 18 19 20	SSOFMSW (13.3) and digestate (10.1)	Biogas production and methane yield (Digester 17–19) VFA and pH (Digester 20)
	21 22 23 24	Digestate (10.1)	Biogas production and methane yield (Digester 21–23) VFA and pH (Digester 24)

3.3.1.3 Chemical analysis

Methane samples were analyzed with a gas chromatograph according to the method used by Westerholm et al. (2010). The VFA content was analyzed by first extracting a 3 ml sample, centrifuging the sample at 6 000 RPM for 10 min and analyzing the clear phase using the Hach Lange cuvette test LCK365. The pH was measured using a standard pH meter. The TS and VS content were determined according to the Swedish standard (Swedish standard, SS-28113).

3.3.2 Membrane filtration

Cleaning the process water used in the anaerobic digestion process can improve the capacity and economics of the plant. The case study included in paper V was performed at the Växtkraft biogas plant in Västerås, Sweden (section 3.1) to evaluate the effects of a membrane filtration installation.

3.3.2.1 Pilot plant configuration

The pilot plant was constructed by Mercatus Engineering AB for batch experiments of up to 70 L to evaluate the use of a ceramic ultrafiltration membrane to reduce the TS content in the process water of a biogas plant. The filtration was operated at temperatures of 70, 90 and 110 °C to increase the rate of filtration (flux) and to reduce the size of the installation and the number of membranes used. The temperature was regulated by a 6 kW oil heater. The ceramic ultrafiltration membrane under evaluation was produced by Atech Innovations Gmbh and has 37 channels, each with an internal diameter of 3.8 mm, a pore size of 50 nm with a molecular weight cut off at 300 kD, a membrane area of 0.53 m^2 and a length of 1 200 mm. The experimental setup and configuration are shown in Fig. 7 and Fig. 8. The membrane is set up for crossflow filtration with the feed flowing parallel to the membrane and the concentrate recirculating back to the inlet tank. On the permeate side of the membrane the flow can either be recirculated to the inlet tank or cooled and released to the outlet tank. A number of pressure valves, pressure meters, thermometers and a flow meter are installed for process monitoring and control, as well as release and safety valves. The flow meter is installed to measure the permeate flow, with values of up to 230 L h^{-1}. The energy consumption of the pump in the pilot plant can be monitored and recorded. The transmodule pressure and transmembrane pressure were kept at 2.4×10^5 Pa and 2.0×10^5 Pa, respectively, during operation to ensure comparability between different temperature conditions. The pressure upstream of the circulation pump was also kept below 4×10^5 Pa during operation to prevent damage to the pump.

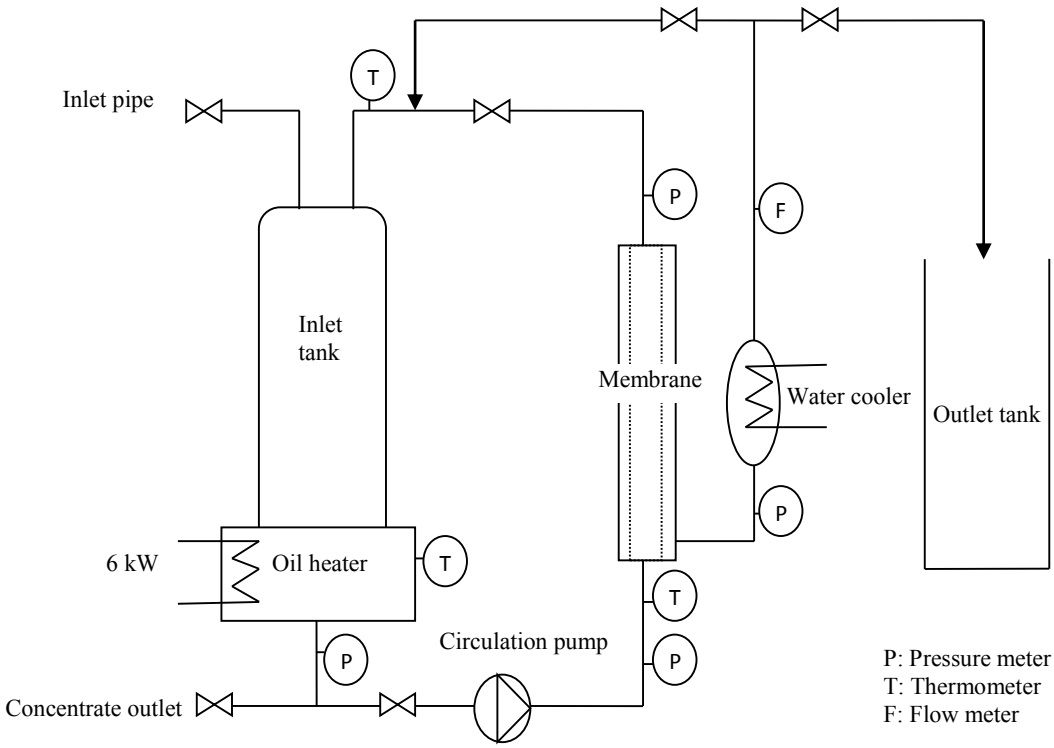

Figure 7. Configuration of the membrane filtration unit

3.3.2.2 Experiment setup

The process water from the centrifuges at the Växtkraft biogas plant were used to perform these experiments. Seven individual test runs were carried out in this series of experiments, three at 110 °C, two at 90 °C, and one at 70 °C, as well as a follow up test at 110 °C to evaluate the clogging effects of the low temperature test. As it was difficult to control the temperature with the oil heater, the experiments were carried out within a temperature interval starting at the set temperature and slowly increasing with time. The process water was pre-filtered with a sieve (2-mm) to remove sand and other large particles and process water samples were taken for TS analysis. The inlet tank was then filled with process water and heated until it reached the desired operation temperature before the start of the experiment. The membrane filtration was first carried out in a closed loop with recirculation of the permeate to the inlet tank. Once the flow of permeate stabilised, flow was diverted to the outlet tank. The flux was determined both by flow meter readings and manually with a measuring cylinder and a stop watch. During permeation three 250 ml permeate samples were taken. A 250 ml sample was also taken from the concentrate produced after it had been allowed to cool down and the inlet tank

was emptied and cleaned before the next batch. The membrane was cleaned by circulating water through the system repeatedly until a clear effluent was obtained.

Figure 8. The ultrafiltration membrane unit
The figure shows the front with the insulated inlet tank, oil heater, pump, and the control panel (left) and the rear with the pipes, the insulated membrane unit, pressure meters and the outlet tank (right).

3.4 Energy and economic calculations

The energy balance of the pre-treatments is calculated as a ratio of the energy content of the increased biogas output and the electricity demand of the pre-treatments at different points in time. The energy balance is calculated for days 36, 48 and 115 for the mechanical treatment, and days 75 and 356 for the electroporation, with a methane energy content of 9 810 Wh/Nm^3 (Eriksson, 2010). Electricity production from the methane is calculated using an efficiency of 40 %. This comparison between electrical energy and an energy carrier like methane is problematic, since they can be and are used for very different applications which are valued differently. This issue is discussed further in the integration section.

The energy demand of the membrane filtration unit is calculated for four cases with different process water flow rates at operating temperatures of

90 °C and 110 °C with heat recovery. Cases 1–4 have flow rates of 10, 20, 26 and 32 m^3/h respectively, and are calculated with a best case temperature difference of 5 °C for the heat recovery, using the minimal number of membranes possible according to the flux and a power demand of 22 kW per membrane unit. The energy value of the methane is calculated according to Eriksson (2010) similarly to the pre-treatment experiments. Details of the calculations performed can be found in paper V.

The case study (section 4.3.5) and the economy of the electroporation is calculated using the mean methane price for vehicle fuel in Sweden at 1.55 Euro/Nm^3 (Energy gas Sweden, 2013b), the electricity price is calculated as 0.079 Euro/kWh (Statistics Sweden, 2013) and the district heating price as 0.099 Euro/kWh (Swedish district heating, 2013) using an exchange rate of 8.78 SEK/EUR (2013-11-07).

4 Results and Discussion

This chapter presents the results reported in paper I-V and discusses the implications of the process changes on the system. The process integration is discussed both from a general point of view and from the perspective of a specific biogas plant in the form of a case study.

4.1 Pre-treatments

The improvement of the substrate preparation step focuses on the evaluation of the two pre-treatments, electroporation and mechanical treatment, and their effects on the system. The results from the mechanical pre-treatment of ley crop silage (paper I) and electroporation pre-treatment of ley crop silage (paper II) are presented in this section.

4.1.1 Mechanical pre-treatment

4.1.1.1 Wet sieving analysis

The size reduction of the ley crop silage was analyzed by performing a wet sieving analysis. The results show that the untreated ley crop silage had its main size distribution between 1 and 8 mm and that the treatment using the Krima disperser and Grubben deflaker reduced the size of 52 % and 60 % of the samples respectively, down to less than 0.125 mm (Fig. 9). Just 0.3 % of the untreated sample was smaller than 0.125 mm. However, when comparing the two treatments the Krima disperser shows a wider size distribution than the Grubben deflaker, and some of the material treated with the Krima disperser passes through the grinding segments without being reduced in size.

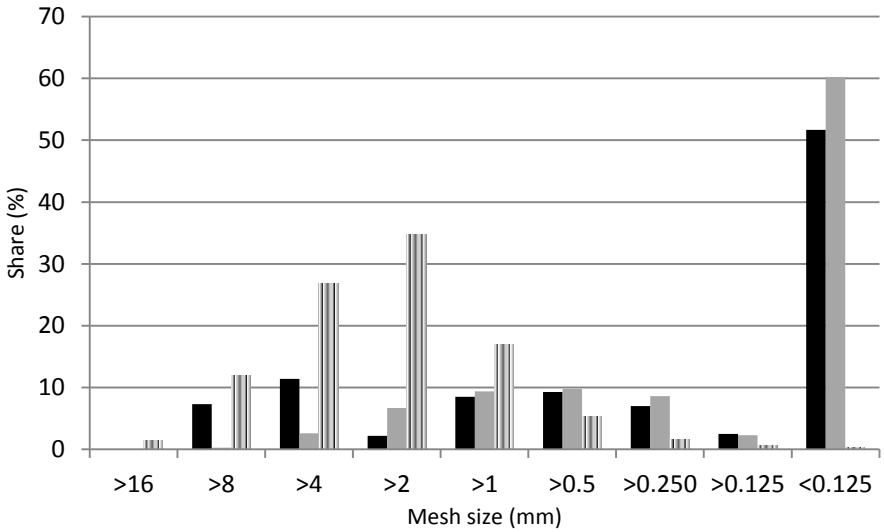

Figure 9. Wet sieving analysis
Result of the analysis shows the share of different fraction sizes in the material after treatment with the Grubben deflaker ( ) and Krima disperser ( ) alongside the fraction sizes in an untreated control sample ( ).

4.1.1.2 Methane potential

The particle size reduction had a substantial impact on the degradability and biogas production of the substrate according to the BMP experiment. The improvement in methane production following treatment with the Krima disperser and Grubben deflaker are presented in Fig. 10. The increase in methane production after the pre-treatments is significant compared to the untreated sample, with both treatments showing similar methane yields and kinetics. The methane content analysis showed that 50 % of the biogas was made up of methane. Fig. 10 presents the methane production per gram VS during 115 days of anaerobic digestion, showing increased methane production by 43 % and 59 % for the disperser and the deflaker treatments respectively. The treatments show signs of inhibiting digestion and lower biogas production during the initial phase of gas production from Day 10 to 25. This inhibition may be the result of components released during the pre-treatment or overloading caused by the increased degradation rate seen during startup. Biogas production levels out after 34 days of the BMP experiment and follows the same trend until the end of the experiment, with a methane production increase ranging from 40–60 Nml and 50–70 Nml per gram VS for the disperser and deflaker respectively.

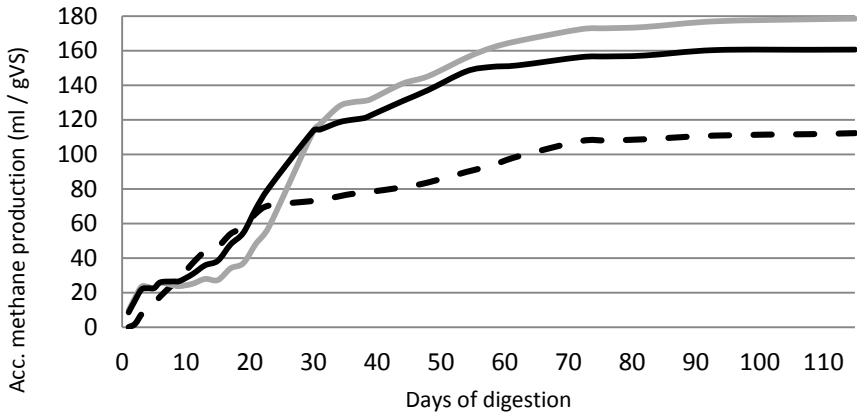

Figure 10. Accumulated methane production
A comparison between the methane production of the mechanically pre-treated substrate using the Grubben deflaker (—) and Krima disperser (—) and the untreated substrate (- - -).

4.1.1.3 Capacity

The capacity of the treatments is calculated from the experimental setup at Cellwood AB, and shows that further improvements are possible. The Grubben deflaker showed a capacity to treat 3.6 ton of ley crop silage per hour compared to the Krima disperser, which was evaluated at a set feeding rate of 1.8 ton per hour. The limited capacity of the Krima disperser is an effect of the feeding regime used and not based directly on the capacity of the disperser. This leads to an underestimation of the capacity and has a negative effect on the calculated energy balance.

4.1.1.4 Energy balance

The energy demand of the Grubben deflaker and Krima disperser are 0.025 Wh/ g VS and 0.192 Wh/g VS respectively. The energy balance calculated for the mechanical pre-treatment is shown in Table 4. The energy output of the deflaker corresponds to 21–26 times the energy input and 2–3 times the energy input for the disperser. If the electrical energy input is produced from biogas, an excess energy production of 8-11 times the energy demand of the deflaker is possible, but for the disperser the ratio is very close to the break-even point due to the relatively low capacity and high energy demand of the treatment. The energy demand of the full scale treatment is 7 kWh/ton for the deflaker and 55 kWh/ton for the disperser. These values are comparable to those of earlier studies of mechanical pre-treatment performed with hammer mills and knife mills on agricultural products and residues which show energy demands ranging from 1 kWh/ton to just under 100 kWh/ton (Kratky and Jirout, 2011).

Table 4. Energy balance of the mechanical treatment
Shows the increase in gas production and the energy balance of the investigated pre-treatment systems at Day 36, 48 and 115.

	Increase in gas production		Energy content of increased methane production.		
Treatment	Nml biogas /g VS	Nml methane /g VS	Wh/g VS	Wh biogas/ Wh electric energy used	Wh biogas/ Wh to produce the electric energy used (η=40%)
Day 36					
Deflaker (Gd)	104	53	0.518	21	8.4
Disperser (Kd)	84	43	0.419	2.2	0.87
Day 48					
Deflaker (Gd)	120	61	0.600	24.4	9.7
Disperser (Kd)	105	53	0.522	2.7	1.1
Day 115					
Deflaker (Gd)	130	66	0.648	26.3	10.5
Disperser (Kd)	95	48	0.474	2.5	1

4.1.1.5 Economic considerations

These types of mechanical treatment are energy demanding and the equipment experiences considerable wear. A comparison between the two evaluated treatments shows that the Grubben deflaker has a lower operational cost in the form of electricity than the Krima disperser. On the other hand, the deflaker requires installation of a mixing tank for the ley crop silage, which adds to the capital cost, space requirements and the operational cost of running the mixing unit, if this equipment is not already integrated into the system. The Krima disperser is in the 200 000 euros price range and the Grubben deflaker is in the 100 000 euros range (not including the mixing unit). Depending on the wear and lifetime of the grinding segments this can have a major effect on the operational cost of the installation. The type of grinding segment used also impacts the wear and lifetime of the segment, with the lifetime ranging from a matter of weeks to several months. The cost of replacing the segments of the deflaker using a similar type of substrate is 45 000–70 000 euros/year, and the costs for the disperser would be expected to be slightly higher because of its larger size.

The Krima disperser used a low profile grinding segment in these experiments, which is likely to reduce the wear caused by the ley crop silage, which may otherwise get caught and accumulate on the teeth of the segments leading to more frequent segment changes. Further development of the mechanical treatment should focus on grinding segments and how they can be improved for better effects on the individual substrate, to reduce wear and extend their lifetime, and on the capacity of the equipment.

4.1.2 Electroporation

4.1.2.1 Methane potential

The digestion experiment showed an improved final cumulative biogas production of up to 16 % in the treated samples. Results from the BMP experiment show increased digestion rates of 17 % and 16 % during 75 and 356 days of digestion (Fig. 11). The lower field strength of test series A and C (48 kV/cm) results in a similar biogas yield to the untreated ley crop silage, while test series B and D, with a field strength of 96 kV/cm show substantial increases of 9% and 16% compared to the control sample. However, a statistical analysis of the data reveals that only test series D shows a clear statistically significant improvement compared to the untreated ley crop silage and that test series B shows large variations between the triplicate digesters. These variations may be related to the heterogeneity of the substrate but may also be an effect of uneven pre-treatment. The electroporation treatment is still under development and it is possible that the biogas yield and energy demand of the treatment of ley crop silage can be improved further. The importance of field strength is clear in these results and optimization of the process should focus on higher field strengths.

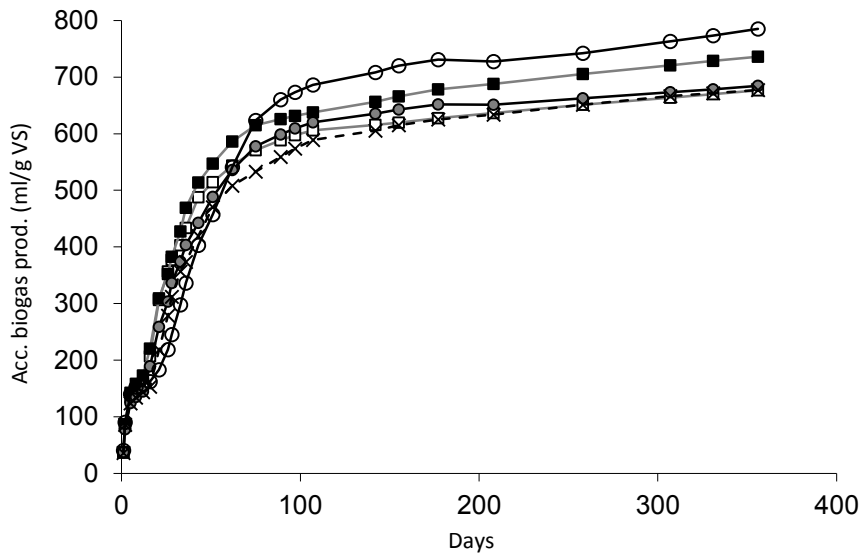

Figure 11. Cumulative biogas production after electroporation treatment of ley crop silage

The graph shows the cumulative biogas production of test series A (—□—), B (—■—), C (—●—), D (—⊟—) compared to the ley crop silage control sample (-✕-). The values presented are the mean values of triplicates except for the untreated ley crop silage control, which is represented by duplicates.

4.1.2.2 Capacity

The capacity of electroporation for treating ley crop silage cannot be evaluated from this experiment alone. A full scale installation would have to be set up for either batch or continuous treatment. Continuous treatment is an option since the low TS content used in these experiments makes the substrate pumpable. The amount of ley crop silage that can be treated is limited by the distance between the electrodes and depends on the size of the installation. The demonstrated digestion rate increase can increase methane production but can also increase the capacity of the biogas plant for substrate.

4.1.2.3 Energy balance

An energy balance was performed between the increased methane potential and the energy demand of the pre-treatments to evaluate the efficiency of the electroporation treatment. Table 5 shows the energy balance of the electroporation treatment of series B and D at Day 75 and 356. The energy requirement of the treatment is 259 Wh/ kg VS for each of the different settings. The results suggest that the energy content of the increased biogas production can be up to two times the energy demand of the treatment. At an energy efficiency of 40 %, electricity production from the produced biogas leads to a negative energy balance and a combined heat and power solution is needed to boost total efficiency. The specific energy input per pulse is an important parameter (Ade-Omowaye et al., 2000) in electroporation treatment. This parameter was kept constant in these experiments. However, there is potential to optimize this parameter with respect to energy balance, as it has a direct effect on the energy demand of the treatment.

Table 5. Gas production and energy balance of the electroporation treatment
The increase in gas production and the corresponding energy balance for test series B and D after 75 and 356 days of digestion.

Test series	Increase in gas production		Energy production and energy demand		
	Nm^3 biogas /kg VS	Nm^3 methane /kg VS	Wh produced /kg VS	Wh produced /Wh electric energy used	Wh produced/ Wh to produce the electric energy used (η=40%)
75 days					
B	0.082	0.041	402	1.6	0.6
D	0.091	0.045	444	1.7	0.7
356 days					
B*	0.058	0.029	286	1.1	0.4
D	0.108	0.054	527	2.0	0.8

* no statistically significant increase in biogas production.

4.1.2.4 Economic considerations

The capital cost of an electroporation installation is difficult to estimate, since it is dependent on the amount of material to be treated and on whether the treatment is performed continuously or in a batch setup. Rittman et al. (2008) presented a continuous electroporation system for the treatment of 380 m^3/d waste activated sludge and primary sludge at a municipal waste water treatment plant and calculated that the installation and capital cost could be recovered within less than three years at a profit margin of 425 000 euros/year. The electroporation treatment should not cause any excessive wear of the equipment, thus minimizing the non-electrical maintenance and operational cost.

4.2 Digester mixing and process water treatment

The improvement of the digestion and digestate post-treatment step focuses on the evaluation of mixing in the digester to improve the environmental conditions for the microbial community and energy efficiency of the system; and process water treatment to increase the quality of the process water used at a biogas plant by membrane filtration to optimize the capacity of the substrate preparation and to reduce the liquid reject from the system.

4.2.1 Effects of mixing

The mixing regime has been shown to have a substantial effect on the result of the digestion process in a CSTR (paper III and IV). However, there are few if any recommendations and guidelines for the mixing regime. This section presents results of a mixing experiment, focusing on different mixing intensities during low organic loads and during stabilization after an overload (paper III).

4.2.1.1 Digestion of SSOFMSW

The effects of different mixing intensities on biogas and methane production from the SSOFMSW and the post digestion are presented in Fig. 12 and Fig. 13 respectively. Fig. 12 shows improved biogas production from the mixed digesters compared to the minimally mixed digesters from the start of mixing until Day 21 of the experiment. All digesters, including the minimally mixed digesters, experience a decline in the biogas production rate after the start of mixing on Day 7, but the continuously mixed digesters show a smaller decline than the minimally mixed digesters. When digesting the SSOFMSW, methane production seems to increase with increasing mixing intensity (Fig. 13). The results show that methane production at the highest mixing intensity increased compared to the minimally mixed and 25 RPM mixing intensity, respectively.

However, since temperature equilibration led to different biogas production rates from the start of the experiment, the methane values are consistent and follow the same trend as the biogas production, and thus do not represent a real increase in methane concentration in the gas.

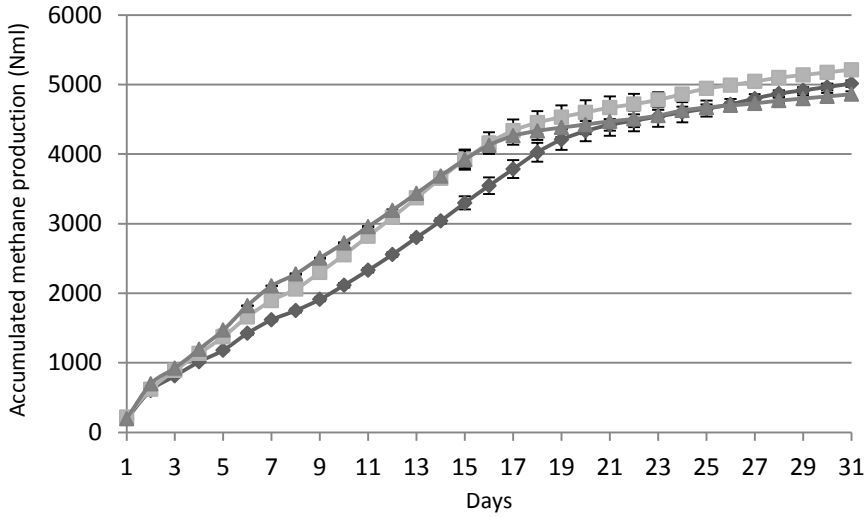

Figure 12. Accumulated biogas production from digestion of SSOFMSW
The figure shows the effects of the 25 RPM ( ), 150 RPM ( ) and minimally mixed mixing regimes ( ) on biogas production. Biogas production is presented as mean values from three flasks with error bars showing standard deviations.

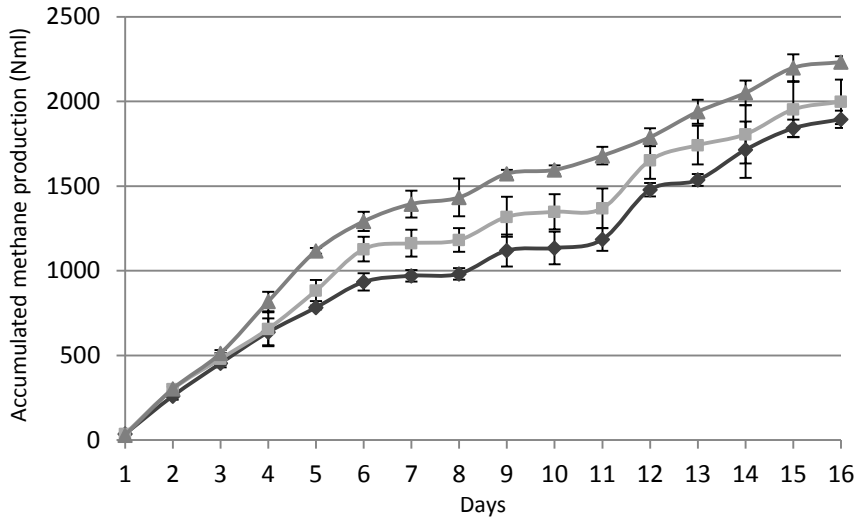

Figure 13. Accumulated methane production from digestion of SSOFMSW
The figure shows the effects of the 25 RPM (—■—), 150 RPM (—▲—) and minimally mixed mixing regimes (—◆—) on methane production. The methane production during the initial 16 days is presented as mean values from three flasks with error bars showing standard deviations.

Even though the biogas production is affected by a slight temperature variation during the first day of incubation that affects the cumulative gas production before the start of mixing, it becomes clear that the 150 RPM mixing intensity and the minimal mixing show a reduced biogas production rate compared to the 25 RPM mixing intensity. However, the minimally mixed digester catches up at the end of the experiment, whereas the 150 RPM mixing show no signs of recovery. Biogas production of the 150 RPM and 25 RPM samples begins to level off from around Day 17, but at different levels, i.e. final biogas production at Day 31 is 295 ± 3 and 317 ± 2 Nml/ g VS added for the 150 RPM and 25 RPM mixing intensities respectively compared to 304 ± 3 for the minimally mixed digesters. The kinetics of biogas production after the start of mixing show that 150 RPM mixing leads to a substantially lower biogas production rate and the minimal mixing sample recovers to the extent that the final accumulated biogas production is similar to that produced by the 25 RPM mixing regime.

The chemical analyses of the VFA content and pH values during the digestion of SSOFMSW are presented in Fig. 14. The results show a high VFA concentration during the first 4 days of mixing, with a corresponding low pH, which decreases relatively quickly after the mixing is introduced on Day 7. The breakdown of VFA in the minimally mixed digesters was slower than in the continuously mixed digesters, but follows a similar trend but delayed by

1–3 days. The lower biogas production rate and total biogas production at the 150 RPM mixing intensity is not due to excess VFA accumulation or acidification relative to the other mixing regimes as is often seen in these types of experiments.

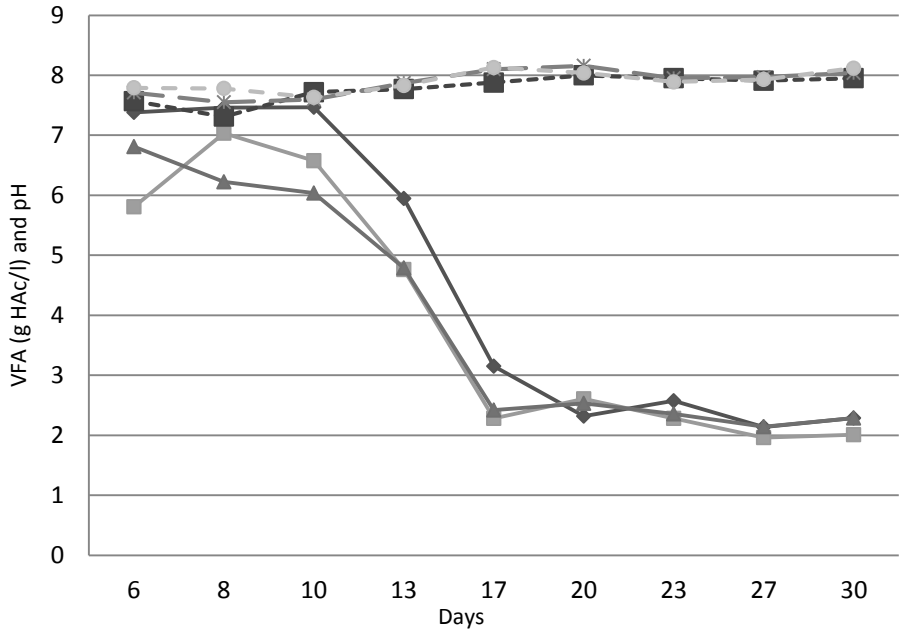

Figure 14. VFA and pH development during digestion of SSOFMSW
The figure shows VFA concentrations during the experiment at 25 RPM (), 150 RPM () and with a minimal intermittent mixing regime () as well as pH values during mixing at 25 RPM (), 150 RPM () and with a minimal intermittent mixing regime ().

4.2.1.2 Post-digestion experiment

At very low organic load, the accumulated biogas production with 150 RPM mixing is lower than that from the 25 RPM mixing and minimally mixed digesters, which are statistically different from each other (Fig. 15). This change is not seen in the accumulated methane production (Fig. 16), since methane effects were only expected during mixing startup, meaning methane monitoring was discontinued after 16 days. Final biogas production at the 25 RPM mixing intensity is 134 ± 1 Nml/ g VS added, 16% higher than for the 150 RPM mixing intensity at 113 ± 1 Nml/ g VS added. The minimal intermittently mixed digester had a final biogas production of 130 ± 2 Nml/g VS added after 31 days.

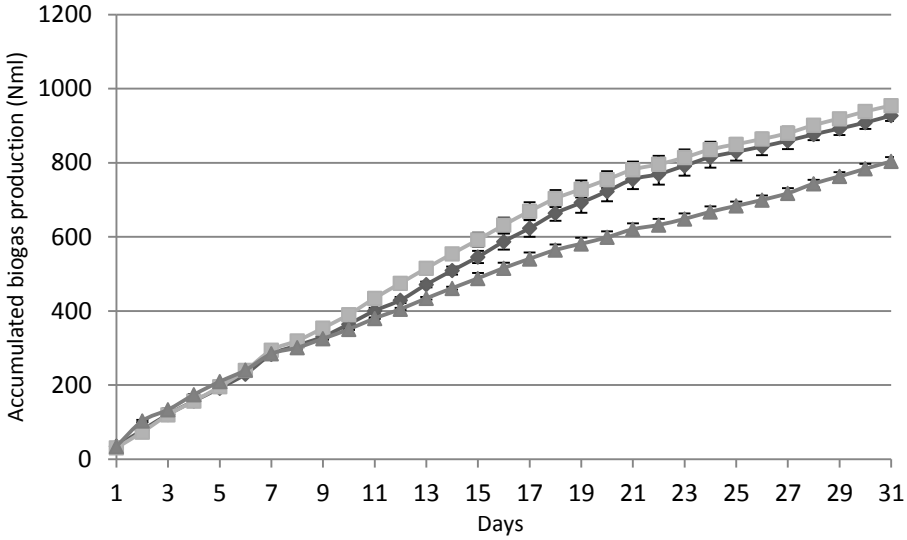

Figure 15. Cumulative biogas production

Biogas production from the post-digestion of residual organic content in the digestate, mixed at 25 RPM (), 150 RPM () and with a minimal intermittent mixing regime (). Gas production is presented as a mean value of triplicates and error bars show the standard deviation.

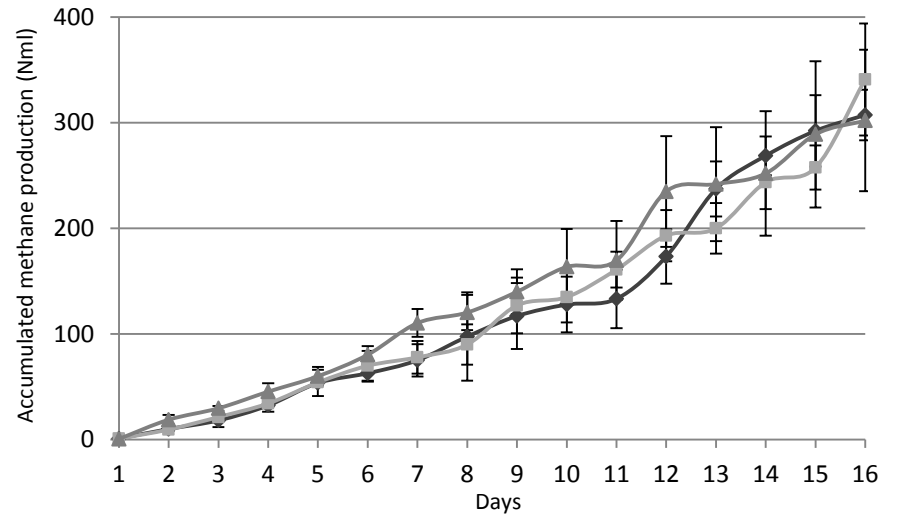

Figure 16. Cumulative methane production

Methane production from the post-digestion of residual organic content in the digestate, mixed at 25 RPM (), 150 RPM () and with a minimal intermittent mixing regime (). Gas production is presented as a mean value of triplicates and error bars show the standard deviation.

The chemical analysis of the VFA content and pH values in the inoculum flasks (Fig. 17) show a slightly higher initial VFA value for the minimally mixed and 25 RPM mixing intensity digesters which increased at the start of mixing. However, no effects were observed on the VFA content at the 150 RPM mixing intensity. The minimally mixed and 25 RPM digesters exhibited a higher biogas production rate up to Day 20, after which the VFA content fell to a similar level as for the 150 RPM mixing intensity.

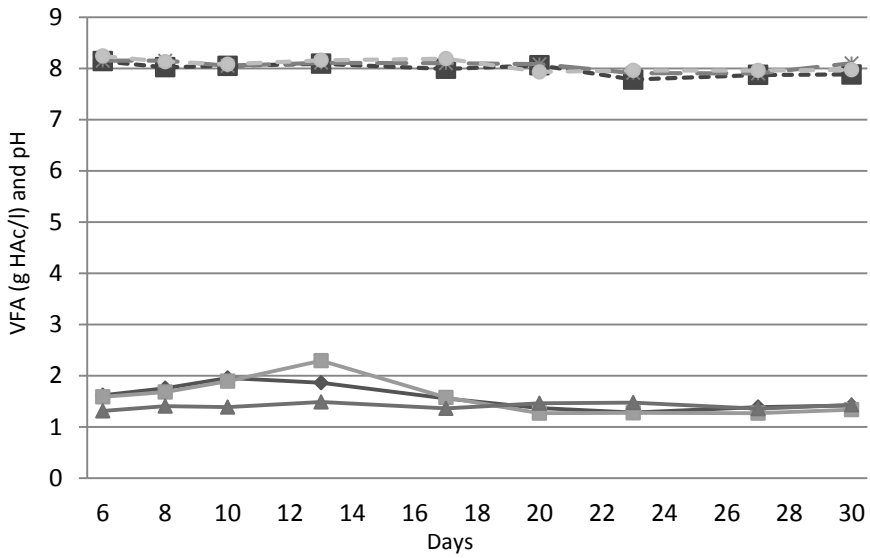

Figure 17. VFA and pH results from the digestion of the residual organic content of the digestate

The figure shows the VFA concentrations during the experiment at 25 RPM ( ), 150 RPM ( ) and with a minimal intermittent mixing regime ( ) as well as the pH values during mixing at 25 RPM ( ), 150 RPM ( ) and with a minimal intermittent mixing regime ( ).

4.2.1.3 Effect of organic loading and volatile fatty acids

The results from the digestion experiments show that mixing at 150 RPM leads to lower biogas production at both organic loadings than the 25 RPM and minimally mixed digesters. The biogas production rate with minimal mixing was however lower to begin with (Fig. 12 and Fig. 13), corresponding to elevated VFA values (Fig. 17). As VFA values fell to levels in line with the other mixing regimes, the biogas production rate also returned to similar levels to those in the continuously mixed digesters. The final biogas production in the 25 RPM digesters at both loadings was only 6 % higher than in the minimally mixed digesters. VFA degradation appears to increase along with

the mixing intensity, however the biogas production rate of the 150 RPM mixed digesters is lower, suggesting that there was lower VFA production in the 150 RPM mixed digester.

Higher VFA concentrations are often used to indicate process instability in the anaerobic digestion process, however the results from these experiment show that the effects of mixing are not limited to the instabilities as indicated by accumulating VFA concentration. The 150 RPM digesters show lower gas production and gas production rate at all VFA contents. In these experiments there is inhibition of the entire process under high intensity mixing conditions, as suggested by Vavilin et al. (2007), and not an imbalance of the process between the hydrolysis/fermentation and methanogenesis steps that leads to acidification of the process, as suggested by Stroot et al. (2001) from their observations during process startup. The unmixed period in these experiments does, however, allow for increased stabilization of the process and mixing is started without acidifying the environment during higher loadings. The relatively low residual organic content relative to microbial biomass of the post-digestion digesters did not alleviate the effects of the higher mixing intensity. High organic loads did however require a mixing intensity of 25 RPM to maintain the high rate of biogas production.

At higher mixing intensities the lower gas production during startup and shock loads are usually accompanied by high VFA concentrations (Stroot et al., 2001; Hoffman et al., 2008; Sulaiman et al., 2009), however, this is not the case in these experiments. Depending on the organic loading of the process, different amounts of mixing are needed. The mixing regime can thus be optimized to the OLR and substrate used in the system. The type of mixing equipment used is likely to be very important and defining the mixing demand simply as the mixing energy per cubic meter of digester volume or RPM is a very blunt tool for mixing design and configuration. It is also difficult to translate these types of results to full scale digesters since it is not trivial to reproduce mixing patterns and intensity at the larger scale. Lower mixing levels have however been shown to result in similar gas production (Hashimoto et al., 1982) and improved digestion (Sulaiman et al., 2009) in both pilot and full scale digesters.

4.2.1.4 Energy considerations

The lower 25 RPM mixing intensity improved biogas production rate compared to the 150 RPM mixing intensity. Reducing mixing intensity from 150 RPM to 25 RPM represents an 83 % reduction in rotation speed which is reflected in reduced mixing energy demand. Reducing the mixing period also has a similar effect on the energy demand. Kowalczyk et al. (2013) observed a 29 % reduction in the energy demand after reducing the duration of the mixing period by 33 %. Controlling mixing with different combinations of mixing intensities and mixing periods of different durations could be used to

increase biogas yields and decrease the energy demand of the process making it more energy efficient.

4.2.2 Membrane filtration

The results of the membrane filtration experiments to treat the process water of an anaerobic digester in a high temperature membrane filtration unit (Paper V) are presented in this section.

4.2.2.1 Flux

The permeate flow through the membrane increased substantially with the process water temperature. The steady state fluxes obtained during the internal circulation of permeate at the different temperature intervals are shown in Table 6. The result obtained in Test 7 indicates a tendency towards clogging at lower temperatures (70 °C). However, high temperature washing is a common method used to dissolve foulants on the membrane surface (US EPA, 2005) and it may be this self-cleansing effect that accounts for the differences between Tests 1 and 2.

Table 6. Maximum flux values during the experiments

Test	Temp	Maximum flux (L h^{-1} m^{-2})
1	110– 116	345
2	112– 114	464
3	110– 113	464
4	92– 101	189
5	94–104	189
6	76– 84	113
7*	112– 116	292

*carried out as a follow up experiment after Test 6 at the lowest temperature interval

The permeate withdrawal phase is plotted in Fig. 18. The flow of permeate during the withdrawal phase is affected by buildup of foulants on the membrane surface and the increased TS concentration of the process water in the inlet tank. At 110 °C the decrease in flux is rapid due not only to foulants and increased TS concentrations but also to the limited process water supply for the filtration at high flux values. Fig. 18. shows that the flux levels off and stabilizes at 60–70 L/ h^{-1} m^{-2} and 90–100 L h^{-1} m^{-2} for the 70 °C and 90 °C temperature intervals respectively but that the 110 °C filtration never levels off at all before the inlet tank is empty. The result does however give an

indication of high fluxes and a possible temperature interval. A larger inlet tank would be needed to determine the steady state flux for the higher temperature level, however the configuration of the pilot plant used in these experiments is not suitable for extended steady state experiments.

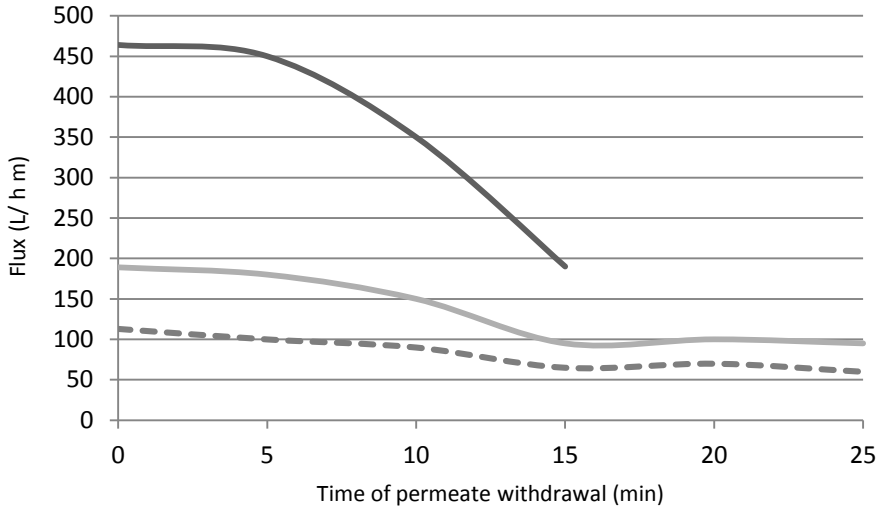

Figure 18. Flux values of the membrane filtration experiment
Flux of permeate through the membrane at three different temperature levels. Filtration curves for Test 6 at a temperature of 70 °C ( ), for Test 4 at 90 °C ( ) and for Test 3 at 110 °C ( ).

The high flux at the 110 °C temperature range indicates that this is the most suitable temperature, among the temperature ranges evaluated, for operation of this type of compact high rate membrane filtration system. Before a steady state flux can be more accurately determined, a low estimated flux of 190 L h^{-1} m^{-2} is used as the dimensioning key of the proposed system, as this flux occurs repeatedly during the experiments before the low water level in the inlet tank causes the permeation to stop.

4.2.2.2 Separation efficiency

The separation efficiency is not only dependent on the membrane used, but also on the temperature selected for the filtration process, with higher temperatures generally leading to lower separation efficiencies. This can be the result of increased solubility or thermal hydrolysis of the organic material due to the high temperatures. Previous results also indicate that temperatures of 120 °C produce permeates with higher TS of approximately 1.9–2.1 % (Thorin, 2009), much higher that the TS values presented for the 70–110 °C range. Higher temperatures therefore reduce the effectiveness of the installation. This effect of high temperature applications of membrane filtration is also seen in other experiments (Wallberg & Jönsson, 2006). The

TS separation in the filtration experiments is shown in Table 7. The TS separations presented are the mean values of the three permeate samples taken during each test series. The permeate is free from suspended solids and consists of water with dissolved low molecular weight compounds, e.g. sugars, salts, amino acids.

Table 7. TS separation
The TS content before and after filtration at the different temperature intervals.

		TS (%)			TS Reduction in the permeate
Test	Temp	Process water	Permeate	Concentrate	
1	110–116	3.97	1.63	8.43	59 %
2	112–114	3.93	1.62	10.63	59 %
3	110–113	4.13	1.63	10.29	61 %
4	92–101	4.09	1.55	5.46	62 %
5	94–104	4.16	1.52	6.46	63 %
6	76–84	4.29	1.60	6.52	63 %
7	112–116	4.39	1.66	-	62 %

4.2.2.3 Capacity

Dewatering of digestion residues is an important but problematic part of the anaerobic digestion process, which can have both economic and process related consequences. In digestion systems where the filtered liquid is recirculated as process water, dewatering can have a direct effect on the capacity of the plant. Experience from the Växtkraft biogas plant in Västerås, Sweden, shows that a high and accumulating TS content in the process water leads to a capacity problem, and fresh water must be added to dilute it before it can be utilized in the process. As TS increases, the centrifuges used for dewatering also experience more problems and process water production is thus reduced as a result. In order to avoid these complications, the TS content of the feed should be maintained below a maximum of 10% to reduce the problems caused by increased viscosity. If the process water were to be filtered using the high temperature membrane filtration setup evaluated in this thesis, this could in theory mean a capacity to pre-process as much as 29 % more SSOFMSW in a best case scenario, where the accumulated TS has been removed from the system. These calculations are based on the measurement of TS and not viscosity, since there is no way of testing the effects of the viscosity changes on the process itself. However, even if there is a capacity increase in the pre-treatment, the OLR and general status of the digestion process will still limit the amount of substrate that can be added. The useful capacity increase of the substrate pre-processing step is therefore severely

limited by the constraints of a reasonable OLR if no additional digesters can be added. If substrate availability is a problem or if the OLR cannot be increased, the extended capacity of the water treatment can also be used to reduce the water demand of the process from a maximum of 32 m^3 h^{-1} to just over 22 m^3 h^{-1}, which will reduce the load of the water treatment and centrifuges.

4.2.2.4 Energy balance

The energy balance of the system was evaluated in paper V for the operating temperatures 90 °C and 110 °C, including a system for heat recovery. During the experiments no increase in the energy demand for pumps could be seen between a TS content of 4 % and 11 %. For the four different flow cases (section 3.3) 4–11 and 7–20 membrane units were needed to treat the incoming process water at 110 °C and 90 °C respectively. The power demand of the system for the different flow cases is shown in Fig. 19, with energy allocations for the pump and the heating. For comparison the energy content in the additional biogas produced by using this system is in the range of 600–1 800 kW, calculated from a substrate TS of 30 %. The results presented here show that the proposed membrane filtration system results in a positive energy balance in this general case if no limitations is set on the OLR.

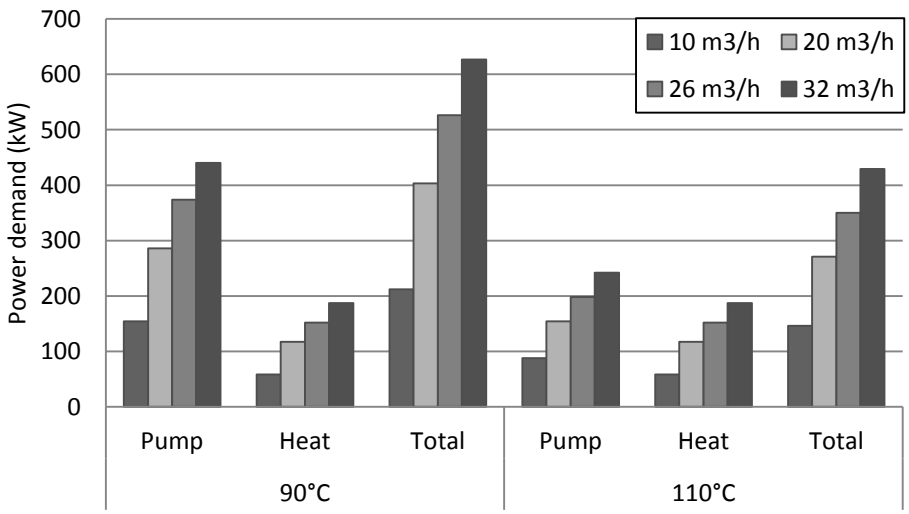

Figure 19. The power demand of the 90 °C and 110 °C ultrafiltration membrane system

4.2.2.5 Economic evaluation

The membrane is the most expensive component of the proposed membrane filtration system. Because of this the operating temperature of 110 °C is the only system evaluated. The capital cost of the membrane installation for Cases 1–4, treating process water flows of 10, 20, 26 and 32 m^3/h, is around 600, 900, 1 200 and 1 400 thousand euros, and the operational costs are shown in Fig. 20. The membrane filtration experiment was set up for batch experiments, however, continuous experiments are needed to evaluate the lifespan of the membranes and the cleaning intervals. This uncertainty is dealt with in the economic analysis by considering a range of annual operating costs between 6.5 % and 10 % of the capital cost.

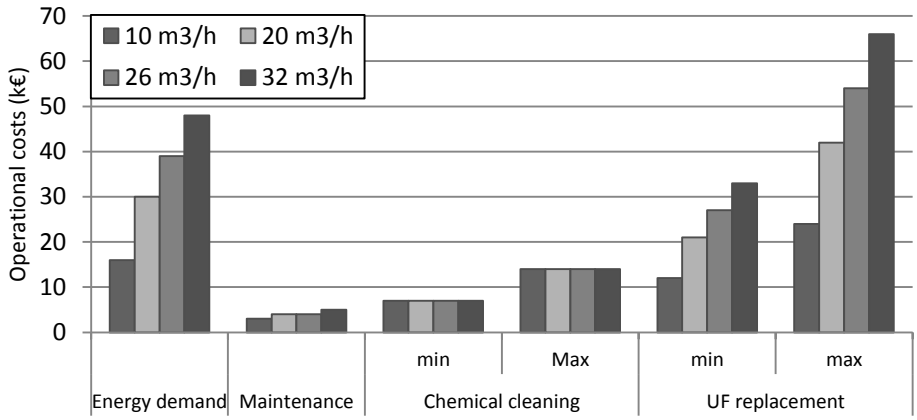

Figure 20. The annual operational cost of a membrane installation used at 110 °C (260 operating days annually) in thousands of euros (k€).

Revenues from the increased capacity are in the range of 90–130 thousand euros per year when sold as vehicle fuel. However, because of the high capital and operational cost, this economic calculation is very sensitive to approximations, assumptions made and long term performance of such an installation.

4.3 System perspective

The pre-treatment of ley crop silage, the effects of mixing and the membrane filtration application studied in this thesis can be integrated in the anaerobic digestion process to improve its efficiency (Fig. 21). In this section the total capacity, energy efficiency and improved methane production of the different technical solutions are discussed from a system perspective.

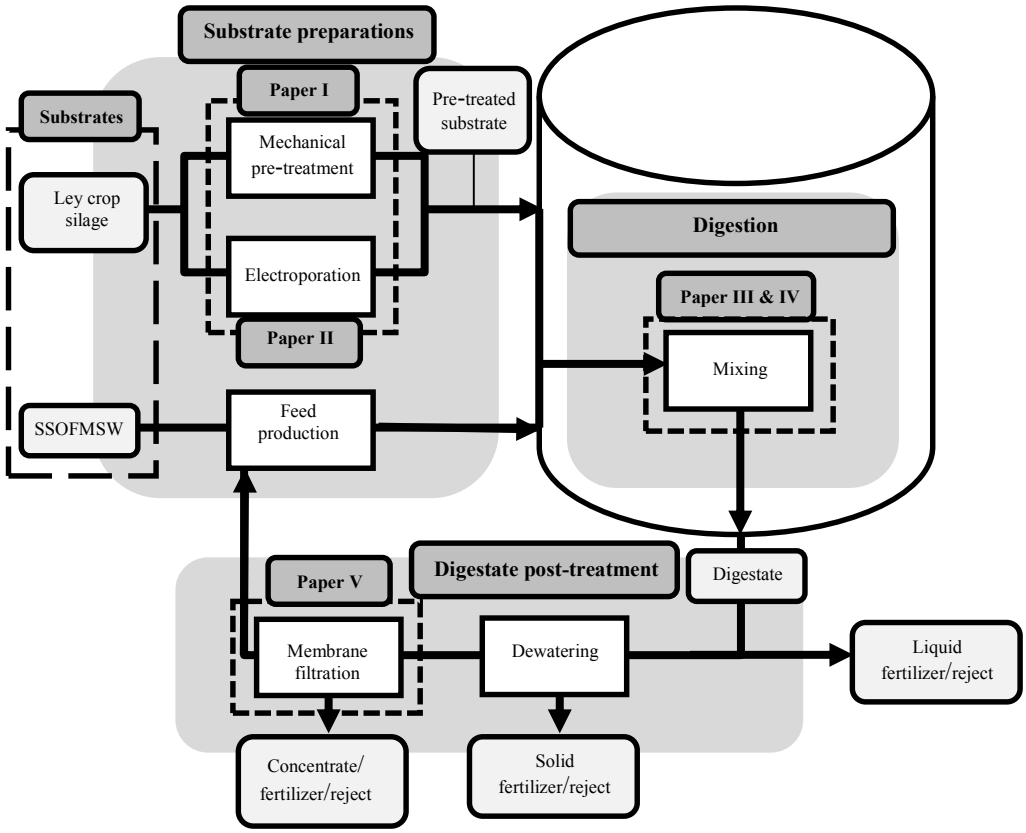

Figure 21. Process scheme of a general anaerobic digestion process
Showing how the different contributions of paper I–V can be integrated in the system. The process is divided into substrate preparation, anaerobic digestion and digestate post-treatment.

4.3.1 System integration

The different stages of the anaerobic digestion process are interconnected and interact with each other. The characteristics of the substrate, the substrate preparation and the pre-treatments performed affect each of the following process steps including digestibility, biogas production, the tendency of the substrate to sediment and float, and the dewaterability of the digestate. All downstream problems can be seen as symptoms of inefficiencies in upstream process steps. Which makes it important not only what technology that is chosen but also in which order process changes are made.

Size reduction of agricultural crops can lead to decreased energy demand of the pumping and mixing equipment (Nordberg & Edström, 1997). Pre-treatments can also affect the dewaterability of the digestate (Agyeman & Tao, 2014) and a well-functioning digestion process can improve substrate degradation and by doing so reducing the suspended solids in the process. This can affect the demand for both mixing and dewatering.

The selected mixing regime can decouple the solid retention time (SRT) from the HRT and in doing so increasing the digestion time of the substrate and reducing the TS in the digestate which is subsequently removed from the digester (Ong et al. 2002). A lower amount of suspended material also decreases the need for dewatering, however, this can also lead to accumulation of material in the digester that must be handled. The HRT is an important control value that dictates the digestion time of the substrate as long as the digester is perfectly mixed and the substrate is always kept in suspension. Decoupling of the SRT and HRT is enhanced by decreasing the mixing in the digester and by short-circuiting flows.

Reducing the mixing period and intensity of a CSTR can be associated with problems such as foaming, floating layers and sedimentation, depending on the substrate and the pre-treatment utilized. It is therefore important to identify the problems that can occur in each individual system. Stroot et al. (2001) and Kowalczyk et al. (2013) observed problems with foaming during absence of mixing and during mixing breaks when digesting sludge from waste water treatment and a mix of agricultural crops and residues, respectively. During the experiments performed for this thesis, ley crop silage showed a tendency to form a floating layer. Other common agricultural substrates like cattle manure stratify in three distinct layers, with a lower suspended solids content in the middle layer when unmixed (Schofield & Rees, 1988). When designing a digester a hopper bottom and mixing at the surface can alleviate problems associated with low mixing. However, heating issues also need to be considered. In order to sustain the process temperature in the digester a minimum amount of mixing may be required as performed in the study of Rico et al. (2011). Moreover, in a low mixing configuration the substrate should be pre-mixed or added to a circulation line to ensure good contact between the feed and the anaerobic microorganisms.

There are several reasons for dewatering of the digestion residues, including to reduce the amount of sludge that needs to be disposed of and to produce process water for recirculation to the substrate preparation step. When producing a feed from a solid substrate, dilution is needed before digestion. This means that treatment of recirculated process water can have a large effect on the capacity of the plant, as well as affecting the amount of bulk materials recirculating in the system and the amount of water that will end up in the reject/liquid fertilizer that needs to be transported from the plant. By recirculating the process water there is however always a risk of accumulating inhibitory substances that may reduce biogas production if their concentrations are allowed to increase (Shahriari et al., 2012). Increased amounts of dry solids being recirculated in the process has also been shown to have a negative effect on the separation efficiency of centrifuges, increasing the need for maintenance and resulting in reduced permeation.

4.3.2 System capacity

There are many factors that contribute to the system capacity, including the feed mixture, OLR, HRT and process temperature (Parawira 2004). From a technical point of view the system capacity to pre-process and digest substrate is affected by bottlenecks in the substrate preparation step as well as the status of the anaerobic digestion process. By reducing bulk TS in the process water, the capacity of substrate pre-processing can be improved as well as reducing wear on the plant. An improved capacity to process the substrate can translate to a proportional increase in methane production if the digester can handle the organic load, or if additional digesters are constructed. Changes in the substrate preparation, mixing or in the environmental conditions of the digester may however reduce the amount of solids and particles in the digestate and in the process water, and in doing so also reduce the need for further water treatment, as well as increasing the capacity to digest more substrate.

Pre-treating ley crop silage can increase the rate of degradation by reducing the particle size and destroying the cells and structure of the material, leading to increased methane production and a degradation rate of 16–59 % (paper I & II). The increased degradation rate also increases the capacity of the plant for digesting more substrate. The capacity of the pre-treatment equipment may however limit the amount of substrate that can be treated, and the operation time and effect of the pre-treatment is also affected by wear and maintenance needs. Mechanical pre-treatment is especially sensitive to wear since the machines are in direct contact with the substrate, which can be both abrasive, corrosive and contain contaminants like metal, sand and rocks, and the grinding segments are subjected to large forces. The benefits of the mechanical pre-treatment are also likely to decrease with time as the grinding segments are worn down and will recover first after the segments are replaced.

This will affect the treatment result between maintenance of the equipment. Mechanical pre-treatment is an alternative for treating various agricultural biomass before digestion, however, not all biomass will respond with an increased biogas production. Rice straw and maize stalks for example showed no significant increase in gas production while barley and wheat straw improved significantly as shown in a recent study (Menardo et al. 2012)

High intensity mixing has been shown to reduce biogas production at both high and low organic loadings and to slow down the conversion to biogas at low organic loadings when minimal mixing is applied (paper III & IV). However, it is not yet possible to estimate the potential of these types of process modifications for full-scale digesters. Reducing mixing speed during periods of instability and increasing mixing periodically to homogenize the digester content and temperature and break up floating or sedimentation layers shows great potential to improve process stability, increasing biogas production and decreasing energy demand.

4.3.3 Energy considerations

Application of these types of technical solutions is often associated with increased energy demand and it is important that the energy balance is evaluated. Membrane filtration technology has the highest energy demand of the evaluated technologies, in the form of both heat and electricity, but it also has the greatest theoretical potential to increase biogas production. Dewatering and solids separation is generally highly energy intensive but is usually necessary for digestate post treatment.

Comparison of the two different pre-treatments demonstrate that the mechanical treatment has by far the better energy efficiency with a best case biogas output to electricity input ratio of 26:1 compared to 2:1 for electroporation. However, the electroporation treatment is still under development and further improvements of the energy efficiency may be possible. Nevertheless, the energy efficiency is usually subordinate to the economic efficiency within the industrial sphere.

The literature review and experiments performed to evaluate the effects of mixing on anaerobic digestion (paper III & IV) show that a lower mixing intensity is possible without a corresponding loss in gas production. Mixing can account for a large proportion of the total energy demand at a biogas plant, especially in a farm scale or agricultural biogas plant which has less extensive substrate preparation and digestate post-treatment steps. Kowalczyk et al. (2012) and Hashimoto et al. (1982) observed no negative effects when reducing the mixing period to 30 % and 10 % of the original mixing period respectively, and these reductions were reflected in the energy demand. According to the results of paper IV, the reduction of mixing by almost 100% from continuous mixing (25 RPM, 24 h/day) to minimally intermittent mixing (manually by inverting the digestion flasks once per day) only leads to a

maximum reduction in biogas production of 6 %. Furthermore, in low organic loadings the digestion kinetics were almost identical between the two mixing modes. It is not yet clear at what level of TS content and viscosity the rheological properties of the digestate change to the degree that the mixing intensity needs to be increased.

4.3.4 Economic considerations

Favourable economics are important for the further development and expansion of the biogas industry. Improved methane yields by pre-treatment of the substrate (paper I & II) decreased energy demand of mixing (paper III & IV) and improved capacity of feed production by improving the substrate/process water ratio through reduction of process water TS (paper V) can all be exploited to improve the economics of a biogas plant. The economic efficiency is however dependent on many factors, including the local biogas market, the need for transport, maintenance and replacement of worn out parts. Biogas can be valued very differently depending on whether it is sold to a gas grid, as transport fuel or used to produce electricity or heat. The value of the produced methane is often linked to availability and price of petroleum and natural gas in the same region or the electricity and heat prices if there is no local market for methane. The economic incentives to develop and optimize the process are, thus, very different among regions and countries, and in areas with large quantities of fossil fuels the main goal of anaerobic digestion might be to reduce the environmental impact of an organic residue rather than the optimization of gas production. Biogas in Sweden is primarily used as vehicle fuel and the market is still growing. The price of methane is linked to the price of petroleum when sold as vehicle fuel but is not subject to the same high taxes, making it more profitable for the producer. The revenues from methane when sold as vehicle fuel are double those when it is used for electricity production. Moreover, there is a low loss of methane during upgrading to vehicle fuel compared to the energy losses during electricity production.

Process water treatment can also improve the economics of a biogas plant by reducing the amount of fresh water needed in the process and reducing some of the costly transports associated with reject disposal or fertilizer transportation with high water content. The cost of transportation and disposal of waste material and sludges can be substantial and is the main reason for a large proportion of Swedish municipal waste water treatment plants having a biogas plant to begin with. As the Swedish biogas market has developed, the economic incentive to increase biogas production has also increased. However, membrane filtration technology is very expensive and cost reduction may be necessary for its application in the anaerobic digestion process.

4.3.5 Case study

To put the efficiency improvements in perspective, the capacity, energy efficiency and economics have been calculated for the full scale co-digestion biogas plant Växtkraft which treats 15 800 ton SSOFMSW, 2 400 ton ley crop and 2 100 ton fat removal sludge (Swedish Växtkraft AB, 2013). The biogas plant is allocated a total energy input of 4 691 kWh electricity and 6 980 kWh heat per day of which 23 % of the electricity is used for digester mixing, making it the single most energy demanding equipment at the plant (Liljestam, 2011). A recirculation loop connected to the digester also contributes to the electricity demand of the mixing with 6% of the plants total energy demand (Liljestam, 2011), which would make the total energy demand of mixing as high as 29 %, but is left out of the mixing calculations since it has many purposes. The methane potential is calculated as 97 m^3 methane/ton SSOFMSW, 83 m^3 methane/ton ley crop and 37 m^3 methane/ton fat removal sluge respectively with the ley crop characteristics 33.5 % TS and 90.1 % VS (Weiland & Ahrens, 2006). The increased capacity of the plant is calculated from the best case scenario presented in the energy balance for each pre-treatment, which show that the pre-treatments can make a clear contribution to the biogas plant's methane production even though ley crop is not the main substrate, and for Case 1 for the membrane filtration, during which 10 m^3/h of process water is treated in the high temperature high rate membrane filtration setup (Table 8). The calculations show that the pre-treatments can increase the total methane yield of the plant by 2–6 %, and the process water treatment can increase the total methane yield up to 10 %. However, an approximation of the plant's OLR shows an already high value of 3.5 kg VS/m^3, and that the potential to increase the biogas production by feeding more substrate is limited. The result of the membrane filtration in Table 8 should therefore be viewed as a possible increase and not an actual increase, since the capacity of the pre-processing cannot be utilized with the current limited digester volume. Pre-treating the main substrate, SSOFMSW, would of course have a larger effect on the production capacity of this particular biogas plant since it corresponds to 78 % of the total substrate amount. The capacity improvements resulting from the pre-treatments are good even though ley crop silage is a relatively small part of the total substrate amount (12 %). The membrane filtration unit would reduce the number of problems experienced in the process and the capacity of the plant to treat the SSOFMSW can be restored, but the increased capacity of the substrate pre-processing cannot be fully utilized without additional digester volume.

Table 8. Methane yield per day before and after process modifications

	SSOFMSW	Ley crop silage	Fat removal sludge	methane production increase
Biogas plant original yield:				
Calculated yield (m^3 methane/day)	4 199	546	213	-
After pre-treatments:				
Grubben deflaker (m^3methane/day)	-	868	-	6 %
Krima disperser (m^3methane/day)	-	780	-	5 %
Electroporation (m^3methane/day)	-	633	-	2 %
After TS separation:				
Membrane filtration (m^3methane/day)	4 679[a]	-	-	10 %[a]

[a] results are based on the capacity of the pre-processing but the methane yield is also limited by the OLR

If the biogas plant used a higher proportion of ley crop in the feed, the pre-treatments would of course have a larger impact on the total biogas production. However, if the ratio of ley crop silage were increased at the expense of a substrate with a higher methane potential like SSOFMSW, there would be a decrease in total biogas production unless inhibiting substances or changes in the nutritional value of the feed are a major issue.

The process improvements studied in this thesis also indicate that energy can be saved by operating at a lower mixing intensity and operating the mixing intermittently while still obtaining similar or improved biogas production. Unmixed or minimal mixing is however unsuitable at higher OLR and can lead to a decrease in the biogas production rate. The Växtkraft biogas plant is mixed by biogas injection. Gas-lift mixing produces good surface movement to reduce the effects of flotation or foam production but is worse when handling sedimentation than a vertical shaft stirrer (Lindmark et al. 2009, Lindmark et al. 2012). Reducing the mixing intensity from continuous to intermittent mixing has been shown to improve the energy efficiency by reducing the energy demand without a reduction in biogas yield. Reducing the mixing period from continuous mixing to 10-30% of full mixing has shown similar gas production to that of the continuous mixing regime at both full and small scale (Kowalczyk et al., 2012; Hashimoto et al., 1982). Even though the research on mixing control is not mature enough to determine the best mixing regime, the trend points towards reduction of mixing periods or intermittent mixing. One benefit of these types of process modifications is that the transition can be slow to see the effect which lower mixing intensities can have on the process.

It is important to note that the electroporation was performed on a mechanically pre-treated sample and that the combined effects of the size

reduction and electroporation could lead to a higher biogas production than electroporation on the original sample. However, the size reduction in this case was not very extensive. An energy analysis of the studied process improvements shows that the pre-treatment has a substantially higher energy output than input and also that the energy demand of the membrane filter unit is high (Fig. 22). The membrane filter accounts for the largest increase in the energy demand among the evaluated technologies with an electricity demand of 0.70 Mwh/day and a heating demand of 0.46 Mwh/day, which increases the total energy demand of the plant by 10 %. The two mechanical pre-treatments, Grubben deflaker and Krima Disperser, have an electricity demand of 0.05 and 0.38 Mwh/day and the electroporation has an energy demand of 0.51 Mwh/day. The energy demands of the pre-treatments correspond to 0.43 %, 3.26 % and 4.4 % increases in the energy demand of the plant for Grubben deflaker, Krima Disperser and electroporation respectively. The proposed reduction in mixing can save electrical energy in the range 0.76–0.97 Mwh/day.

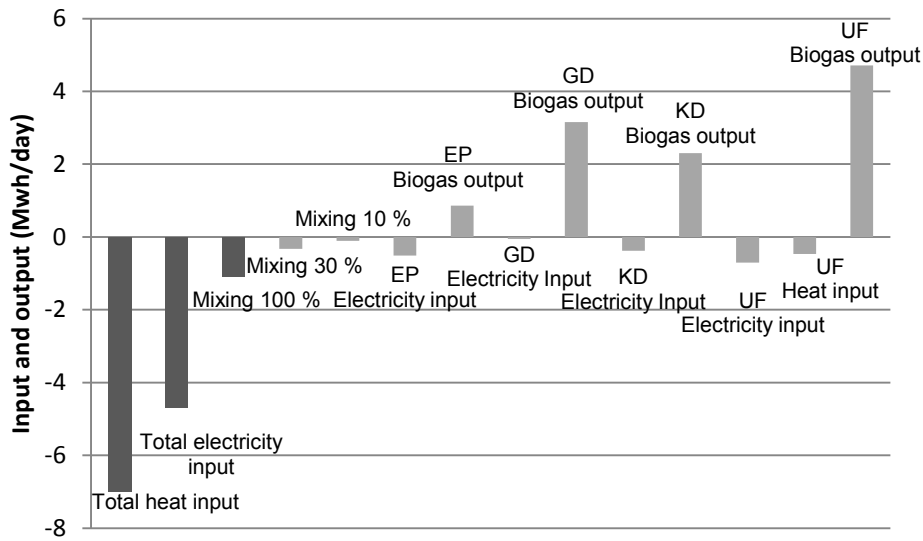

Figure 22. Energy input and output of the biogas process and evaluated technical solutions

The mechanical treatments, Grubben deflaker (GD) and Krima disperser (KD), and the electroporation (EP) and ultrafiltration (UF) membrane energy balance. The dark bars indicate the energy demand of the Växtkraft biogas plant and the light bars indicate the studied technical solutions.

It is important to remember that a comparison between electrical energy and methane is problematic since they have different economic values and different uses. The economic results are dependent on the local biogas and energy market and how the gas is sold, with increased profitability when sold as vehicle fuel under Swedish conditions (Table 9). Today's Swedish biogas market is focused on the production of vehicle fuel, causing the pricing of the gas to be linked to petroleum prices, which is economically beneficial. This also supports the reduction of greenhouse gas emissions and reduced dependence on fossil fuels in the transportation sector.

Even though process water treatment shows potential to improve the capacity of the substrate pre-processing, the capital cost of the membrane filtration unit and the energy and operational costs are relatively high, which makes the economic evaluation very sensitive and the design of such a unit may have to be revised to lower these costs.

Table 9. Revenues/savings, energy and capital costs

	Biogas market revenues/savings (€/day)				
	Electricity[a]	Heat	Fuel	Energy cost (€/day)	Capital costs (k€)
Pre-treatments:					
Grubben deflaker	99	314	499	4	100
Krima disperser	72	229	364	30	200
Electroporation	27	85	135	40	92[b]
Process improvment:					
Membrane filtration	148	468	744	304	581
Mixing reduction to:					
30 %	59	-	-	-	-
10 %	76	-	-	-	-

[a] 40 % efficiency in the energy production

[b] approximated and scaled down from economics presented by Rittman et al. (2008).

In summary, the case study shows that the water treatment cannot contribute to increase the substrate fed to the digester and increase of methane production because of an already high OLR. The pre-treatments show a substantial effect on the methane yield of the process even though ley crop silage is not the main substrate of this co-digestion biogas plant. A gradual transitioning to an intermittent mixing regime has the potential to save large amounts of energy while allowing the process to be monitored for any problems that may arise.

5 Conclusions

Introducing pre-treatments in the substrate preparation step of ley crop silage shows positive results with respect to factors like capacity, energy and economics. Methane production can be increased by 16% to 59% according to the evaluations performed using the electroporation and mechanical pre-treatment respectively. Commercial pre-treatment equipment is already available and there are developing technologies like electroporation that can improve the rate of degradation of the substrate. The pre-treatment is the most influential technical solution evaluated since it affects all downstream process steps and it also holds the greatest potential for improving the efficiency of a biogas plant according to the experimental results.

Decreasing mixing by changing from continuous mixing to an intermittent mixing regime and lowering mixing intensities can reduce the energy demand of the plant and increase process stability. Reducing mixing is sometimes associated with practical problems, but similar gas production can be achieved at lower operational costs. High mixing intensities may even be associated with reduced gas production. Rethinking the use of continuously stirred tank reactors, one of the most common reactor designs, and running them as intermittently stirred tank reactor holds great promise. Energy savings as a result of mixing reduction is, however, limited to the energy used by the mixing equipment, but increased research in this area could potentially lead to actively controlled mixing to increase gas production. During digestion startup or after a shock load, biogas production is often inhibited by VFA accumulation at higher mixing intensities. An unintended overload of the digestion process should therefore be managed by both pausing the substrate feed into the digester and reducing the mixing intensity for faster recovery. Even after the initial shock load, higher mixing intensities still exhibit lower biogas production rates without accumulation of VFA, which means that VFA accumulation due to instabilities in the process may not be the only or main reason for the observed effects of mixing. Reducing mixing is thus economically beneficial and it can reduce the impact of any instability that may arise during the plant's operation.

Improved water treatment can have large effects on the capacity of a biogas plant by improving the substrate to process water mixing ratio during feed production and reducing wear and operational problems associated with recirculation of large amounts of suspended solids. The evaluation of the high temperature high rate ultrafiltration membrane showed higher capacities with

increasing temperatures, with flows from 189–464 L h^{-1} m^{-2}, and solids reduction of 60 %, which could improve the capacity of the plant by enabling it to treat up to 29 % more substrate in a best case scenario. A membrane filtration application is however expensive both in terms of capital investment and operation cost making the economic balance very sensitive. Dewatering and solid separation is very energy intensive in general, and in this case the extent to which the feed mixing ratio can be optimized is limited. This type of technology could be used to reduce process problems with increasing bulk material in the process and/or support the production of more feed. However, the limited OLR of the digester limits the amount of feed that can be fed to the process. Moreover, by introducing pre-treatment and improving the environmental conditions in the digester an appended water treatment could be rendered redundant.

The case study shows that the pre-treatments has an effect on the methane yield of the process of 2-6 %, even though ley crop silage only makes up for 12 % of the total substrate amount. Reducing mixing has the potential to lower the total electricity demand of the biogas plant by up to 23 %, however, there is as of yet no possibility to determine the resulting biogas production in a full scale installation as an effect of a changed mixing regime. In theory treating the process water could increase the capacity of the plant and biogas production with up to 10 %, however, in this case the organic loading of the process limits its effectiveness.

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