AALBORG UNIVERSITY
COPENHAGEN

FORSK EL PROJECT No. 10209

FiberMaxBiogas -
Increasing the biogas yield of manure fibers by wet explosion – demo-scale

Project period 01/06-2009 – 31/03-2014

Institution responsible for the project:
Section for Sustainable Biotechnology
Aalborg University Copenhagen,
A.C. Meyers Vænge 15, 2450 København, Denmark.
CVR no.: 29102384

Authors:
Hinrich Uellendahl, AAU Cph
Birgitte K. Ahring, AAU Cph
Rajib Biswas, AAU Cph
Mattias Ljunggren, BioGasol ApS
Rune Skovgaard-Petersen, BioGasol ApS
Martin Hostrup, BioGasol ApS
Jens Munck, M-tek

5 May 2014

Financed by ENERGINET.DK

Preface

This is the final report of the project “FiberMaxBiogas - Increasing the biogas yield of manure fibers by wet explosion – demo-scale”, which was granted by the ForskEL program (no. 10209).

The project was carried out from June 2009 to March 2014 by the Section of Sustainable Biotechnology at Aalborg University Copenhagen (SSB-AAU) in collaboration with BioGasol ApS, M-tek and Biokraft A/S.

The report comprises the main results and conclusions of the project. For more detailed information please refer to the different articles in the list of dissemination of results at the end of the report.

Copenhagen, 1 May 2014

Hinrich Uellendahl, Associate Professor,

Section for Sustainable Biotechnology, Aalborg University Copenhagen

Content

Introduction

Biogas produced from manure, organic waste and plant biomass is becoming increasingly attractive in terms of reducing greenhouse gas emission, nutrient recovery as well as renewable energy alternatives to fossil fuels. It was shown in a recent life cycle assessment that biogas production from manure has the highest reduction effect on greenhouse gas emissions compared to other biofuels production processes (Thyø and Wenzel, 2007). Despite the environmental benefits, the economical operation of centralized biogas plants based on manure alone is difficult due to a low methane yield per volume unit of manure (Gerin et al., 2008). Thus manure based biogas plants are currently depending on the co-digestion of industrial waste with a high methane yield, typically originating from food industry. While for example 40 mio. tons of manure produced annually in Denmark represent a huge biogas potential, only 5% of this amount is currently treated in biogas plants and the implementation of centralized biogas plants in Denmark has stagnated throughout the last 10 years due to the fact that the operation based on manure alone has not shown viable and the availability of industrial organic waste is limited (Jensen et al., 2009). The Danish governmental program “Green Growth” targets an exploitation of up to 40% of manure in 2020 (Danish Government, 2009), according to an increase in biogas plant capacity by eight-fold, equivalent to more than 70 new centralized biogas plants of the largest scale. Since manure will be the main substrate for these future biogas plants it is a prerequisite to achieve an economically feasible operation of manure-based biogas plants in order to see this program coming into full implementation. For economic operation of a biogas plant biogas yields of more than 30 m3 per m3 feed are needed to compensate for the transportation costs (Uellendahl et al., 2007). The biogas yield of manure in conventional biogas plants is often lower since the organic matter content in manure is typically less than 10%, of which 60-80% is fiber material, which leads to methane yields of only 30-50% of the methane potential (Hartmann et al., 2000; Christensen et al., 2007; Boe and Angelidaki, 2009). Intensive research has been carried out for improving the biogas yield of manure and sludge by implementing a wide range of biological, chemical, mechanical, and thermal pretreatment methods (Angelidaki and Ahring, 2000, Hartmann et al. 2000, Carrère et al., 2010), in co-digestion with organic waste (Angelidaki and Ellegaard, 2003), in combination with solid-liquid separation of manure (Mladenovska et al., 2006, Christensen et al., 2007, Møller et al. 2007, Kaparaju and Rintala, 2008), and in different digester configurations (Boe and Angelidaki, 2009; Kaparaju et al., 2009). Comparing the different treatment methods for increasing the biofuels yield from lignocellulosic biomass, it was found that thermo-chemical treatment was the most suitable for the treatment of lignocellulosic biomass for subsequent conversion into biogas (Angelidaki and Ahring, 2000; Lissens, et al. 2004; Uellendahl et al., 2007). Thermal hydrolysis has proven commercial viability for enhancing biogas production of sludge and household waste by implementing a number of large-scale plants worldwide by the company Cambi (Elliott and Mahmood, 2007).

Implementation

Wet explosion (WEx), a steam explosion process with or without addition of oxygen, has previously shown a high potential for the destruction of the lignocellulosic structure of biomass, in order to enable the hydrolysis for subsequent ethanol fermentation (Klinke et al., 2002; Lissens et al., 2004; Sørensen et al. 2008). Generally, WEx includes both physical disruption and a partly chemical degradation of the biomass (Sørensen et al., 2008). The WEx treatment equipment, patented by the Danish company Biogasol ApS, can handle material up to 30% dry matter, and results in high sugar yields, which can subsequently be converted into ethanol or methane (Christensen et al., 2007; Ahring and Langvad, 2008). Previous studies revealed that the effect of the WEx treatment is correlated to the content of lignin in lignocellulosic fiber material (Uellendahl et al., 2007). As a consequence, the combination of the WEx treatment with biogas production from manure was evaluated to be most beneficial when applying the treatment to manure fibers separated from the effluent of a biogas reactor after digestion.

The target of the ForskEl project "FiberMaxBiogas - Increasing the biogas yield of manure fibers by wet explosion – demo-scale" was to develop a new concept for economically efficient treatment of manure in biogas plants by recirculation and wet explosion of the digested fiber fraction of manure (Figure 1). The efficiency of the concept and the adjustment of the pretreatment parameters were performed in lab-scale before the demo-scale set-up at the end of the project period.

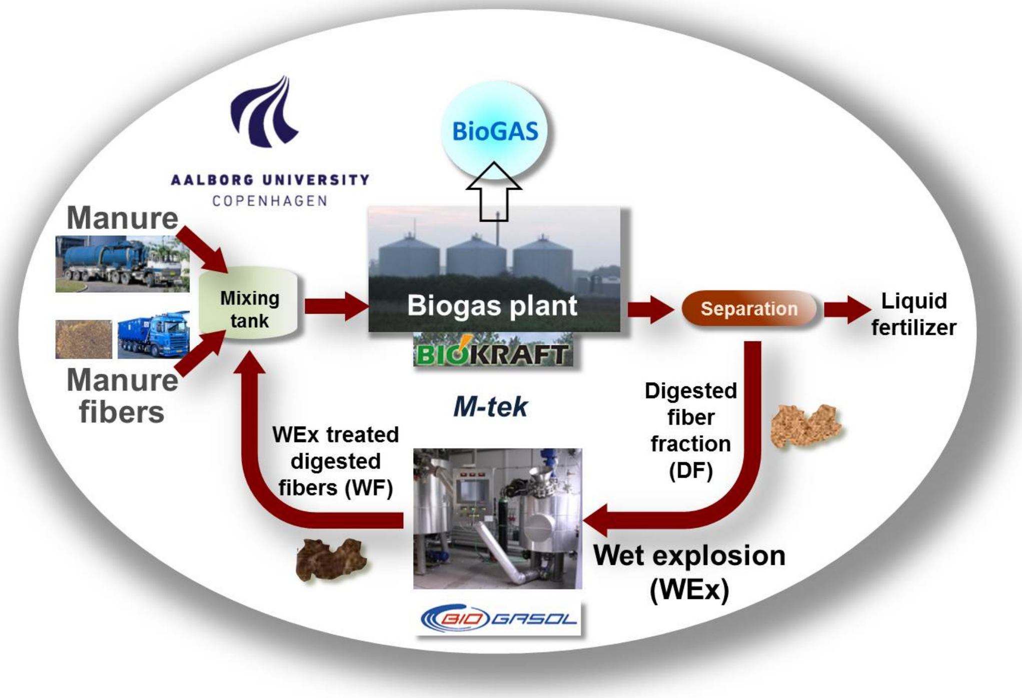


Figure 1. Overview of the FiberMaxBiogas concept with recirculation and wet explosion (WEx) treatment of the digested fiber fraction of manure

The work packages of the project

The FiberMaxBiogas project was divided into five work packages, namely the construction of the demo-scale wet explosion reactor (WP1), the set-up of the wet explosion reactor and integration into the biogas plant (WP2), the operation of the wet explosion reactor and further adjustment of the wet explosion process connected to Biokraft's biogas plant (WP3), the lab-scale process optimization of the pretreatment connected to the biogas process (WP4), and an economical evaluation – benefit for the biogas plant in relation to the costs for the pretreatment (WP5).

SSB-AAU was responsible for performing work package WP4, while BioGasol was responsible for WP1, WP2, and WP3 in cooperation with Biokraft A/S. The tasks of WP 5 were performed by M-tek based on data from Biokraft A/S in collaboration with SSB-AAU and BioGasol.

The tasks of the different work packages and the respective milestones are listed in Table 1.1 and 1.2, respectively.

Table 1.1. Work packages of the FiberMaxBiogas project

WP 1 Construction of demo-scale wet explosion reactor (BioGasol)
WP 1.1 Building of the continuous demo-scale wet explosion reactor as a mobile unit in a container, dimensions and specifications in agreement with Biokraft (Capacity 0.75 t-fibers/h=5250 t-fibers/year, 30% dry matter)
WP 1.2 Functional test of the wet explosion reactor
WP 1.3 Shipping of wet explosion reactor to Biokraft

WP 2 Set-up of wet explosion reactor and integration into the biogas plant (BioGasol, Biokraft)
WP 2.1 Preparation of the site at the biogas plant for installation of the wet explosion unit (Biokraft)
WP 2.2 Installation of wet explosion unit at the biogas plant (BioGasol, Biokraft)
WP 2.3 Functional test of wet explosion unit at the biogas plant (BioGasol)
WP 2.4 Start-up and adjustment of wet explosion reactor on digested manure fibers from the biogas reactors 1+2 (BioGasol)
WP 2.5 Adjustments on biogas reactor 3 for treating wet oxidized manure fibers (Biokraft)

WP 3 Operation of the wet explosion reactor and further adjustment of the wet explosion process connected to Biokraft's biogas plant (BioGasol, Biokraft, SSB-AAU)
WP 3.1 Semi-continuous operation of the wet explosion reactor and sampling of raw and pretreated substrate (Biokraft)
WP 3.2 Operation of biogas reactor 3 on pretreated digested fibers under low loading rate (Biokraft)
WP 3.3 Further adjustment of the demo-scale wet explosion parameters (dry matter content, temperature, retention time, addition of oxidizing agent) according to the optimal process parameters found in the first round of the lab-scale process tests (BioGasol, Biokraft, SSB-AAU)
WP 3.4 Continuous operation of the pretreatment connected to the biogas plant and sampling of raw and pretreated substrate (Biokraft)
WP 3.5 Analysis of the efficiency of the pretreatment in increasing the biogas yield related to different parameters applied for the pretreatment (BioGasol, Biokraft, SSB-AAU)

WP 4 Lab-scale process optimization of the pretreatment connected to the biogas process (SSB-AAU, BioGasol)
WP 4.1 Testing of the biogas process performance at different loading rates of pretreated digested fibers and different mixture ratios with raw manure and/or digested liquid fraction (SSB-AAU)
WP 4.2 Analysis of the efficiency of the pretreatment in increasing the biogas yield related to different parameters applied for the pretreatment (SSB-AAU)
WP 4.3 Analysis of the efficiency of the biogas process related to specific composition of the digested fibers, different loading rates and mixtures of raw manure and/or digested liquid fraction (SSB-AAU)
WP 4.4 Analysis of built-up of compounds that are inhibiting for the biogas process related to different parameters applied for the pretreatment (SSB-AAU)

WP 5 Economical evaluation – benefit for the biogas plant in relation to the costs for the pretreatment (M-tek, Biokraft)
WP 5.1 Collecting performance data of the biogas plant before implementation of the pretreatment (reference)
WP 5.2 Listing of investment and operational costs for implementation of the wet explosion pretreatment at the biogas plant for treating manure/manure fibers – from WP 1 and 2
WP 5.3 Collecting performance data of the biogas plant in connection with the pretreatment –from WP 3, 4
WP 5.4 Calculation of cost-benefit of the wet explosion for different sizes of the biogas plant and different scenarios (energy price, +/- connection to a CHP etc.) for treating manure/manure fiber under tested and optimized pretreatment conditions
WP 5.5 An environmental evaluation

Table 1.2. Milestones of the FiberMaxBiogas project

WP 1 Construction of demo-scale wet explosion reactor (BioGasol)
M 1.1 Demo-scale wet explosion reactor ready to be installed at Biokraft's biogas plant (BioGasol)

WP 2 Set-up of wet explosion reactor and integration into the biogas plant (BioGasol, Biokraft)
M 2.1 Wet explosion reactor is implemented in the biogas plant, treating digested fibers from reactor 1 and 2 and supplying reactor 3 with pretreated fibers (Biokraft)

WP 3 Operation of the wet explosion reactor and further adjustment of the wet explosion process connected to Biokraft's biogas plant (BioGasol, Biokraft, SSB-AAU)
M 3.1 Long-term efficiency of the biogas production on pretreated digested fibers at different organic lading rates and with admixing different ratios of raw manure and/or digested liquid fraction (SSB-AAU)

WP 4 Lab-scale process optimization of the pretreatment connected to the biogas process (SSB-AAU, BioGasol)
M 4.1 Identification of possible inhibiting factors from the pretreatment on the biogas process (SSB-AAU)
M 4.2 First round of identification of optimal parameters for the pretreatment of digested manure

fibers in combination with the biogas process (SSB-AAU)

M 4.3 Identification of optimal parameters for the pretreatment of digested manure fibers with highest increase in biogas yield, no limitation of the biogas process and low costs for the pretreatment (SSB-AAU)

WP 5 Economical evaluation – benefit for the biogas plant in relation to the costs for the pretreatment (M-tek, Biokraft)

M 5.1 Full cost-benefit analysis of biogas production from manure/manure fibers and waste biomass pretreated by wet explosion (M-Tek)

In order to make full use of the results from the lab-scale optimization of the wet explosion process, the construction, implementation and operation of the demo-scale wet explosion reactor (WP 1-3) were performed after the process had been tested and optimized in lab-scale (WP 4). Therefore, the results of the lab-scale tests and optimization are mentioned before the description of the demo-scale implementation.

Lab-scale process optimization of the pretreatment connected to the biogas process (WP 4)

The lab-scale optimization was performed by the Section of Sustainable Biotechnology of Aalborg University Copenhagen, with respect to find the best conditions of the wet explosion (WEx) treatment for the digested manure fibers in order to achieve the highest increase in methane yield with a stable process performance.

Materials and methods of the lab-scale tests

Digested fiber fraction. The effect of the wet explosion treatment was tested on digested fibers separated from the effluent of one of the biogas reactors of Biokraft's centralized biogas plant on Bornholm, Denmark. For separation of the digested fiber fraction the industrial scale decanter centrifuge installed at the biogas plant was used. The Biokraft biogas plant is operated under mesophilic conditions (38°C) with a hydraulic retention time (HRT) of 20 days, treating manure (>90% vol.), co-digested with agricultural residues (<5% vol.) and industrial waste (<5% vol.) from food processing industries.

Filtered Manure. The digested fiber fraction was added to the lab-scale reactors in co-digestion with filtered cow manure (FCM). FCM was obtained from cow manure delivered to the biogas plant of Biokraft A/S filtered through 10 mm sieves in order to avoid clogging of the influent tube. Filtered mixed manure (FMM) was used for the co-digestion of the digested fiber fraction from day 138 to 180. FMM was obtained from mixture of manure from cows, pigs and poultry in a ratio of 70:25:5 on TS basis.

Wet explosion treatment. The wet explosion treatment was performed in a lab-scale 3.5 L batch reactor with a maximum active volume of 2.0 L, provided by BioGasol A/S. The reactor is equipped with continuous stirring (990 rpm), gas and liquid dosage system for supply of additives (H_2O_2, H_2SO_4, O_2, Na_2CO_3 etc.), and a flush valve for sudden pressure release into a 25 L subsequent flash tank. The reactor is heated by an external oil heater. The denoted process temperature was the temperature measured at the reactor top.

Digested fibers were treated in 1 kg batches, adding 400 g of tap water to 600 g of fiber material for achieving a TS concentration of 12% inside the reactor. After the denoted treatment time in the reactor the biomass was flushed into the flush tank. The different treatment conditions are displayed in Table 1. Heating times to reach the start temperature varied between 7 and 15 minutes due to the different final temperature.

Batch experiments. The methane yields of treated and untreated digested fibers were determined in laboratory-scale anaerobic batch tests using 117 mL vials under mesophilic condition (38±0.5°C). Inoculum for the batch experiments was supplied from one of Biokraft's biogas reactors and stored at 4°C. Before batch set-up, the inoculum was pre-incubated at 38°C for one week.

Two different inoculum to substrate ratios (ISRs) were tested, i.e., 1.0 g VS/vial (ISR 1) and 0.5 g-VS/vial (ISR 2) of the substrate were added to vials with 25 mL inoculum. After filling with the respective biomass and inoculum, batch vials were flushed with N_2/CO_2 (80%/20%) prior to closing air tight with rubber stoppers and aluminum crimps. Experimental set-up was performed in triplicates and a triplicate of vials filled with 25 mL inoculum and water instead of substrate was used as control. The vials were incubated until no significant further biogas production was detected (48 days). The methane yield of the treated and untreated digested fibers was determined by measuring the methane concentration in the headspace using GC (SRI-GC-310) and calculated according to equation (Eq. 1). Overpressure in the vials was released whenever necessary and the methane concentration in the headspace was determined before and after the gas release for calculation of the cumulative methane yield. Methane production in the controls filled with inoculum only was subtracted to calculate the methane yield from the added substrate (mL/g-VS_{added}). A gas mixture of CH_4/N_2 (30%/70%) was used as standard gas mixture for gas chromatography (GC).

$$CH_4\ yield_S = (CH_4\%_S \cdot V_{headspace,S} - CH_4\%_C \cdot V_{headspace,C})/g\text{-}VS_{added,S} \qquad (Eq.\ 1)$$

Index S: added substrate, index C: control vials (without substrate)

Table 1. WEx conditions tested for the treatment of digested manure fibers (DF)

Batch	Treatment time (min)	Temperature (°C)	Pressure (bar)	Addition of O_2 (bar)
145-10	10	145	2.2	-
165-10	10	165	3.3	-
165-20	20	165	7.4	-
165-10-O_2	10	165	12.4	6
180-10	10	180	9.9	-

CSTR experiments. Two 5 L stainless steel continuous stirred tank reactors (CSTRs) with a working volume of 3L were operated with a hydraulic retention time (HRT) of 20 days. The reactor temperature was maintained at 38±0.5°C by circulating hot water in the heating jacket using a water bath. In order to evaluate the biogas process of WEx treated digested fibers CSTR experiments were performed by feeding WEx treated digested fibers (WF) in a test reactor (R1) and non-treated digested fibers (DF) in a control reactor (R2). The fiber fraction was in both reactors co-digested together with filtered manure (FCM). The wet exploded digested fibers (WF) were pretreated at 180°C for 10 min. Both reactors were fed (150 mL) twice a day using peristaltic pumps (Watson-Marlow 610 series). The produced biogas was registered using volumetric gas meters, logging the gas production automatically in 10-mL intervals. Reactors were stirred for 5 min. 10 times a day. The performance of the reactors was monitored on the basis of methane yield, VFAs concentration and pH.

During start-up, both reactors R1 and R2 were filled with 3L of inoculum, originating from one of Biokraft's biogas reactor. The feeding was started with filtered cow manure (FCM) alone (days 0-54) with an OLR of 2.5 g-VS·L^{-1}·d^{-1} and a HRT of 20 days. On day 55, co-digestion of the DF with

FCM was initiated in R1 and R2 at a feed ratio of 1:1 (w/w, % VS basis) with an increased OLR of 3.5±0.5 g-VS·L^{-1}·d^{-1} between days 55 and 76. After reaching the steady-state in both reactors on day 77, WF was gradually introduced in R1, replacing the same amount of VS of the DF in feed until only WF was used for co-digestion with FCM in feed of R1 (day 101). The feeding mixture in R2 was kept unchanged as on day 76 until day 214 when the experiments were terminated. From day 138 to day 180 filtered mix manure (FMM) was added used instead of FCM in both reactors.

Analytical methods. Analyses of total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), volatile suspended solids (VSS), volatile solids (VS), and chemical oxygen demand (COD) were carried out for both raw and pretreated material. COD was determined in Hach Lange cuvette tests according to the company's method LCK 914. TS, TSS, VSS, and VS were analyzed in accordance with standard methods (APHA 2005). Samples from both reactors were taken for measuring pH and volatile fatty acids (VFAs) 2-3 times per week. 125 µL of 17% H_3PO_4 was added in 1 mL sample in a 2 mL Eppendorf tube and centrifuged at 14,000 rpm for 10 minutes. The supernatant was transferred into VFA vials for analysis in a gas chromatograph (GC) PerkinElmer Clarus 400 series, equipped with flame ionization detector (FID) and a Hewlett Packard FFAP capillary column, 30 m x 0.53 mm I.D., film thickness 1.0 µm, using nitrogen as a carrier gas. The oven temperature was programmed from 115°C (hold for 3 min) to 125°C at a rate of 5°C/min and then increasing 45°C/min to 230°C and held at final temperature for 2 min. Nitrogen was used as a carrier gas at 18 mL/min and, the injector port and detector temperature were 175°C and 200°C respectively. Methane content (CH_4) in produced biogas for both batch and CSTR experiments was measured 2-3 times per week using GC (SRI-GC-310), SRI Instruments, USA, equipped with thermal conductivity detector and a packed column (Porapak-Q, 6ft. x 2.1 mm I.D.), where nitrogen was also used as a carrier gas. The pH was measured using an InoLab® pH 727 meter (WTW Inc.), with 0.001 pH accuracy).

Main results of the lab-scale optimization

Effect of wet explosion on substrate characteristics

The characteristics of digested manure fibers (DF) and WEx treated digested manure fibers under five different treatment conditions (145-10, 165-10, 165-20, 165-10-O_2, and 180-10) are displayed in table 2. The TS and VS of the digested manure fibers were 20.0% and 14.8%, respectively with a COD/VS ratio of 1.5. Generally, the COD/VS ratio did not alter significantly during WEx treatment (145-10, 165-10, 165-20 and 165-10-O_2). However, a significant higher COD/VS ratio of 1.7 was found for the WEx treated fibers 180-10, where the treatment was performed at 180°C and 10 minutes treatment time. This may be explained by the fact that due to the higher temperature a higher amount of lignin was broken into lower molecular compounds like phenols with a higher COD/VS ratio.

The relatively high pH of the digested fibers even increased for all WEx treatment conditions except for batch 165-10-O_2 where O_2 was added. Furthermore, TS, and VS after the treatment 165-10-O_2 were found lower than for the untreated material, obviously due to a higher conversion of the material to CO_2 by addition of O_2. The amount of total dissolved solids (TDS) in the pretreated materials increased under all five conditions.

Table 2. Characteristics of digested manure fibers before and after WEx treatment under five different conditions

Batch	TS (g/L)	VS (g/L)	TSS % of TS	TDS % of TS	VSS (g/L)	COD (g/L)	COD/VS	pH
DF	199.5 (2.4)	147.6 (1.9)	89.4 (0.7)	10.6 (0.7)	136.1 (4.6)	218.5 (15.7)	1.48	8.31
145-10	120.1 (2.6)	89.5 (2.2)	86.5 (2.1)	13.5 (2.1)	78.3 (2.1)	135.2 (0.0)	1.51	9.04
165-10	121.0 (2.9)	89.9 (2.5)	82.8 (2.3)	17.2 (2.3)	75.7 (1.0)	131.3 (0.0)	1.46	8.79
165-20	118.6 (2.4)	89.6 (2.2)	83.9 (0.5)	16.1 (0.5)	74.3 (1.6)	130.8 (1.3)	1.46	8.84
165-10-O_2	109.7 (0.2)	80.7 (0.6)	77.9 (0.0)	22.1 (0.0)	53.5 (0.6)	123.2 (9.0)	1.53	7.60
180-10	120.5 (1.9)	89.9 (1.7)	80.0 (0.6)	20.0 (0.6)	71.9 (0.7)	152.7 (5.5)	1.70	8.80

Samples were diluted before WEx treatment (3:2); - not determined; values in brackets are standard deviation.

Change of methane yield by wet explosion

The course of methane production and the final methane yields during the batch digestion of DF and WEx treated DF under the five tested WEx conditions are displayed in Figure 2. Generally, increasing the treatment temperature resulted in higher methane yields (Figure 2A). The highest methane yield (224 mL/g-VS) was found for the digested fibers treated at 165°C under the addition of oxygen at a batch loading of 0.5 g-VS/vial, ISR 2 (Figure 2B).

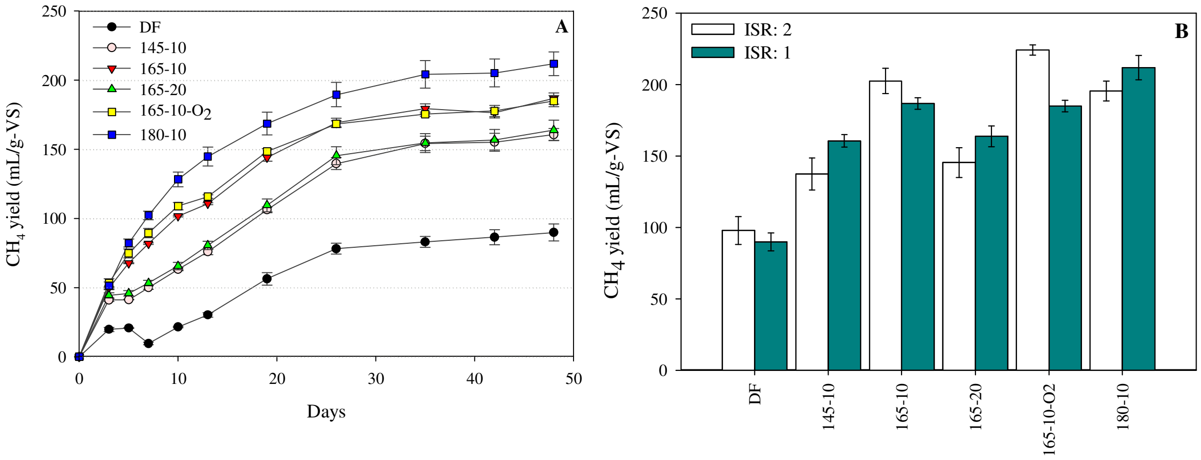


Figure 2: Accumulated methane yield in batch experiments of digested manure fibers (DF) and WEx treated DF under five difference WEx conditions (145-10, 165-10, 165-20, 165-10-O2, and 180-10). (A) Methane yields for a batch load of 1.0 g-VS/vial (ISR 1) and (B) Final methane yields after 48 days for the two different batch loads (ISR 2 and ISR 1). Error bars indicate the standard deviation of three replications.

At a higher load the final methane yield of the material treated with addition of O_2 was, however, significantly lower. This indicated an inhibiting effect from the WEx treated material with oxygen that counteracted the increase in degradability. For all other treatment conditions the increase in loading of the batch vial had only a minor effect, indicating no or only low production of inhibiting compounds during WEx treatment. Without addition of oxygen, the WEx treatment at 180°C for 10 minutes resulted in the highest increase of the methane yield of 136%.

CSTR Experiments

The performance of the test reactor R1 and control reactor R2 was monitored during 214 days by methane yield, VFA concentration, and pH (Figure 3). In the initial start-up, both reactors were fed with filtered cow manure (FCM) alone for 54 days. From day 55 untreated digested manure fibers were added to the feed of both reactors with the filtered manure. While maintaining the OLR at 3.5±0.5 g-VS/(L·d) the methane yield per gram organic matter decreased in both reactors significantly from around 180 mL/g-VS_{added} to 118 and 111 mL/g-VS_{added}, in R1 and R2, respectively (Figure 3A), due to the higher content of organic matter with a low degradability. After steady-state conditions were established in both reactors, the untreated fibers DF in the reactor feed of R1 were from day 77 gradually replaced by WEx treated fibers WF, replacing 1/3 of the DF from day 76, 2/3 from day 90 and feeding 100% WF in co-digestion with FCM from day 101. The average methane yield in R1 increased in the following gradually and reached in average 194 mL/g-VS_{added} (days 101 to 214) when feeding WF compared to 111 mL/g-VS_{added} in the control reactor R2 with untreated DF (Figure 3A). Both reactors show a decrease in methane yield from day 121 to 140 due to a process disturbance after blockage in the influent tube of both reactors which made cleaning of the reactors necessary. The performance of both reactors recovered, however, during the period from day 137 to 180, when the fiber fractions were co-digested in both reactors with filtered manure mix (FMM). Despite these fluctuations the methane yield in R1 remained significantly higher than in R2 for all times.

During start-up of both reactors the VFA concentration in both reactors exhibited very similar patterns with a rise above 20 mM and subsequent decrease to values lower than 10 mM (Figure 3B). This indicated very similar performance of both reactors with an adaptation phase during start-up. Also when introducing WEx treated fibers WF in R1 on day 76 the VFA concentrations remain generally very similar in both reactors. In the period from day 107 to 119 a significant increase of VFA up to 19 mM in R2 and 32 mM in R1 was observed. Although the origin of this increase remained unclear the higher increase in R1 may indicate that the performance of reactor R1 was more sensitive when only WEx treated fibers were added. On day 152 an increase of the VFA to 27 mM in R2 was caused by a process disturbance after blockage in the effluent tube. In the long run, however, and despite the change of FCM to FMM from day 137 to 180 the VFA concentration remained low in both R1 and R2. Furthermore, the generally very stable process performance of both reactors can be seen by the pH values of the reactors that remained 7.6±0.2 throughout the whole operation period.

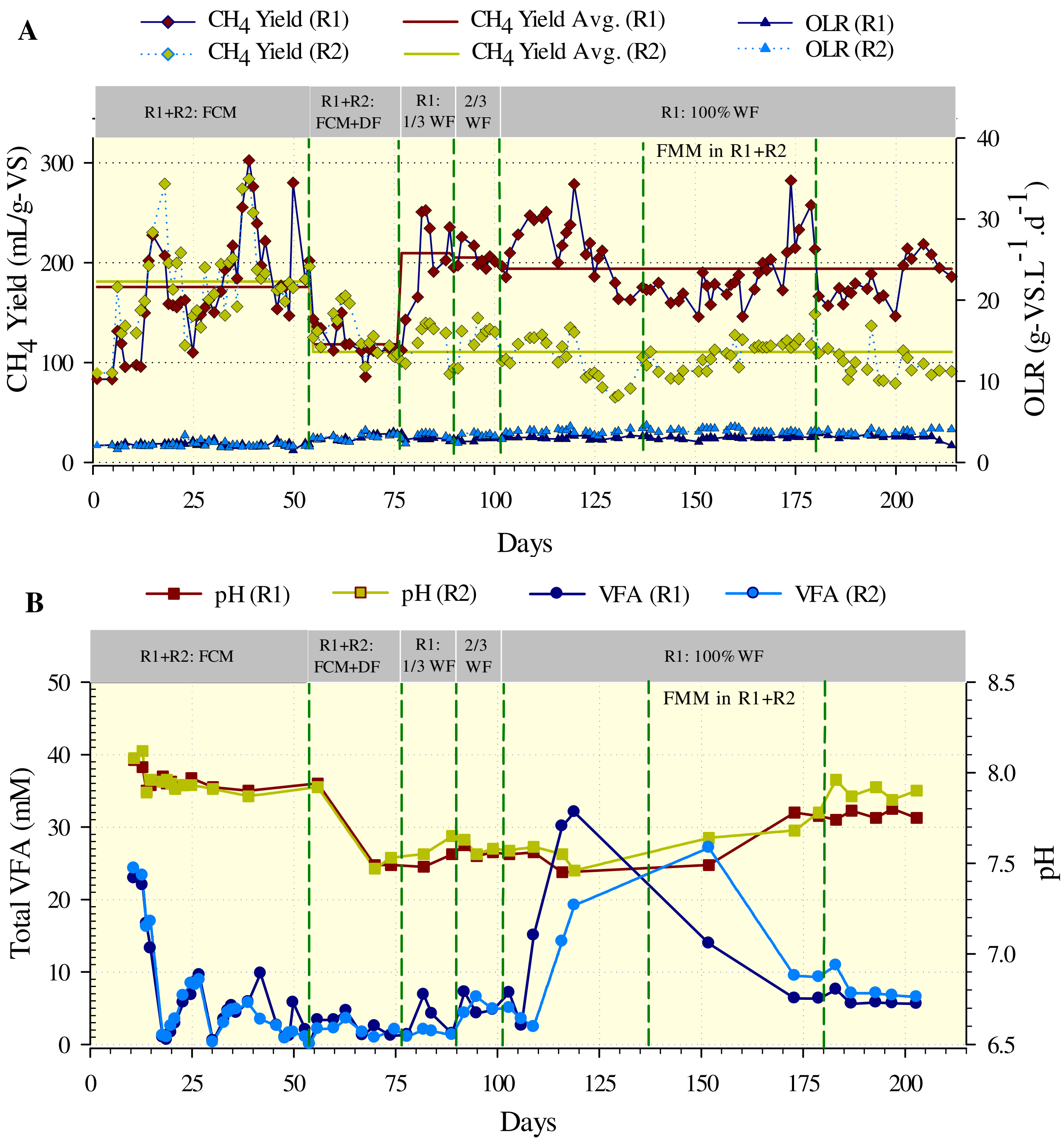


Figure 3: Methane yield, OLR (A), VFA and pH (B) in reactor R1 and R2 in the different experimental phases. Phase 1 until day 54: start-up of both reactors with filtered cow manure (FCM). Phase 2 (day 55-76) addition of digested fibers in R1 and R2. Phase 3-5 (day 77-214: Change of feed in R1 to WEx treated fibers (WF)).

Main conclusions from the lab-scale optimization

The testing of the FiberMaxBiogas concept for increasing the biogas yield of manure by combination of anaerobic digestion with wet explosion of the digested fiber fractions showed in both batch and reactor experiments that the methane yield of the fiber fraction can be significantly enhanced. Testing the WEx treatment under different conditions revealed optimum conditions at a temperature of 180°C and a treatment time of 10 minutes without addition of oxygen, resulting in a 136% higher methane yield as compared to the untreated digested fibers in batch experiments. The continuous feeding of WEx treated fibers in co-digestion with filtered manure revealed in average a 75% higher total yield. The batch experiments indicate that the addition of oxygen during the WEx treatment may lead to inhibiting compounds. The reactor experiments with digested fibers treated at 180°C for 10 min. revealed no significant signs of inhibition after a short adaptation phase when introducing WEx treated fibers in co-digestion with manure.

Construction of the demo-scale wet explosion reactor (WP 1)

Description of the pretreatment reactor Carbofrac®

The wet explosion reactor used for the demo-scale tests of the FiberMaxBiogas project was a modified pretreatment reactor designed and constructed by BioGasol A/S, called Carbofrac®. The Carbofrac® system comprises a dewatering module, a shredder, a retention module and a flash-out system (Figure 4). In the dewatering module the digestate (the liquid effluent from the biogas reactor) is, as the name implies, dewatered and the solid fraction forms a plug which is torn apart by the shredder. The shredded material is subjected to high pressure steam and heated to the target temperature. The heated biomass falls down into the retention module were the thermo-chemical pretreatment process takes place and is subsequently transported to the flash-out system by a screw. The speed of the screw determines the retention time of the biomass in the high temperature and pressure zone. The biomass then reaches the flash-out system (two valves in sequence with a small vessel in between) where it is discharged to atmospheric pressure.

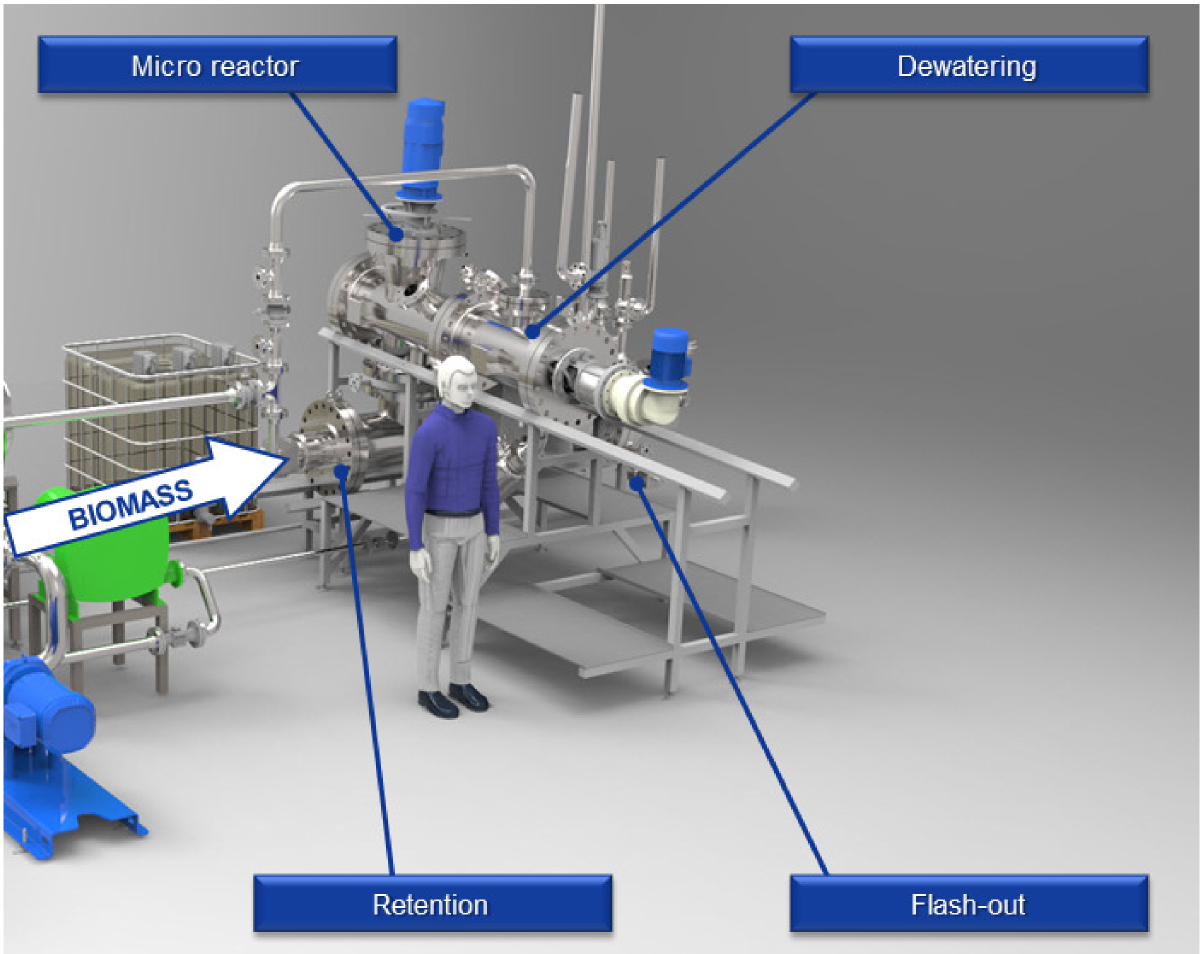


Figure 4. The Carbofrac® 10 pretreatment core system

Design and construction

The design of the pretreatment reactor was based on a previously built pretreatment unit in demo-scale for 2nd generation bioethanol production with a capacity of 500-1000 kg/h (under a EUDP grant). Once BioGasol had completed and operated the larger demonstration unit for a period of time, the learnings from this were used to design the pretreatment reactor system for the FiberMaxBiogas project. A novel dewatering unit especially for digested manure fiber was designed, constructed and tested under the FiberMaxBiogas project. During testing, excessive abrasion from the biomass was observed and the unit was re-calculated, modified and re-tested. The second test showed acceptable levels of abrasion and an impressive dry matter concentration of between 34 and 37%. BioGasol continued working with strength calculations, detailing of the remaining parts of the system so they could be manufactured. During 2012 all parts of the reactor were ordered and subsequently delivered to BioGasol at the end of 2012 and beginning of 2013.

After a meeting and in dialogue with Biokraft (February - March 2013) on utilities and integration with Biokraft's biogas facility the need for auxiliary equipment was identified. This equipment was not part of the Carbofrac® core process (the reactor) and had to be ordered or designed and manufactured (e.g. a monotube heat exchanger for product cooling and a compressed air booster). In June 2013 the pretreatment unit had been manufactured and assembled at the workshop in Køge and successful tests were carried out and thereby achieving M1.1.

Initial equipment tests and factory acceptance test

The equipment was manufactured and initial tests of the separate units were carried out. Most of the equipment worked as predicted and did not require modifications. The shredder, which is the core of the Carbofrac® system, was slightly modified to increase the steam flow rate. The main issue found was for the dewatering unit, which had difficulties dewatering the digestate. Further testing was required and 2 m^3 digestate was supplied by Biokraft. It proved to be very difficult to dewater the digestate. However, after substantial testing it was believed a solution was close. The original Piping and Instrumentation Diagram (P&ID) of the implementation of the Carbofrac® unit at the biogas plant was significantly changed, as the peripheral systems constituted the main integration effort and needed to be adapted to the core pretreatment process unit.

Therefore a factory acceptance test (FAT) was carried out in Køge using straw as a feedstock. The test proved successful and the equipment was sent to Bornholm even though the issue with the dewatering unit was not yet solved. The idea was to carry out the final testing of the dewatering unit on-site where sufficient quantity of digestate, with consistent properties and accurate temperature, needed for testing the dewatering unit was available.

Set-up of wet explosion reactor and integration into the biogas plant (WP 2)

Concept

Two different concepts for the integration of the wet explosion (WEx) for the treatment of the digestate into the biogas plant were discussed (Figure 5):

1. To pretreat the solid fraction in digestate from one reactor and feeding it to another reactor or
2. To treat the digestate from Reactor 3 and feed the treated digestate back to the same reactor.

Concept 1 would imply a reduction of the retention time and potentially also an increase of the solid content in the second reactor receiving the pretreated digestate. These changes on the operation of the biogas reactors were not acceptable for BioKraft; therefore, it was finally agreed on the implementation according to concept 2.

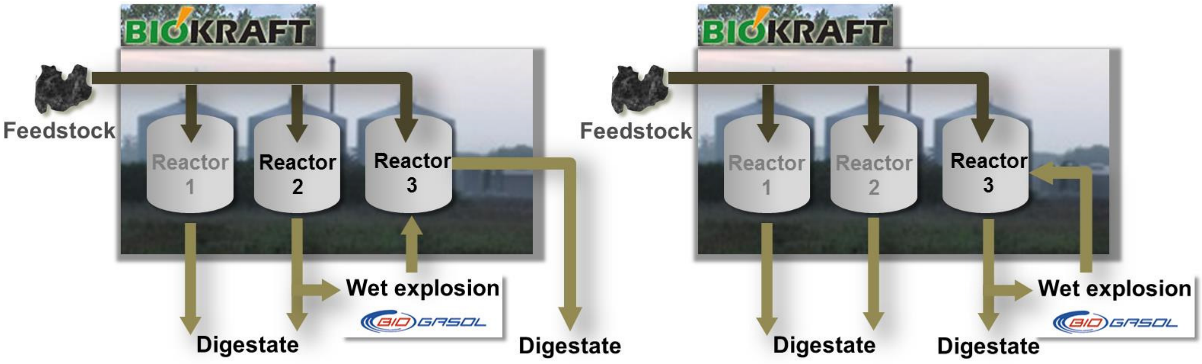


Figure 5. The two concepts for implementation of the WEx treatment at the biogas plant. (1) WEx treatment of the digestate of reactor 2 and feeding of reactor 3 with the pretreated digested fibers (left) and (2) recirculation of the treated digested fibers into reactor 3 (right). Concept (2) was finally implemented at BioKraft's facility.

In concept 2 the digestate is taken out from the reactor and fed to the pretreatment reactor where it is dewatered. The liquid fraction (reject water) is fed to a mixing tank, where the liquid is mixed with the treated solid effluent from the WEx process. The solid fraction is fed to the micro-reactor where the material is shredded and subjected to high pressure and temperature (140-180°C). The temperature and pressure is achieved and sustained by direct injection of pressurized steam. The heated material is then retained at high temperature in the retention module for a predetermined time (10-20 minutes). The retention time in the retention module is determined by the speed of the screw which transports the material through the retention module. The material is then flashed out into the mixing tank where it is mixed with the liquid fraction from the dewatering step. The flash out system works by operating two valves that are alternatingly opening and closing with a small buffer volume between the valves. The pretreated slurry (a mixture of the pretreated solid and reject water) is then fed back to the biogas reactor.

Auxiliary equipment

During the course of the project the original P&I diagram was substantially modified and extended with auxiliary equipment which was added. The need of additional equipment was identified in spring 2013, especially concerning cooling of the pretreated digestate before feeding it back into the biogas reactor. This gave rise to a need of a quite substantial cooling system. Luckily a cooling tower at Biokraft was not in use and in close proximity of the installed WEx unit so it could be used. To complete the cooling system two cooling water pumps (one for the pretreated biomass heat exchanger and one for a heat exchanger for condensing excess steam), a buffer tank and piping had to be included. Also, an additional dewatering system had to be installed prior to the original dewatering unit, which introduced further complexity to the system.

Assembly at BioKraft's biogas facility

All equipment was shipped to Biokraft's facility on Bornholm, where it arrived on June 26, 2013 (Figure 6). The unit was thereafter assembled and wired for operation (completed at the end of July 2013). The site of installation was changed in the last minute to one with more space. This showed later to be a good decision since the equipment list and therefore the space required, got much bigger with an extra feeding pump and a completely new dewatering solution, as can be seen in Figure 7.

New dewatering solution

In parallel to the assembly additional dewatering tests were carried out to find the final and appropriate dewatering setup. However, after some minor successes and failures it was concluded that the design of the dewatering unit that is part of the Carbofrac® unit was not appropriate for dewatering of the digestate (due to a high viscosity) and that the issue could not be solved by modifying the existing dewatering unit. The positive results seen before in the workshop in Køge were probably due to a significant change of the properties of the digestate during transport and storage (for example sedimentation) and after separation and mixing (the amount of digestate available required reuse of dewatered digestate).

Figure 6. Implementation of the unit at Biokaft's biogas plant, July 2013. Arrival of the Carbofrac®unit (top left), installed Carbofrac® unit with auxiliary equipment such as tanks and the mono-tube heat exchanger (top right) and the whole installation (bottom). At the time of the pictures dewatering trials were still ongoing and therefore no screw press is present.

Therefore, a search for an add-on solution was initiated and the focus was on technologies that were proven viable for biogas plants. The most promising alternative that could be readily implemented was to place a screw press prior to the dewatering unit. A suitable solution (although with a too high capacity) was a Börger screw press that was available through the company AL-2 Agro A/S. For the implementation of the screw press, the following additional piping and process controls had to be included:

- New feeding pump which could operate high solid concentrations
- Buffer tank for the reject water from the screw press

- High pressure piping from the buffer tank and the new solid feeding pump to the dewatering unit
- Load cells on the feeding pump and reject water buffer tank
- New algorithms to control the screw press (which had to run discontinuously due to a too high capacity) and the pump for pumping the reject water out of the buffer tank. These controls were based on the input from load cells.

The screw press performed beyond expectations and could produce a solid effluent ranging from 19 to 32 % total solids (TS) (Table 3). The screw press could probably achieve both slightly higher and lower TS but the boundaries were not tested, as it was not deemed necessary. Estimates based on experiments showed that the screw press captures roughly 40 % of the total solids when the TS content in the solid effluent is 32 %. The reason why the screw press could separate digestate and the original dewatering could not is due to the use of two very different separation principles:

The initial separation in the original dewatering unit of the Carbofrac® is based on self-drainage (gravitation-driven separation) while the Börger screw press is based on mechanical/physical separation, i.e. pressure supplied by the feeding pump and the screw drives the separation in the screw press. Due to the viscous nature of the digestate gravitational separation is very slow, if not non-existent (see short discussion later about the digestate).

Table 3. Total solid content in the solid effluent from the screw press. The distance refers to the distance between the pressure spring and the cover (a measure of how hard the spring was tightened (higher value = tighter spring).

Distance (mm)	90	50	40	35	30
TS (%)	31.8	27.0	25.4	21.7	19.0

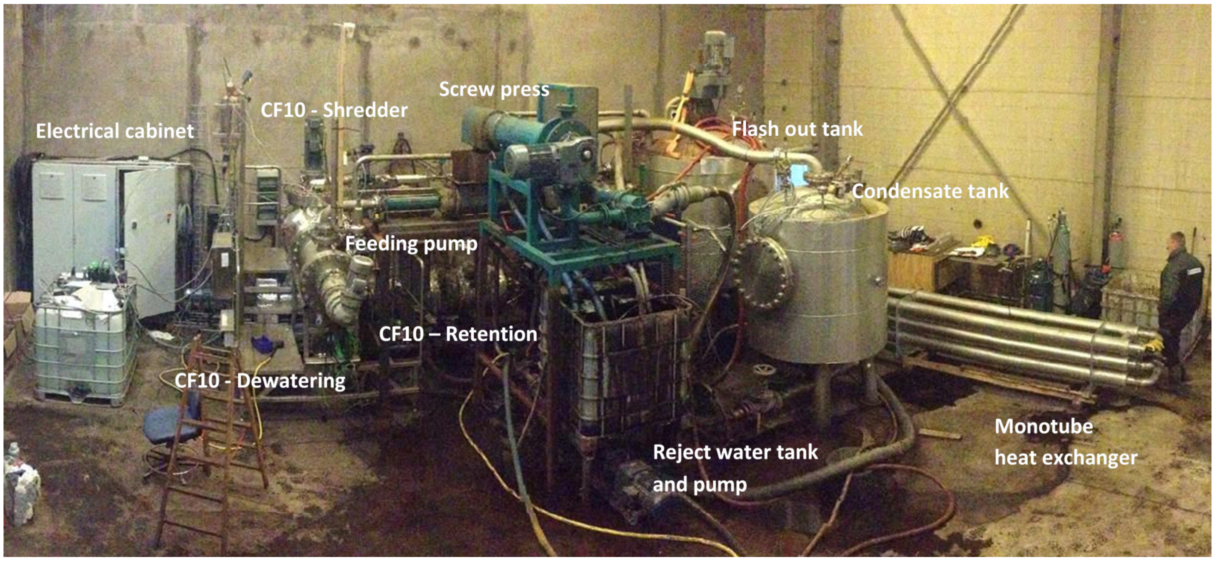


Figure 7. Final implementation of the Carbofrac® unit at the biogas plant including the screw press prior to the dewatering unit of the Carbofrac® unit.

The feeding pump had some difficulties pumping the dewatered digestate. The screw fed the material forward but instead of being transported out through the stator (Figure 8, bottom, the letter N is visible on the stator) it was pressed back to the biomass feed chamber (Figure 8, top). To prevent the biomass to be pressed back a metal plate was welded on just above part of the feed screw (see Figure 8, middle). After this modification the pump worked properly and could feed the dewatered digestate.

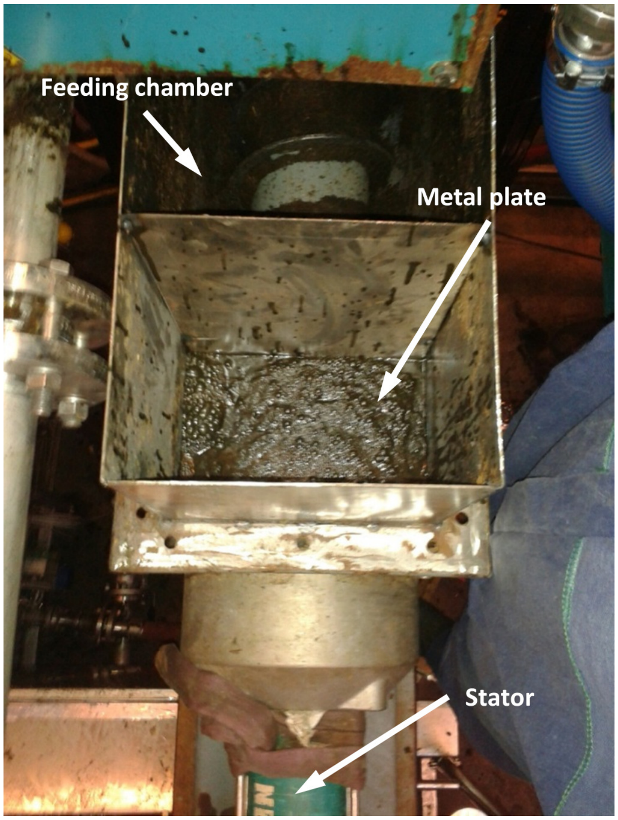


Figure 8. The modified feeding chamber on the feeding pump

Even though the original motor on the screw press was replaced with a smaller one, the capacity of the motor and the solid feeding pump were too high for the Carbofrac® 10. Therefore the feeding system had to run discontinuously, making the installation of a buffer tank in between necessary. The capacity of the pump was three to four times too high and the solution implemented was to run it for a specific time, e.g. 5 seconds and then stopping it for 13.5 seconds. A timer function was implemented in the control system which handled the sequence. The screw press was in turn controlled by the system based on load cells on the feeding pump. A hopper was attached to the feeding pump which dealt as a small buffer tank. The load cells on the feeding pump were then calibrated and used to control when to run the screw press. The readings from the load cells were influenced by the pressure in the dewatering unit, e.g. an increased pressure resulted in a higher load cell reading which potentially could result in the pump running dry. This phenomena was important to consider during start-up and if the system did not run stable (especially if the pressure in the dewatering unit varied).

Hot test

The first test of the whole plant was carried out on the 10th of October 2013 and was considered a success, although some new issues were revealed such as:

- Substantial amounts of condense water out of the retention chamber, originating from:
  - condensation within the system
  - the steam supply
- Inability to sustain a plug in the dewatering unit
  - the dewatering unit was able to build a plug but the plug collapsed immediately
  - the system could rebuild the plug but the plug would collapse again.
- High temperature out of the pretreated biomass heat exchanger due to:
  - Higher temperature in the flash-out tank than anticipated. This was due to:
    - Condensation of flash-out steam in the flash-out tank
    - Additional mass and energy from the substantial amount of condense water out of the retention chamber
    - A solid content in the feed to the system on the low end of the design estimates for the heat exchanger
  - A slightly underestimated overall heat transfer coefficient was used for the design of the heat exchanger
  - The flow through the retention was not continuous causing some of the flash-outs being empty (steam only). This caused fluctuations in temperature and pressure in the retention module.

Digestate

Since biogas plants operate with different feedstock compositions (cow/pig/chicken manure, slaughterhouse waste, corn, glycerol, etc.) and different solid content it is not possible to generalize the properties of the feedstock blend and the digestate. The digestate from Biokraft's biogas reactor showed a relatively high viscosity, making it more difficult to separate the solids from the liquid compared to for example fresh manure (which showed in other trials a viscosity much closer to that of water, when it primarily consists of fibres suspended in water). One effect of the high viscosity was that the fibers in the digestate did not settle. Even sand, which settles rapidly in water, took a long time to settle in the digestate. The high viscosity of the digestate from Biokraft's reactor may be due to the fact that, Biokraft receives other feedstock besides manure with high dry matter content like, for example, separated manure fibers, intestine content and corn, that will increase the viscosity of the influent and also affect the properties of the digestate.

The digestate from Biokraft's biogas facility on Bornholm had a total solid content of about 6.7 % and the fiber content was about 2.5 % or 40 % of the total solids.

Operation of the wet explosion reactor and further adjustment of the wet explosion process connected to Biokraft's biogas plant (WP 3)

Mode of operation

The hot test and following trials showed that the system was not able to sustain a plug which caused pressure and temperature variations in the dewatering and retention modules (Figure 9). After several test runs a new way of operating the unit was adopted; this reduced the fluctuations significantly (Figure 10). The trials showed that as long as the pressure in the dewatering unit was kept below the pressure of the retention unit (1 – 1.5 bar lower) the plug could be sustained. This solution only worked when the pressure and temperature fluctuations in the retention module (which also was identified as a problem during the hot test) were also reduced. The fluctuations could be reduced by increasing the flash-out time (i.e. fewer flash-outs per minute). This reduced the number of empty flash-outs, which were caused by the uneven biomass flow through the retention module. A possible explanation for the uneven biomass flow is that the friction between the biomass and the retention modules inner-casing is lower than the friction between the biomass and the screw. This could make the biomass follow the screw and hence make it accumulate. The increased flash-out time reduced the problem but did not solve the core issue. A permanent solution (which could not be implemented on-site at the biogas plant on Bornholm) would be to increase the friction between the biomass and the inner-casing further.

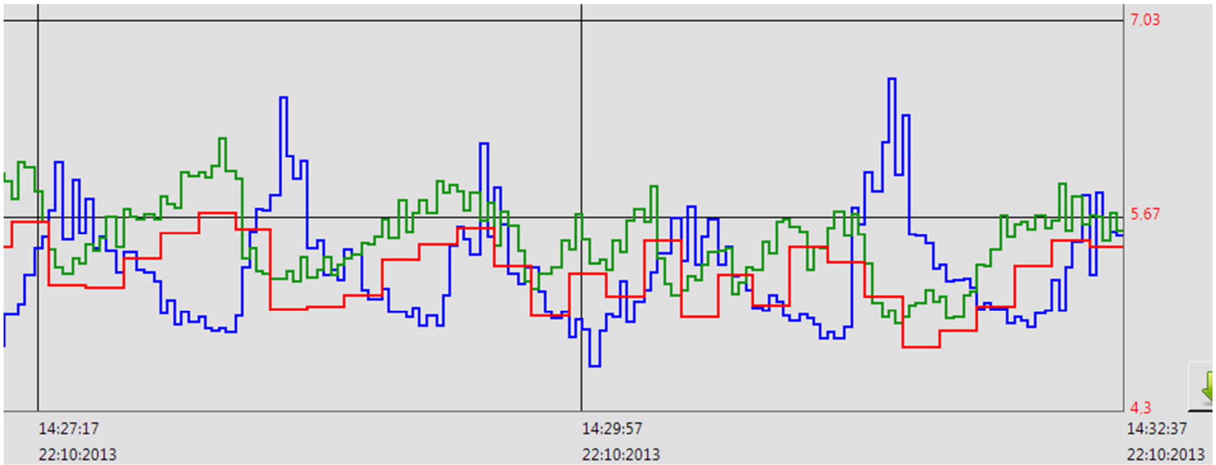


Figure 9. Pressure fluctuations in the system. Green line – pressure in dewatering (same axis as the red line), Red line – pressure in the retention module, Blue line – Shredder torque. The rapid increase in the torque is due to plug being pushed against the shredder and the plug is lost which is also indicated by the decreasing pressures. The pressure decreases due to steam condensation which in turn is due to the colder environment in the dewatering unit.

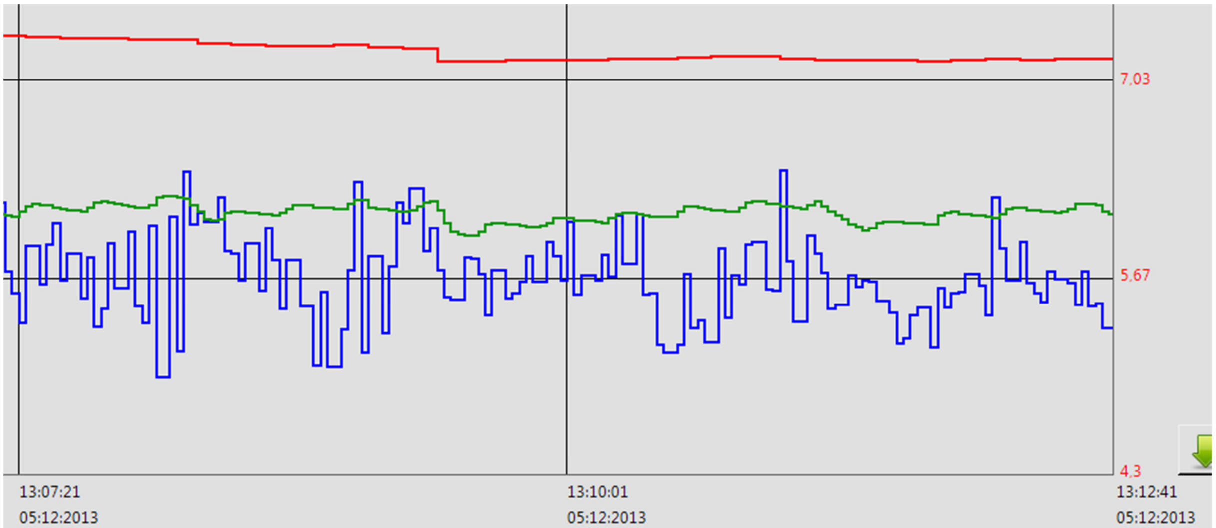


Figure 10. Reduced pressure fluctuations after the new operating strategy was implemented. Green line – pressure in dewatering (same axis as the red line), Red line – pressure in the retention module, Blue line – Shredder torque. There are still fluctuations in the shredder torque, however they have been reduced and the system manages to sustain the plug. The small periodic variations in the dewatering pressure (green line) are due to (and coincide with) the on/off operation of the feeding pump.

Control error between main system communication and add-on feeding system

On one occasion the dewatering unit stopped due to a high torque alarm from the shredder, this should also have stopped the feeding pump and screw press. This did, however, not happen and the feeding to the dewatering unit continued. This was not noticed by the operators and resulted in biomass accumulation in the dewatering sieve. The force delivered by the pump was actually enough to tear apart the metal sieve inside the dewatering unit (Figure 11). The reason for this was an error in the control system. The error was fixed and the problem did not occur again.

Figure 11. The ruptured sieve caused by feeding biomass to the dewatering unit after the dewatering stopped running.

Equipment wear

The wear on the equipment (especially the flash-out system) was significant (Figure 12). The wear was caused by excessive sand in the digestate. The concentration of sand in the dewatered digestate was estimated to be roughly 3%. A compensator located between the flash-out valves and the flash-out tank had to be replaced three times. First the worn out compensator was replaced with an identical but new compensator, the worn out compensator was a few years old. However, the new compensator soon wore out as well and instead a rubber compensator was installed, but it also wore out quite fast. To resolve the issue a new construction was implemented where the flash-out pipe was modified so it passes the compensator and the pretreated material, which is hot and moves at a high velocity, is prevented from ramming the compensator (see Figure 13). The compensator still functions as a shock absorber but is not subjected to any forces other than vibrations. The combination of high velocity of the pretreated material and the high sand content will wear out most metal alloys, but could be counteracted in future installations by introducing other solutions and/or materials e.g. ceramic liner in the discharge piping.

Figure 12. Wear on parts of the equipment was evident. The wear is caused by the sand in the feeding stream. Left: Flash-out out-coning pipe. Right: Compensator on the flash out pipe.

Figure 13. The elongated flash-out pipe. The pipe goes through the compensator which is bolted to the flange.

Sand

As described above the digestate of the biogas plant (which is the influent to the CarboFrac® unit) contains sand. Beside wear, as described above, this caused blockings in pipes on two occasions (Figure 14). Both times the blockings caused the rubber hose between the flash-out tank pump and the monotube heat-exchanger (250HEB01) to disconnect, causing a large volume of hot pretreated material to be spilled out on the floor. In both instances a sewer cleaning truck had to come and assist in the removal of the plugs (several blockings were removed in the monotube heat-exchanger and the piping to the biogas reactor).

In an effort to reduce the amount of sand, a simple sand trap was constructed in the screw press reject water tank. The sand trap could catch a portion of the sand but it was not sufficient. The reason is probably that the settling time of sand in the dewatered digestate is long due to the high viscosity of liquid and also that more sand is fed to the system via the dewatered digestate. The amount of sand in the feed to the equipment could probably be reduced by moving the extraction point for the digestate from the bottom to the middle of the biogas reactor. The digestate was extracted from the bottom of the reactor at Biokraft since this was the only available alternative and it was not possible to move the extraction point within the frame of this project due consideration for Biokraft's production targets. A change of extraction point will require the reactor to be shut-down and thus several working days would be required. One reason for the excessive sand could be the changes of feedstock from when the reactor was originally commissioned, e.g. the switch to maize silage could very well be the source of the higher than expected sand content, which does not match the extraction point in the reactor.

Figure 14. A portion of the sand removed from the monotube heat-exchanger after a blocking.

Operation time and effect on biogas production

The total operating hours with feeding of WEx treated material to the biogas reactor was about 170 hours. From 5th to 31st of November the unit was operated for about 45 hours (with feeding to Reactor 3) and from 1st to 18th of December the unit was run for 125 hours. Three long runs were achieved for 60, 44 and 12 hours respectively, all however ended prematurely due to either plugging or compensator failure. During the long runs the unit was under constant observation (three shifts with two persons per shift). In general the unit ran smoothly with minor interventions from the operators. This indicates that the process can operate without significant additional labour requirements (other than normal observation and maintenance work) and therefore could be automated in future industrial settings.

The operation during the FiberMaxBiogas project proved the technical suitability of the WEx equipment in its final design to separate and treat the solid fraction of the digestate from the biogas plant. The total operating period of the WEx reactor connected to the biogas plant was, however, too short to evaluate the effect of the treatment on the biogas yield of the biogas plant in the long run. During the operating period the biogas production increased in all three reactors but the production rose slightly more in Reactor 3 than Reactor 1 and 2 (Figure 15 and Figure 16). Compared to Reactor 1 the biogas production was lower in Reactor 3 at the start of the operation, but higher at the end of the period, which can be seen in Figure 16. This could give an indication that the WEx treatment had a positive effect on the biogas yield. The positive effect could, however, also be due to the fact that the biogas production of Reactor 3 was initially lower since it was temporarily running at a lower temperature than Reactor 1. The reason for this was that part of the insulation on Reactor 3 was blown off during a storm at the end of October (2013).

- The total operation time was shorter than the goal which was set and so the overall effect on the biogas production in Reactor 3 would have been difficult to discern.

The biogas production of Reactor 2 was not included in Figure 15 since it always shows significantly lower biogas production (which is, according to Biokraft, probably due to a faulty flow meter).

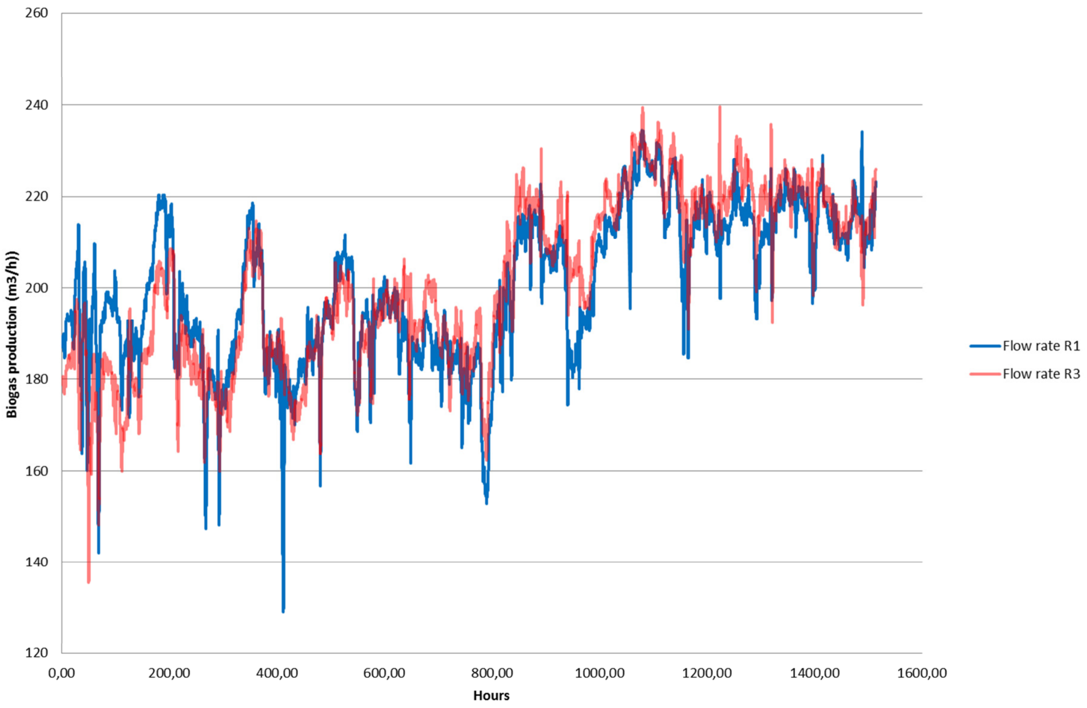


Figure 15. Biogas production from Reactor 1 and 3. 0 hour was the 9th of November 2013.

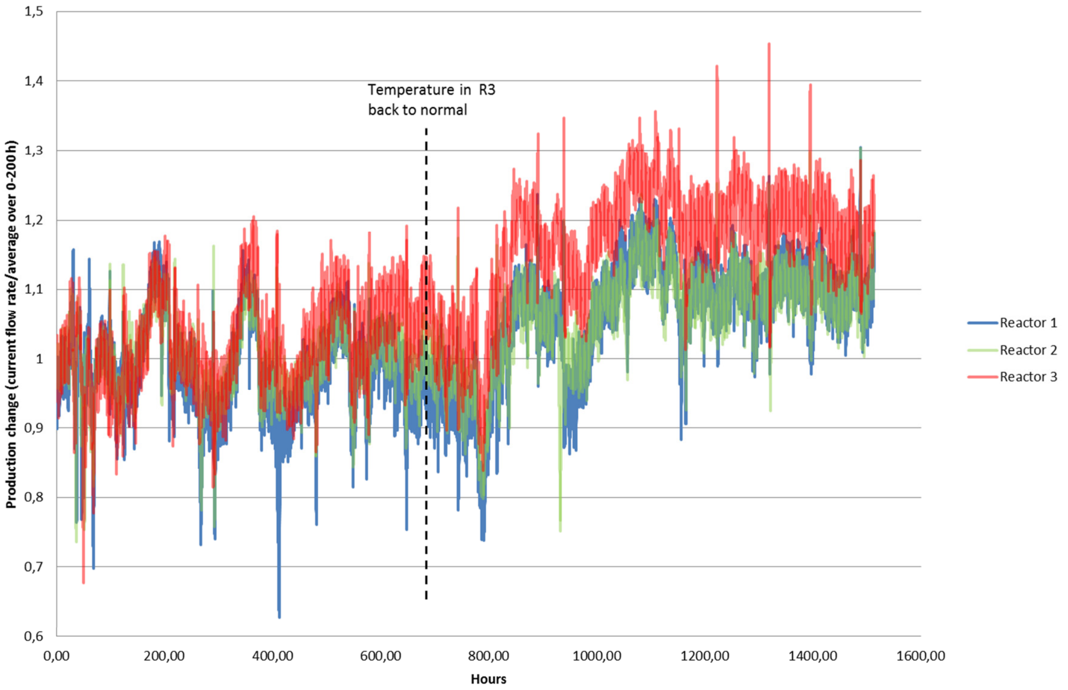


Figure 16. Change in biogas production over the period in reactor 1, 2 and 3. The change is calculated by dividing a 2 hour reading average with the average over the first 200 hours.

Analysis of biomethane potential (BMP) before and after the Carbofrac® unit

During the operation campaign, samples were taken from the feed, solid and liquid effluent from the screw press, after flash-out and after the mono-tube heat exchanger. The total and volatile solid contents were measured as well as the biogas potential (Table 4). The increase in biogas potential agrees well with the results obtained from experiments using the batch pretreatment reactor (in WP 4). This shows that the performance was not affected by scaling up the process. Hence, it proves the concept in pilot scale.

Table 4. Biogas potential of different in- and output of the Carbofrac® unit installed at the biogas plant. During sampling, the process was operated at 165°C with a retention time of 10 minutes. The biogas potential tests were carried out by Aalborg University Copenhagen.

Sample location	TS (w%)	VS (w%)	Biogas potential (mL-CH_4/g-VS)
Feed to WEx unit (digestate)	6.7	4.8	84.7
Reject Water from feed	4.3	2.8	87.4
Solids from feed	22.1	17.0	102.2
Pretreated solids	11.4	8.7	221.9
Pretreated solids + reject water	5.3	3.8	143.7

Conclusion

There have been many operational challenges for the implementation of the Carbofrac® unit to treat the digested fiber fraction of manure due to the composition of the feedstock and the , digested manure fibers, especially due to the high content of silica. However, the modified treatment system with a screw press prior to the internal dewatering unit of the Carbofrac® unit can be applied in an industrial setting and automated, if the right precautions are implemented (e.g. ceramic liner in the piping). The treatment has a positive impact on the biogas yield and the increase in biogas yield, which was shown in lab-scale tests, has been confirmed in the large-scale tests, both on biogas production data at the biogas plant and with biogas potential tests of the in- and output of the Carbofrac® unit.

The large-scale testing revealed that the technical implementation of the Carbofrac® on the digestate may be more difficult than on the influent biomass to the biogas plant. From the experiences of the large-scale tests it is recommended to withdraw the digestate for the treatment from the middle and not from the of the biogas reactor. Furthermore, for the implementation of the Carbofrac® unit at different biogas plants the following advantages and disadvantages of the treatment of the digested fibers versus the upfront treatment should be taken into consideration:

Advantages of the treatment of digested fibers

- Easily digestible organic matter has been converted prior to the treatment
- More specific treatment of the recalcitrant fiber fraction left after the biogas process
- No loss of volatile components, which may be the case when treating the influent to the biogas plant

Advantages of the treatment of "fresh" fibers

- Treatment could (possibly) be connected to a separate receiving tank for treating feedstock with high fiber content (manure, separated manure fibers, corn stover etc.).
- No recirculation necessary, therefore no effect on retention time in the reactors.
- Combination of pretreatment and removal of sand and other unwanted material may be possible.
- Upfront treatment is easier to heat integrate.
- Easier dewatering of the fresh feedstock (manure for example); parts of the feedstock to the biogas facility may arrive already dewatered.
- Potentially lower treatment capacity required due to treatment of selected feedstocks and not a random treatment of all remaining solids.

Overall, it might be concluded that the treatment of the digested fiber fraction is preferable if the feedstock of the biogas plant consists mainly of manure and manure fibers while the treatment specifically on fresh manure fibers may be of advantage if the biogas plant receives larger fractions of industrial organic waste. To determine the best option in each case, the effect of the Carbofrac® treatment on the biogas yield of the separated "fresh" fibers and on the separated digested fibers should be analysed in detail.

Economical evaluation – benefit for the biogas plant in relation to the costs for the pretreatment (WP 5)

WP 5.1 *Collecting of operational data for the existing biogas plant*

The existing biogas plant of Biokraft A/S on Bornholm, Denmark is designed to treat different kinds of feedstock such as manure from cows, pigs, biowaste from fish industries, abattoirs and organic biodegradable material from other industries.

The plant consists of the following main units (Figure 17):

- Receiving tanks for the feedstock to be treated (101, 102, 103 in Figure 17).
- Hygienisation, mixing, heating units and feeding pumps.
- Anaerobic reactors, 3 units of 3,050 m^3 each (121, 122, 123 in Figure 17).
- Biogas conversion with cleaning system, a gas storage tank (167 in Figure 17) and 2 electricity generators of 2 MW each
- District heating system for utilization of the surplus heat generation from the electricity generators.
- Tanks for the digested biomass effluent from the reactors.

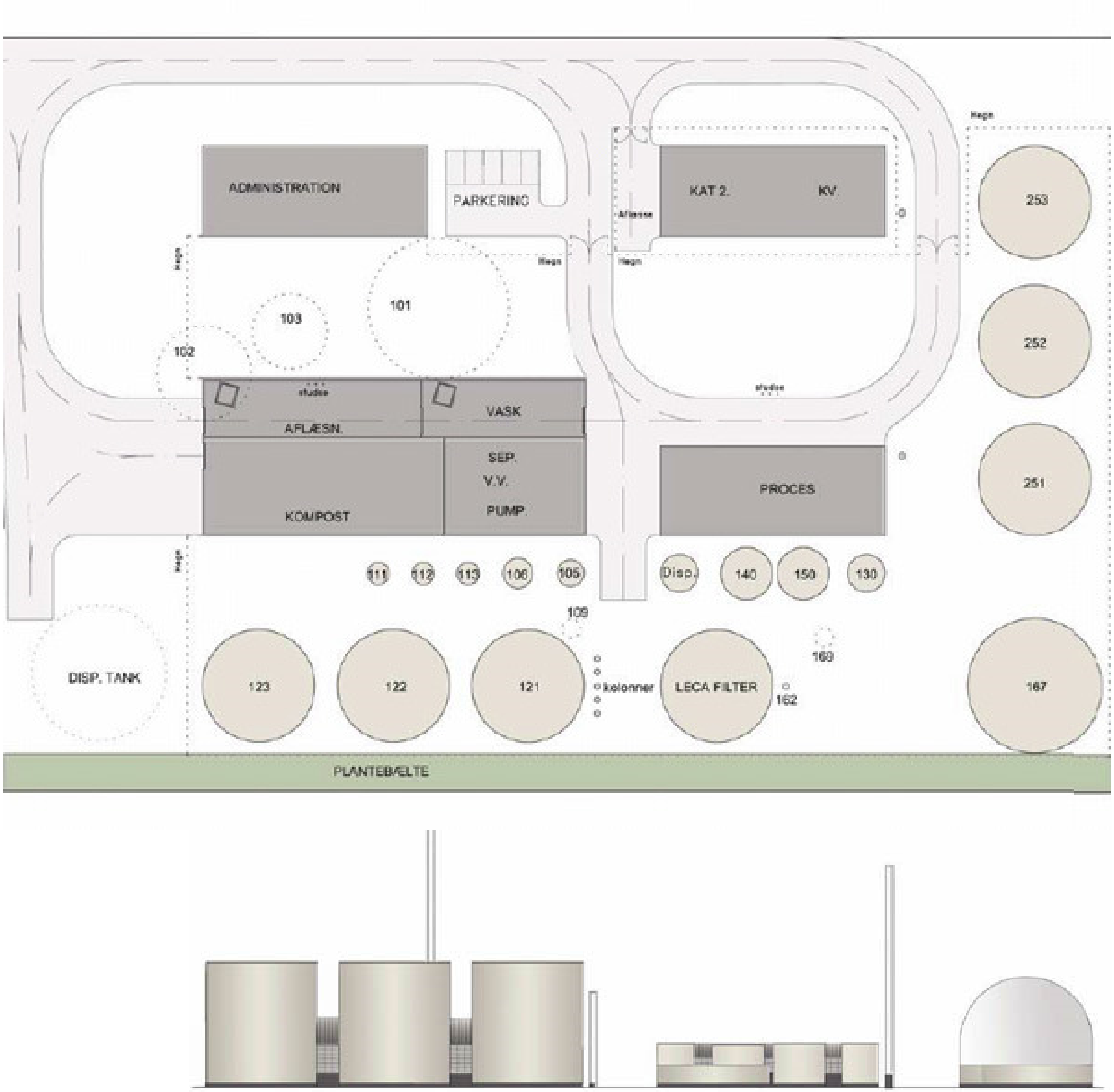


Figure 17. Biokraft biogas plant layout (top) – with side view from East (below)

Input and output data collected from the biogas plant over the previous three years (table 4 and 5) gave solid knowledge of the performance of the plant. In 2011, the district heating system was set in operation and was fully implemented in the beginning of 2012. Consequently, it is relevant for this project to analyze the performance of the plant from 2012 to 2013.

Table 4. Input data and calculated yields for Biokraft's biogas plant 2010-2013

	Input				Calculated							
Period	Manure	Dewatered manure	Organic waste	Total	Seperated manure	Organic waste	Total DM		Total COD		Ratio COD/DM	HRT
	tons	*tons*	*tons*	*tons*	*%*	*%*	*tons*	*%*	*tons*	*%*		*days*
01-03-09 - 28-02-10	4,221	705	590	5,516	12.8%	10.7%	643	11.7%	814	14.8%	1.265	50.5
Jan 2010	5,355	679	705	6,739	10.1%	10.5%	754	11.2%	956	14.2%	1.268	42.1
Feb	4,048	333	862	5,243	6.4%	16.4%	565	10.8%	729	13.9%	1.292	48.9
Marts	7,361	752	698	8,811	8.5%	7.9%	953	10.8%	1,203	13.7%	1.263	32.2
April	5,626	437	366	6,429	6.8%	5.7%	670	10.4%	843	13.1%	1.259	42.7
Maj	4,465	827	401	5,693	14.5%	7.0%	673	11.8%	843	14.8%	1.253	49.8
June	6,418	613	522	7,553	8.1%	6.9%	808	10.7%	1,019	13.5%	1.261	36.3
July	5,954	591	484	7,029	8.4%	6.9%	755	10.7%	952	13.5%	1.260	40.4
Aug	7,164	599	265	8,028	7.5%	3.3%	838	10.4%	1,048	13.1%	1.251	35.3
Sep	7,502	537	585	8,624	6.2%	6.8%	894	10.4%	1,129	13.1%	1.263	31.8
Oct	6,510	644	795	7,949	8.1%	10.0%	860	10.8%	1,092	13.7%	1.270	35.7
Nov	6,479	833	1,229	8,541	9.8%	14.4%	964	11.3%	1,233	14.4%	1.280	32.1
Dec	2,944	709	1,085	4,738	15.0%	22.9%	594	12.5%	768	16.2%	1.294	59.9
Total input 2010	69,826	7,554	7,997	85,377	8.8%	9.4%	9,326	10.9%	11,817	13.8%	1.267	40.1
Jan 2011	5,693	799	1,173	7,665	10.4%	15.3%	877	11.4%	1,123	14.7%	1.281	37.0
Feb	5,673	481	1,197	7,351	6.5%	16.3%	794	10.8%	1,025	13.9%	1.291	34.9
Marts	5,925	785	1,299	8,009	9.8%	16.2%	910	11.4%	1,169	14.6%	1.285	35.4
April	4,707	904	916	6,527	13.9%	14.0%	782	12.0%	996	15.3%	1.273	42.1
Maj	5,766	954	1,056	7,776	12.3%	13.6%	909	11.7%	1,158	14.9%	1.274	36.5
June	5,231	649	1,133	7,013	9.3%	16.2%	790	11.3%	1,016	14.5%	1.286	39.1
July	5,536	588	1,043	7,167	8.2%	14.6%	790	11.0%	1,013	14.1%	1.283	39.6
Aug	6,165	466	1,102	7,733	6.0%	14.3%	822	10.6%	1,057	13.7%	1.286	36.7
Sep	5,295	355	998	6,648	5.3%	15.0%	700	10.5%	903	13.6%	1.290	41.3
Oct	4,804	464	553	5,821	8.0%	9.5%	627	10.8%	796	13.7%	1.269	48.7
Nov	6,509	687	1,222	8,418	8.2%	14.5%	927	11.0%	1,189	14.1%	1.283	32.6
Dec	6,033	667	1,076	7,776	8.6%	13.8%	860	11.1%	1,101	14.2%	1.280	35.3
Total input 2011	67,337	7,799	12,768	87,904	8.9%	14.5%	9,787	11.1%	12,545	14.3%	1.282	39.4
Jan 2012	5,969	650	942	7,561	8.6%	12.5%	832	11.0%	1,062	14.0%	1.276	36.3
Feb	5,754	475	1,005	7,234	6.6%	13.9%	774	10.7%	994	13.7%	1.284	37.9
Marts	5,679	622	1,030	7,331	8.5%	14.0%	810	11.0%	1,038	14.2%	1.281	37.4
April	5,246	860	849	6,955	12.4%	12.2%	810	11.7%	1,029	14.8%	1.270	39.5
Maj	5,808	587	1,053	7,448	7.9%	14.1%	815	10.9%	1,045	14.0%	1.282	36.9
June	5,614	708	926	7,248	9.8%	12.8%	813	11.2%	1,037	14.3%	1.275	37.9
July	5,761	609	1,022	7,392	8.2%	13.8%	813	11.0%	1,041	14.1%	1.281	37.1
Aug	5,826	580	1,131	7,537	7.7%	15.0%	825	10.9%	1,060	14.1%	1.285	36.4
Sep	5,802	603	855	7,260	8.3%	11.8%	793	10.9%	1,011	13.9%	1.275	37.8
Okt	7,220	669	446	8,335	8.0%	5.4%	885	10.6%	1,112	13.3%	1.256	32.9
Nov	7,156	607	806	8,569	7.1%	9.4%	910	10.6%	1,155	13.5%	1.270	32.0
Dec	7,702	567	644	8,913	6.4%	7.2%	927	10.4%	1,172	13.2%	1.264	30.8
Total input 2012	73,537	7,537	10,709	91,783	8.2%	11.7%	10,008	10.9%	12,758	13.9%	1.275	37.1
Jan 2013	7,803	1,048	862	9,713	10.8%	8.9%	1,092	11.2%	1,379	14.2%	1.263	28.3
Feb	7,972	774	765	9,511	8.1%	8.0%	1,022	10.7%	1,292	13.6%	1.264	28.9
Marts	9,124	622	859	10,605	5.9%	8.1%	1,098	10.4%	1,392	13.1%	1.268	25.9
April	8,561	582	995	10,138	5.7%	9.8%	1,054	10.4%	1,342	13.2%	1.273	27.1
Maj	8,529	791	878	10,198	7.8%	8.6%	1,091	10.7%	1,382	13.6%	1.267	26.9
June	7,381	508	882	8,771	5.8%	10.1%	914	10.4%	1,164	13.3%	1.274	32.3
July	9,159	580	1,230	10,969	5.3%	11.2%	1,138	10.4%	1,455	13.3%	1.278	25.9
August	8,847	491	1,190	10,528	4.7%	11.3%	1,081	10.3%	1,383	13.1%	1.280	26.9
September	8,198	470	1,010	9,678	4.9%	10.4%	994	10.3%	1,269	13.1%	1.277	29.3
Oktober	8,778	617	830	10,225	6.0%	8.1%	1,061	10.4%	1,346	13.2%	1.268	27.7
November	8,414	568	773	9,755	5.8%	7.9%	1,008	10.3%	1,278	13.1%	1.267	29.1
December	9,651	702	714	11,067	6.3%	6.5%	1,147	10.4%	1,448	13.1%	1.262	25.6
Total input 2013	102,417	7,753	10,988	121,158	6.4%	9.1%	12,701	10.5%	16,130	13.3%	1.270	27.9
Avg 2010-2013	10,271	1,050	1,450	12,770	8.2%	11.3%	1,391	10.9%	1,643	14.1%	1.274	35.9
Avg 2012-2013	9,980	913	1,296	12,189	7.4%	10.5%	1,309	10.7%	1,666	13.6%	1.27	32.2

Table 5. Output data and calculated yields for Biokraft's biogas plant 2010-2013

	Output	Calculated			Output		Calculated						
Period	Degassed manure	Total DM	Total COD	Utilised COD	El prod	Heat prod	CH4 prod.	CH4 yield			of CH4 pot	El-prod	Heat-prod.
								m3-CH4	m3-CH4	m3-CH4		kWh	kWh
	tons	tons	tons	tons	MWh	MWh	m3-CH4	/ton	/kg DM	/kg COD	%	/kg-DM	/ton-DM
01-03-09 - 28-02-10	5,212	370	327	487	719	0	170,442	30.9	0.265	0.209	60%	1.117	0.000
Jan 2010	6,854	487	430	526	1,090	0	183,981	27.3	0.244	0.192	55%	1.45	0.00
Feb	4,945	351	310	419	482	0	146,662	28.0	0.260	0.201	57%	0.85	0.00
Marts	8,845	628	555	648	652	0	226,876	25.7	0.238	0.189	54%	0.68	0.00
April	7,828	556	491	352	626	0	123,192	19.2	0.184	0.146	42%	0.93	0.00
Maj	7,417	527	466	378	631	0	132,297	23.2	0.197	0.157	45%	0.94	0.00
June	7,794	553	489	530	835	0	185,348	24.5	0.229	0.182	52%	1.03	0.00
July	7,467	530	469	484	741	121	169,230	24.1	0.224	0.178	51%	0.98	0.16
Aug	8,960	636	562	486	564	240	170,001	21.2	0.203	0.162	46%	0.67	0.29
Sep	8,427	598	529	600	596	456	209,962	24.3	0.235	0.186	53%	0.67	0.51
Oct	8,471	601	532	561	802	855	196,192	24.7	0.228	0.180	51%	0.93	0.99
Nov	9,032	641	567	667	869	640	233,295	27.3	0.242	0.189	54%	0.90	0.66
Dec	4,161	295	261	507	723	713	177,488	37.5	0.299	0.231	66%	1.22	1.20
Total output 2010	90,199	6,404	5,661	6,156	8,610	3,025	2,154,524	25.2	0.231	0.182	52%	0.92	0.32
Jan 2011	9,271	658	582	541	723	683	189,490	24.7	0.216	0.169	48%	0.82	0.78
Feb	8,801	625	552	472	754	583	165,261	22.5	0.208	0.161	46%	0.95	0.73
Marts	8,534	606	536	634	811	689	221,863	27.7	0.244	0.190	54%	0.89	0.76
April	7,679	545	482	514	806	719	179,783	27.5	0.230	0.181	52%	1.03	0.92
Maj	8,879	630	557	601	742	655	210,240	27.0	0.231	0.182	52%	0.82	0.72
June	7,659	544	481	535	832	515	187,283	26.7	0.237	0.184	53%	1.05	0.65
July	7,243	514	455	559	753	525	195,499	27.3	0.248	0.193	55%	0.95	0.66
Aug	8,561	608	537	519	856	566	181,761	23.5	0.221	0.172	49%	1.04	0.69
Sep	8,988	638	564	339	506	526	118,673	17.9	0.169	0.131	38%	0.72	0.75
Oct	5,826	414	366	430	450	241	150,561	25.9	0.240	0.189	54%	0.72	0.38
Nov	6,195	440	389	800	828	707	280,068	33.3	0.302	0.236	67%	0.89	0.76
Dec	8,644	614	543	558	837	673	195,337	25.1	0.227	0.177	51%	0.97	0.78
Total output 2011	96,280	6,836	6,043	6,502	8,898	7,082	2,275,820	25.9	0.233	0.181	52%	0.91	0.72
Jan 2012	7,801	554	490	572	823	688	200,298	26.5	0.241	0.189	54%	0.99	0.83
Feb	7,366	523	462	532	739	573	186,211	25.7	0.240	0.187	54%	0.95	0.74
Marts	8,561	608	537	500	783	796	175,074	23.9	0.216	0.169	48%	0.97	0.98
April	7,855	558	493	536	718	474	187,670	27.0	0.232	0.182	52%	0.89	0.58
Maj	8,560	608	537	508	731	635	177,849	23.9	0.218	0.170	49%	0.90	0.78
June	262	19	16	1,021	758	607	357,296	49.3	0.439	0.344	98%	0.93	0.75
July	8,268	587	519	522	817	684	182,746	24.7	0.225	0.176	50%	1.01	0.84
Aug	8,181	581	513	547	832	701	191,428	25.4	0.232	0.181	52%	1.01	0.85
Sep	6,911	491	434	577	667	640	202,105	27.8	0.255	0.200	57%	0.84	0.81
Okt	5,355	380	336	776	513	437	271,551	32.6	0.307	0.244	70%	0.58	0.49
Nov	8,905	632	559	596	462	370	208,716	24.4	0.229	0.181	52%	0.51	0.41
Dec	8,862	629	556	616	788	622	215,651	24.2	0.233	0.184	53%	0.85	0.67
Total output 2012	86,887	6,169	5,453	7,305	8,631	7,227	2,556,595	27.9	0.255	0.200	57%	0.86	0.72
Jan 2013	10,287	730	646	734	808	643	256,738	26.4	0.235	0.186	53%	0.74	0.59
Feb	9,477	673	595	697	735	615	244,070	25.7	0.239	0.189	54%	0.72	0.60
Marts	10,411	739	653	738	824	695	258,410	24.4	0.235	0.186	53%	0.75	0.63
April	9,984	709	627	716	792	661	250,452	24.7	0.238	0.187	53%	0.75	0.63
Maj	10,197	724	640	742	741	685	259,795	25.5	0.238	0.188	54%	0.68	0.63
June	8,371	594	525	638	801	812	223,475	25.5	0.245	0.192	55%	0.88	0.89
July	10,621	754	667	788	806	0	275,823	25.1	0.242	0.190	54%	0.71	0.00
August	9,786	695	614	769	791	228	269,247	25.6	0.249	0.195	56%	0.73	0.21
September	10,085	716	633	636	812	674	222,505	23.0	0.224	0.175	50%	0.82	0.68
Oktober	9,724	690	610	735	713	524	257,348	25.2	0.242	0.191	55%	0.67	0.49
November	9,435	670	592	686	712	492	240,009	24.6	0.238	0.188	54%	0.71	0.49
December	11,822	839	742	706	790	538	247,167	22.3	0.215	0.171	49%	0.69	0.47
Total output 2013	120,199	8,534	7,544	8,586	9,325	6,567	3,005,040	24.8	0.237	0.186	53%	0.73	0.52
Avg for 3 years	13077	928	821	951	1,208	809	332,920	26.0	0.239	0.188	54%	0.86	0.57
Avg for 2 years	11,759	835	738	928	1,063	841	324,729	26.4	0.247	0.194	55%	0.80	0.63

For the full evaluation of the effect of the integration of the WEx treatment to the biogas plant It was the intention that the WEx-unit should have been in operation for more than 2 months, according to 2 times the retention time of the bioreactors. However, due to the technical problems as described in WP 3 the demo-scale Carbofrac® unit has only been in operation in connection with the biogas plant for about 200 hours. The detailed calculations of the energy yield from the in- and output of the plant (table 4 and 5) were based on a mass- and energy balance and were meant as a tool for the evaluation of the impact of the WEx operation in connection to the biogas plant. The direct evaluation on the influence on the biogas production of the whole biogas plant was, however, not possible due to the short test period.

The main results of the analysis, with relevance to the WEx test, are as follows:

From 2012 to 2013, there has been an increasing load of 20% on the plant, mainly due to a still greater amount of unseparated manure and other organics, while the amount of separated manure is nearly constant. However, the increased amount means, an increased production of biogas, even though the retention time in the reactors decreased from 37 to 28 days due to the increased load. Accordingly, the specific CH_4 production decreased from 28 to 25 m^3/t-TS, which indicated that the capacity of the plant was reached.

The load and production data for 2013 were as follows:

Feedstock load

• Manure	102,417 ton/year
• Separated manure (solid fraction)	7,753 ton/year
• Other organics	10,988 ton/year
• Total	121,158 ton/year

Production

• Digestate	120,302 ton/year
• El-production	9,325 MWh/year
• Heat-production	6,567 MWh/year

The basic economy of the biogas plant was as follows:

Economy 2013					DKK/y
Electricity-production	9,325	MWh/year	1,150	DKK/MWh	10,723,750
Heat-prod	6,567	MWh/year	130	DKK/MWh	853,710
Degassed biomass	120,302	ton/year	5	DKK/ton	601,510
Total					12,178,970

WP 5.2 *Investment and operational* cost of the Carbofrac® treatment *unit*

With reference to information from BioGasol, the investment costs (capital expenditure, CAPEX) for a Carbofrac® unit at a biogas plant depends on the capacity and specific conditions for the implementation, and whether it is a supplement to an existing plant or it is a unit included in the design of a project. Consequently, it is not possible to give an exact price, as in the case with single components like e.g. pumps.

The implementation costs for a WEx-unit to Biokraft, as a turnkey project, is conservatively estimated to be in the range of 6 to 8 million DKK, for an industrially mature unit capable of up to 1 ton/hr. This also depends on local conditions e.g. cost of labor, manufacturing etc. The nominal capacity will be determined by the biogas plant capacity and how much feedstock that can be readily utilized. Another factor which determines the size of the pretreatment unit is if the process concept is to treat the fiber fraction before the reactors or after (FiberMaxBiogas). In the first case a unit capable of approx. 1 ton dry matter (TS) per hour is required and in the latter a unit rated for approx. 500 kg-TS/h. would be appropriate. Due to the added complexity of the pretreatment of fibers after the reactor, the CAPEX will be approximately in the same range for both process concepts. The unit cost would decrease, depending on production volume, product maturity and narrowing of the process window (process conditions), why the estimate is conservative.

The operational costs (OPEX) consist of the following, based on information from BioGasol (WP3):

- Electrical power, estimated to 43 kW in 8,000 h per year or 323 MWh per year
- Manpower, estimate to 340 h per year or 102,000 DKK/year (300 DKK/h)
- Maintenance incl. labor and wear parts, estimated to 402,000 DKK/year
- Others, unspecified, estimated to 50,000 DKK/year

WP 5.3 *Collecting data for the pretreatment of digested fibers in the WEx unit*

The digestate is taken out from the biogas reactors at a flow rate corresponding to the effluent flow rate.

The digestate is fed to the WEx reactor where it is dewatered; the liquid fraction (reject water) is fed to a mixing tank, where the liquid is mixed with the solid effluent from the WEx-process.

The solid fraction is fed to the Micro reactor where the material is shredded and subjected to high pressure and temperature (preferably 180°C).

The high temperature and pressure are achieved and sustained by direct injection of high-pressure steam. The heated material is retained at high temperature in the retention module for a predetermined time (preferably 10 minutes).

The holding time in the retention module is determined by the speed of the screw, which transports the material through the retention module. The material is flashed out into the mixing tank where it is mixed with the liquid fraction from the dewatering step. The flash out system works by alternatingly opening and closing two valves with a small buffer vessel between the valves.

The pretreated slurry (a mixture of the pretreated solid and reject water) is fed back to the biogas reactors via a heat exchanger. The heat exchanger is heat-integrated with the plant, for example the feed to the biogas reactor or the water to the steam unit can be heated by the pretreated slurry.

Based on information from WP 3, it can be calculated that the methane yield increases by 22%, which means an additional profit from electricity and heat production as follows:

• Electrical power production	2.356 million DKK/year
• Heat-production	0.188 million DKK/year
• Total	2.544 million DKK/year

The costs of operation are as follows:

• Electrical power	370,875 DKK/year
• Manpower	102,000 DKK/year
• Maintenance	410,000 DKK/year
• Others	50,000 DKK/year
• Total	932,875 DKK/year

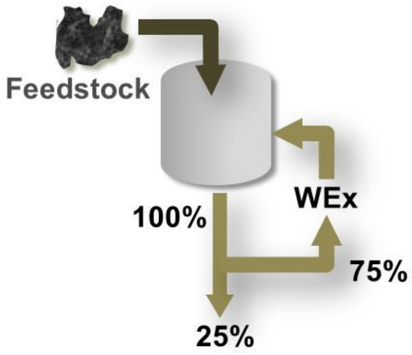
The calculated net profit can thereby be estimated to approximately 1.6 million DKK/year.

WP 5.4 *Calculation of the benefit of the WEx-unit for different conditions*

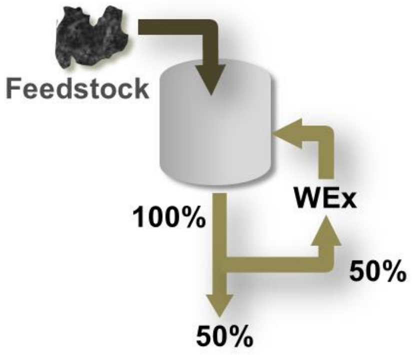
The typical financing model for this type of plant will be depreciation over 10 years, it means that it allows an investment of 16 million DKK with an interest rate of 0% p.a. and with an interest rate of 2% p.a. it means an investment of 13 million DKK.

However, in order to analyze the potential of the implementation of the WEx process, three different concepts will be evaluated.

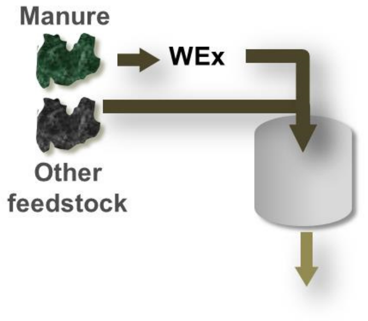
Concept 1 (Basic concept as tested in the FiberMaxBiogas project):
Implementation of a WEx-unit treating all effluent from the three reactors, with a flow of 75% of the reactor effluent.



Concept 2:
As concept 1, but with 50% flow of the reactor effluent.



Concept 3: Implementation of the WEx-unit upfront of the biogas reactors and only treating manure, which has to be stored separately and therefore may cause an investment in separate storage tanks.



Concept 3 with the WEx-unit upfront may offer several technical advantages, amongst the following:

- A simpler process system with less components and ancillary systems
- A more homogeneous fiber fraction, which can give a better and stable treatment in the WEx-unit
- The spent steam can directly be used for heating of the influent feedstock to the biogas plant
- Sand, gravel and other impurities from the AD reactor can be reduced before the treatment, which also reduces equipment cost (design complexity and construction material cost)

The investments and profits for the three concepts based on the production data of Biokraft's biogas plant from 2013 are:

Concept	Flow m^3/h	Investment DKK	Increase MWh	Electricity MWh/year	Heat MWh/year	Net profit DKK/year	Pay Back Years
1	11	8,000,000	22.0%	2,049	1,443	1,611,108	5.0
2	8	7,000,000	14.6%	1,366	962	763,114	9.2
3a	13	7,000,000	17.0%	1,585	1,116	1,035,293	6.8
3b	13	7,000,000	13.0%	1,212	854	572,195	12.2

For concept 3 two cases are calculated with an increase in energy production by 17% (**3a**) and by 13% (**3b**). The calculations show that the profitability of concept 3 depends on this specific increase when treating the input fibers. If in concept 3 the increase is lower than 17% it is obvious that only concept 1 is of relevance.

The key factors for the economy are the sales price of electricity and the electricity production, while the profit from the sales of digestate and heat only contribute with less than 10%.

If the electricity sales price would be lowered by 10% from 1.15 DKK/kWh to 1.035 DKK/kWh, the payback time increases with 0.9 years in concept 1, with 2.4 years in concept 2, with 1.4 years in concept 3a, and with 3.9 years in concept 3b.

Consequently, it is very important to keep the focus on how to achieve a higher electricity production and in the case of Biokraft the increase in electricity production must be more than 15%.

WP 5.5 *Environmental Impact*

The digestate is used as a fertilizer, which means that the fiber materials can cause a methane production on the field. By implementation of the WEx-unit, a significantly higher amount of the fiber fraction will be converted to methane inside the biogas plant, which will be further converted to CO_2 in the subsequent energy conversion process (combustion).

Therefore, the reduction in greenhouse gas emissions through implementation of the WEx unit will be two-fold by:

1. Substitution of a higher amount of fossil energy resources through a higher methane production from manure
2. Lower methane emissions from the field through lower output of organic matter in the effluent from the biogas plant.

For the overall evaluation of the environmental impact of the new concept for a higher conversion of the manure fiber fraction it has to be taken into account that all potential leakages of methane into the atmosphere have to be avoided during production, storage, supply and combustion of the methane from the biogas since methane has a greenhouse gas potential which is more than 20 times higher than of CO_2.

Overall conclusion

Based on data of the economy of the biogas plant, on prospected CAPEX and OPEX of the WEx equipment and on an increase of the biogas yield as determined in lab-scale and large-scale, the implementation of the WEx treatment for increasing the biogas yield of manure fibers could significantly improve the biogas plant’s economy.

As the large-scale test has shown that the treatment of the digested fiber fraction in the new treatment concept may be more technically challenging, the economy of the treatment for both digested and non-digested fibers was evaluated. While CAPEX of the equipment for the treatment of the digested fiber fraction may be a bit higher than for the treatment of the non-digested fibers, the OPEX may be higher for the treatment of the non-digested fiber fraction since the load would be higher (13 m^3/h compared to 11 m^3/h). Since the WEx treatment for both concepts would only be on the separated solid fraction, the volumetric input flow to the WEx treatment would be quite similar. The difference in final benefit for the 2 concepts would, therefore, mainly depend on if the increase in biogas yield by the treatment would be different for the 2 concepts. An increase as measured in the samples before and after the WEx treatment of the digested fibers would be equivalent to increasing the overall methane yield from 25 m^3 to 30 m^3 per ton of feedstock delivered to the biogas plant. For production data of 2013, this would be equivalent to an additional electricity production of 2,049 MWh. A similar enhancement of the energy production would be achieved for an increase of the methane yield of the non-digested fibers by 22%.

The pay-back time for the investment would be about 5 years for the concept tested in the FiberMaxBiogas project, treating the digestate from the biogas reactors. For the up-front concept (3), where the whole feed is processed, a pay-back time of 7 years is estimated. However, slight changes in the economic prerequisites e.g. electrical power price, can change the figures, why some sensitivity and feasibility determination should dealt with for each specific biogas plant. Also, process improvements, which are obtained over a longer operational period, and additional energy optimization will also contribute positively to the economy, why the results obtained within this project are deemed relatively conservative. Furthermore, applying the technology on larger biogas plants will also improve the pay-pack time due to economy-of-scale. The economical evaluation shows that the implementation of the WEx treatment, either before or after the biogas reactor, is attractive.

The large-scale test showed that the Carbofrac® unit could be used for the different treatment concepts. The final decision on which implementation concept would gain the highest benefit for a given biogas plant depends on the amount and composition of the fiber fraction, the content of other impurities (sand etc.) in the input, and the increase of the biogas yield of the undigested fibers by the treatment.

Dissemination of project results

- ✓ Biswas, R., Uellendahl, H., and Ahring, B.K. (2010). **Increasing the biogas yield of manure by wet explosion of the digested fiber fraction.** Proceedings 12th World Congress on Anaerobic Digestion, 31 October – 4 November 2010, Guadalajara, Mexico (Oral presentation).
- ✓ Biswas, R., Uellendahl, H., and Ahring, B.K. (2011). **Improving biogas yields using an innovative pretreatment concept for conversion of the fiber fraction of manure.** Proceedings International IWA-Symposium on Anaerobic Digestion of Solid Waste and Energy Crops, 28 August – 1 September 2011, Vienna, Austria (Oral presentation).
- ✓ Biswas, R., Ahring, B.K., and Uellendahl, H., 2012. **FiberMaxBiogas – a new concept for improving the economy of manure based biogas plants.** Nordic Biogas Conference, Copenhagen, (Poster presentation).
- ✓ Biswas, R., Ahring, B.K., Uellendahl, H. (2012). **Improving biogas yields using an innovative concept for conversion of the fiber fraction of manure.** Water Science & Technology, 66 (8), 1751–1758.
- ✓ Skøtt, T. (2012). **Højere biogasudbytte ved vådeksplosion af gyllefibre.** Forskning i Bioenergi 40, 31.
- ✓ Uellendahl, H. (2013). **Towards economically feasible biogas production from manure and other waste biomass.** International Anaerobic Digestion Symposium "BiogasWorld", Berlín, 23-25 April, (Oral presentation).
- ✓ Molinuevo-Salces, B., Larsen, S. U., Biswas, R., Ahring, B. K. and Uellendahl, H. (2013). **Key factors for achieving profitable biogas production from agricultural waste and sustainable biomass.** 13th World Congress on Anaerobic Digestion in Santiago de Compostela, Spain, June. (Oral presentation).
- ✓ Uellendahl, H. Ljunggren, M., Skovgaard-Petersen, Ruiz, B., and Kragelund-Rickers, C. (2014). **A new concept for biogas plants to make biogas production based on manure and straw economically feasible.** Nordic Biogas Conference, Reykjavik, Iceland, Aug 2014, (Submitted for oral presentation).

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