Report

Selective hydrolysis of wastewater sludge

Part 3, June 2015

Efficiency of selective hydrolysis
on anaerobic mineralisation of WWTP sludge,
Esbjerg West waste water treatment plant, Denmark

PSO-F&U project no. 2014-1-12272

Project by: SEGES
CVR. no.: 32 34 69 87

Report by:
Niels Østergaard, SEGES
Flemming Andersen, DIN forsyning, Esbjerg

0 Summary

0.1 Summary in English

This project ”Selective hydrolysis of wastewater sludge” is supported by EnergiNet.DK under the PSO-F&U projects having project number 2014-1-12272.

The project constitutes the phase 3, process verification of a full scale hydrolysis to treat sludge at waste water treatment plant to enhance the production of biogas based power and heat production besides reduce the costs for final disposal of the sludge.

The project is completed for EnergiNet.DK by company SEGES in corporation with the Esbjerg West wastewater treatment plant.

The hydrolysis plant was established at the wastewater treatment plant Esbjerg West and completely incorporated in the technical and the control system during project phase 2. Thus the plant works as a natural part of the whole plant.

The Esbjerg West plant is a traditional build plant based on the activated sludge concept besides traditional digester technology. The plant treats combined household and industrial wastewater with a considerable amount of the wastewater received from the industries.

The hydrolysis system is based on the fact, that an anaerobic digestion before a hydrolysis treatment enhances the hydrolysis efficiency, as the production of volatile organic components, which might inhibit the hydrolysis efficiency, are not produced to the same extent as may be the case for a hydrolysis made on un-digested material.

The results of operating the plant show as follows:

- Hydrolysis efficiency on primary sludge about 10 % on VS basis
- Hydrolysis efficiency on biological excess sludge about 40 % on VS basis.

The de-water ability of the digested sludge seems independent of the hydrolysis. Still the daily operation characteristics indicate that the sludge has changed structure towards a more fibres and hair-containing sludge mass.

Thus the balances may be changed as follows at the plant as is:

- Sludge dry matter reduction about 150 tons of TS per year or 725 tons of dewatered sludge
- Enhancement of biogas production 140.000 m^3 per year
- Nitrogen N production about 12 tons per year

The energy balances are found to be influenced as follows:

- Power demand for nitrification is enhanced with about 55 MWh per year
- Diesel oil demand for transportation is reduced with about 15 MWh per year
- Power production from enhanced biogas is 470 MWh per year
- Heat production from enhanced biogas is 550 MWh per year.

The establishing of extensive heat exchange has markedly reduced the heat demand to maintain the digester temperature; still, at high sludge solids concentrations, the pressure drop over the cold side

of the sludge stream to the first step digesters may be inappropriately high why during some periods the first heat exchanger is bypassed. Besides any addition of biological excess sludge bypass the heat exchanger system. It is experienced, that the polymer content of the concentrated biological excess sludge makes it near to impossible to pass through the heat exchangers.

The hydrolysis processing also sanitises the sludge. If the energy consumption from a standard sanitising plant is included in the calculations to value this secondary benefit, the energy balances becomes even more advantageous.

Based on the experience cost-benefit analyses show, that:

- Establishing costs for a technical plant may be about 4.5 mil. DKK ex. VAT
- Simple pay-back time under described conditions in the order of 8 years

As far as there should be a wish for or a demand to sanitise the sludge before administration in agriculture, the marginal simple pay-back time will be about 1 year.

It should be mentioned that the turnover of sludge at the plant is unforeseen high. Thus the efficiency of the hydrolysis system differs from the project part 2, where lower and more common standard turnover as well as higher hydrolysis efficiency was found. The actual data showed a substantially higher income level.

The calculations are based on treating the whole amount of biological excess sludge in the hydrolysis plant. Actually, only during short periods of the project it has been possible to add the whole amount of biological excess sludge to the digesters. This is based on the fact, that the de-watering system for biological excess sludge includes a local control relating to important variables.

Based on the obtained results the utility company continue operating the hydrolysis plant at Esbjerg Renseanlæg Vest waste water treatment plant. The utility company recommends the technology.

SEGES thanks goes to the DIN-forsyning utility company, the Esbjerg West wastewater treatment plant, others project parties and sub-suppliers for a fruitful corporation during this final phase 3 of the project.

0.2 Summary in Danish

Dette projekt ”Selective hydrolysis of wastewater sludge” er støttet af EnergiNet.DK under PSO-F&U projekterne med projektnummer 2014-1-12272.

Dette projekt udgør projektfase 3, proces fastlæggelse af fuldskala Selektiv Hydrolyse anlæg til behandling af slam på renseanlæg, herunder til at forøge omsætningen af slam i rådnetanke under produktion af forøgede mængder biogasbaseret kraft og varme. Her ud over en reduktion af mængderne af afvandet, udrådnet slam med den forøgede biogasproduktion.

Projektet er fuldført for EnergiNet.DK af SEGES i samarbejde med Esbjerg Renseanlæg Vest.

Selektiv Hydrolyse anlægget er etableret på rensningsanlægget og fuldtud indpasset i det tekniske og styringsmæssige system. Således er anlægget i drift som en naturlig del af det samlede renseanlæg.

Esbjerg Renseanlæg Vest er et traditionelt aktiv slam anlæg med rådnetanke. Anlægget behandler spildevand fra husholdninger og industri således, at en betydelig mængde stof til anlægget stadig er af industriel oprindelse.

Filosofien bag Selektiv Hydrolyse er, at en anaerob udrådning før en hydrolysebehandling bibringer en lavere produktion af flygtige organiske syrer under hydrolyse-behandlingen. Høje koncentrationer af flygtige organiske syrer vil typisk produktinhibere.

Resultaterne er som følger:

- hydrolyse effekt på primær slam omkring 10 % på VS basis
- hydrolyse effekt på biologisk overskudsslam omkring 40 % på VS basis.

Der er ingen klar ændring af afvanding af udrådnet slam. Imidlertid indikerer de daglige driftsresultater, at det udrådnede slam har ændret karakter hen mod et mere fiber- og hår-holdigt slam.

Resultaterne medvirker til følgende ændringer af driftsresultaterne på renseanlægget:

- Reduktion af slamtørstof på 150 tons TS per år eller 725 tons afvandet slam
- forøget biogas produktion 140.000 m^3 per år
- nitrogen N produktion 12 tons per år.

Energibalancerne på anlægget påvirkes som følger:

- kraftbehovet til nitrifikation forøges med 55 MWh per år
- dieselolie behovet til transport reduceres med 15 MWh per år
- kraft produktionen fra forøget biogasmængde er 470 MWh per år
- varmeproduktionen fra forøget biogasmængde er 550 MWh per år.

Varmebehovet til opvarmning af slam er reduceret væsentligt ved etablering af ekstensiv varmegenvinding ved varmeveksling. Imidlertid er det fundet, at ved høje koncentrationer af tørstof i det producerede slam er trykfaldet over varmevekslernes kolde side uhensigtsmæssigt højt. Derfor er dette vekslertrin i perioder omgået. Desuden er det erfaret, at det reelt ikke er muligt at pumpe forafvandet biologisk overskudsslam igennem varmeveksleren i blanding med primærslam. Derfor er tilført biologisk overskudsslam igennem hele perioden pumpet direkte til rådnetankene.

Hydrolyse processen hygiejniserer slammet. Dersom energibehovet til drift af et hygiejniseringsanlæg inkluderes i balancerne som en sekundær fordel, vil balancerne være betydeligt påvirket i positive retning.

Cost-benefit analysen på datagrundlaget viser, at:

- etablerings omkostninger for et fuldskala teknisk anlæg vil være I størrelsesordenen 4,5 mil. DKK ex. moms
- den simple tilbagebetalingstid vil være i størrelsesordenen 8 år.

Dersom der måtte være et ønske om eller et krav til hygiejnisering af slammet før udbringning på agerjord, vil den marginale tilbagebetalingstid for anlægget være 1 år.

Alle beregninger er baseret på, at hele den mængde biologisk overskudsslam, der producers på renseanlægget, tilføres anlæggets rådnetanke. I praksis har dette kun været muligt i korte perioder af forsøgsperioden. Baggrunden herfor er, at der ikke fuldt ud er automatisk styring og regulering af anlægget til forafvanding af biologisk overskudsslam, hvorfor anlægget kun er i drift i forbindelse med fuld bemanding på anlægget.

Baseret på de opnåede resultater fortsætter driften af Selektiv Hydrolyse anlægget på Esbjerg Renseanlæg Vest. Forsyningsselskabet anbefaler teknologien.

SEGES takker DIN-forsyning, Esbjerg renseanlæg Vest, projektdeltagerne og underleverandørerne for et frugtbart samarbejde under denne afsluttende projektfase 3.

The relative small hydrolysis tanks in the middle. Digesters at left. Photo Niels Oestergaard

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1 Introduction

This report constitutes the report of the project:

"Selective hydrolysis of sludge, part 3"

PSO-F&U project no. 2014-1-12272

supported by EnergiNet.DK and with company SEGES as project holder.

The project participants are:

- SEGES: Project holder, project management, laboratory scale experiments etc.
- Municipality of Esbjerg, DIN forsyning, Esbjerg Renseanlæg Vest: Host of the hydrolysis plant.

The responsibility for the total project, discrete elements are as follows:

- SEGES, Niels Østergaard: plant design including dimensioning, control system design, auxiliary equipment, establishment, equipment documentation, support during operation, lab analyses and report
- DIN forsyning, Flemming Andersen: P&I diagram, digester plant operation characteristics, lab analyses, data accumulation.

The part 3 project includes:

- On-going control of the plant performance including laboratory analyses and experiments to control performance
- Re-calculating the cost benefit analysis
- Technical scale simplified plant model calculations including cost benefit analysis
- On-going information about the technology progress

and this report describes the results of the project.

Our kind acknowledgement goes to EnergiNet.DK for subsidising the project besides the employees at DIN Forsyning including the wastewater treatment plant for invaluable help during the verification of the plant processing and performance.

2 Description of the hydrolysis system

The hydrolysis system is a further development of existing systems especially designed to enhance the destabilisation of cellulosic components and to enhance selective fermentation of the carbohydrate products. The development is based on many years of experience with anaerobic systems, especially with the digestion of animal manure and straw.

The system is designed to avoid product inhibition of the biological hydrolysis process. As such, initial lab tests have showed, that the hydrolysis should be optimal by using a first digestion of easily digestible constituents, which otherwise would make up an inhibition potential to the hydrolysis. Thus the hydrolysis system is based on the following fundamental downstream treatment:

- A preliminary or step 1. digestion of the biomass, preferably using digestion in the mesophilic temperature interval
- A hydrolysis process at a super-thermophilic temperature level
- A final or step 2. digestion which may find place within a temperature range of 35 to 55°C.

As such the hydrolysis system demands a 2 step digestion.

The temperatures in the different digester steps are controlled by external heating units connected to the digesters as well as by using heat recovery in a specially designed sludge to sludge counter-current heat exchanger. The main purpose of the heat exchanger is to cool the mass from the hydrolysis tanks to the temperature in the step 2. digester.

The flow control design of the system is preferably a sequencing batch system.

3 Esbjerg West wastewater treatment plant

3.1 Overall description of the wastewater treatment plant

The Esbjerg Vest wastewater treatment plant is owned and operated by the DIN Forsyning.

The plant is designed for the following load:

- Organic load: 290.000 PU
- Nitrogen load: 192.000 PU
- Phosphor load: 168.000 PU.

The plant design is based on the activated sludge process including nutrients removal using recycling principles for de-nitrification besides precipitation for phosphor removal.

Sludge from the plant is digested in 2 separate digester lines, each including 2 digesters in series, and the produced biogas is used for heat and power production.

The wastewater treatment plant receives wastewater from industrial sites and private households.

The incoming wastewater shows good settling characteristics; however, the overflow from pre-settling still includes organic matter sufficient for complete de-nitrification.

3.2 Wastewater treatment processes

Wastewater entering the plant undergoes the following processing:

- Pumping station to lift up the wastewater
- Screen station
- Flow metering station
- Combined aerated sand and fat trap
- Primary settling – if the concentration of P is high, iron salts are added for P precipitation
- Activated sludge de-nitrification
- Activated sludge nitrification with simultaneous P precipitation
- Secondary settling of biological sludge, non-bacterial SS and precipitated P
- Outlet metering and sampling station.

The demands to the outlet are as follows:

- SS $\leq$ 30 mg/l
- BOD-5 $\leq$ 15 mg/l
- Total-N $\leq$ 8 mg/l
- Total-P $\leq$ 1,5 mg/l

The outlet demands are met without problems.

3.3 Sludge processing

Sludge is produced as follows:

- Primary sludge is produced during the primary settling or primary precipitation process
- Biological excess sludge is produced during the activated sludge and simultaneous P precipitation process.

The produced sludge undergoes the following treatment:

- Settling and / or precipitation of primary sludge
- Concentration of primary sludge in concentration tanks
- Intermediate storage tank for concentrated primary sludge
- Settling by precipitation of biological excess sludge
- Polymer addition to biological excess sludge
- Belt dewatering by gravitation for biological excess sludge
- Pumping stations to separately pump primary sludge respectively biological excess sludge to the digesters
- 2 step mesophilic digestion in 2 parallel lines, line 1 having 2 digesters á net 2.200 m^3, line 2 having 1 digester á net 2.200 m^3 and 1 á net 2.000 m^3
- Digested sludge intermediate storage tank
- Digested sludge dewatering by belt press.

All the produced primary sludge and most of the biological excess sludge is digested in the anaerobic digesters.

Sludge from external sources are added the main incoming wastewater stream. Fat from the fat trap is pumped to the step 1 digesters.

The sludge is dewatered to a TS concentration of about 18 to 22 % TS; as a mean about 20 % TS. It has not been possible to clarify the reason for the large variation.

The produced and dewatered sludge is used for agricultural purposes as fertiliser apart from a certain amount of biological excess sludge, which is passed to a sludge mineralisation plant.

The part of the sludge, which passes through the hydrolysis plant is sanitised.

3.4 Sludge amounts and de-nitrification

All during the period the de-nitrification has worked without problems. During the project period the activated sludge plant has included a limited oxidation and de-nitrification volume. Relative to the total volume only about 40 % has been in use. This implies that the biological excess sludge age is kept low and the SS content rather high, why the sludge may become less mineralised than during the former project part 2.

3.5 System design using heat exchangers

The heat exchanger system includes as follows:

- Heat exchanger 1: cools digester step 2 outlet counter current to digester step 1 inlet
- Heat exchanger 2: cools hydrolysed outlet counter current to digester step 1 inlet after heat exchanger 1
- Heat exchanger 3: cools hydrolysed outlet before heat exchanger 2 counter current to digested sludge from digester step 1 going to the hydrolysis system
- Heat exchanger 4: heats up sludge from digester step 1 after heat exchanger 3 to hydrolysis temperature counter current to hot water.

The total temperature span is at least 60°C as the untreated sludge temperature typically is below 15°C and the hydrolysis temperature is a bit above 75°C.

It is experienced that mixing primary sludge and biological excess sludge in the pre storage tank for primary sludge, makes it near to impossible to pump the mixture through the heat exchanger 1 and 2, cold sides. Thus biological excess sludge is pumped directly to the step 1 digesters. Besides, during periods with high total solids content in the primary sludge, it has been necessary to bypass the heat exchangers, thus in both cases reducing the heat recovery.

It is expected that polymer addition for de-watering of biological excess sludge is the main reason behind the pressure loss for the mixed sludge.

3.6 Implementation of the hydrolysis plant

During project phase 2 the hydrolysis plant and all auxiliary functions was completely integrated in the existing digester system.

This implies that:

- The hydrolysis plant is designed and dimensioned to treat the whole sludge amounts produced at the plant according to the phase 1 sludge balance data
- Control of the hydrolysis plant is fully integrated in the main control system

Thus the control system at any time show variable operation conditions and parameters and it is possible to change set-point values from the main control system.

The control of the hydrolysis plant makes it possible under full automation to operate the digester system as follows:

- Form 1: None of the 2 digester lines are operated with hydrolysis
- Form 2: Digester line 1 use hydrolysis while digester line 2 does not
- Form 3: Digester line 2 use hydrolysis while digester line 1 does not
- Form 4: Both digester lines use hydrolysis

During the experimental period 1 and 2 includes Form 2 and experimental period 3 includes Form 4.

Hydrolysis plant including engineering building. Photo Niels Oestergaard

4 Materials and methods

4.1 Sludge analyses and lab digestion tests

4.1.1 Analyses performed by Esbjerg Forsyning A/S

The lab of Esbjerg Forsyning A/S has analysed sludge according to the following methods:

- Total solids (TS) drying for 24 h at 105°C, DS
- Volatile solids (VS) ignition for 2 h at 550°C, DS
- COD, Dr. Lange
- Volatile acids, Dr. Lange
- Alkalinity and bicarbonate alkalinity, Dr. Lange
- Tot-N, DS
- Ammonium / ammonia N (Amm-N), DS
- Total phosphor (Tot-P), Merck
- Ortho-phospate (Ortho-P), Merck.

During the intensive analyses and test periods the abovementioned analyses describes the variation through the digester system

4.1.2 Analyses performed by SEGES

Sludge is received from the Esbjerg Renseanlæg Vest wastewater treatment plant for analyses and digestion test experiments.

Sludge is analysed for total solids and volatile solids as follows:

- Total solids (TS) drying for 24 h at 105°C, DS
- Volatile solids (VS) ignition for 2 h at 550°C, DS

Mass is measured using electronic weight, precision ± 10 mg.

Sludge settling experiments are performed using 1.000 ml Imhoff cones.

Samples for TS and VS analyses are taken at levels:

- Top: 950 ml
- Middle: 500 ml
- Bottom: mixed mass below 500 ml.

Digestion tests are performed in glass bottles under the following conditions:

- Sludge digestion 38 – 41°C, temperature controlled water bath.

Produced biogas is collected and metered using lab gas domes in water bath, 15 ± 2°C.

4.2 Full scale digestion and hydrolysis tests

The digester system consists of 2 nearly identical digester lines each constituting 2 digesters in series. The hydrolysis system is dimensioned and designed to service both digester lines.

The experimental period includes the following setup:

- Period 1: Starting the line 1 with hydrolysis
- Period 2: Results of stable operation of digester line 1 with hydrolysis and digester line 2 without hydrolysis
- Period 3: Results of operation both digester lines with hydrolysis.

Full scale tests are operated over 3 periods:

- Period 1: November - December 2014
- Period 2: March - April 2015
- Period 3: May - June 2015.

The main purposes of the 3 periods have been:

- To measure the influence from the relative amount of biological excess sludge on the hydrolysis efficiency
- To measure the hydrolysis efficiency operating both lines with hydrolysis.

As the digester system has to process varying amounts of biological excess sludge over the week, the operating conditions varies substantially. During weekends and holidays only primary sludge is added. During working days most of the biological excess sludge is added directly to the digester step 1, both lines.

Still, during the total experimental period, the digestion results of all digesters have been convincing.

The addition of high amounts of biological excess sludge during working days implies that the biogas production during periods has exceeded the maximum measuring range of the gas meters. Besides, during periods the gas production from step 2 digesters added hydrolysed sludge has been so low, that the gas metering is inaccurate. Thus the efficiency of the system mainly is based on TS and VS turnover, which actually is a quite conservative basis.

Mounting of the J. H. Stål impellers. Photo Niels Oestergaard

5 Results

5.1 General conditions

5.1.1 Control of the digester system

In general the control of the digester system has worked without problems. Only two variables have influenced operating of the hydrolysis plant:

- Problems with siloxane in the produced biogas
- Lag time for establishment of a carbon filter to adsorb siloxane from the biogas.

During the late winter primo 2015 the siloxane filter is mounted and the gas engine is overhauled to ensure safe operation during the experimental period 2 and 3.

Apart from these deviations, which are outside the influence of the control system the implemented system design has worked perfectly.

5.1.2 Temperature of digester tanks

Referring to chapter 3, the digester system includes 4 digester tanks. 2 of those digesters are from the original plant, 2 others are established later. The 2 old ones are scarce insulated, leading to substantial heat loss during winter conditions.

The 2 new digesters constitute digester step 1 and the 2 old digesters digester step 2.

Without using hydrolysis, sludge from digester step 2 is recirculated to step 1 through a heat exchanger. The sludge amounts recirculated amounts about 2,000 m^3 / day, why the digesters more or less constitute common volume.

During operating with hydrolysis there is no recirculation from digester step 2 to digester step 1. Thus digester step 2 temperatures depend on the temperature of the cooled hydrolysed sludge from the hydrolysis plant.

The measured heat loss complies an on-going cooling of the added hydrolysed sludge reaching until 8°C. To maintain the digester temperature of step 2 digesters during winter, it has been necessary to by-pass the primary side of heat exchanger 2.

Thus it has been possible to maintain a digester temperature in all digester tanks of about 40°C with very slow and low variations.

5.1.3 Sand

Below the data on total and volatile solids indicate a loss of ash during the digestion. The sand trap at the main wastewater inlet works with limited efficiency, why sand is carried on to the primary settling, the concentration tanks and accumulates as bottom sludge in the digesters.

To hinder uncontrolled accumulation of sand in the digesters, sand may become evacuated using vacuum pumps. According to analysis this settling and evacuation of sand complies a TS and ash reduction of about 2 kg / ton sludge.

In general sand is not found in biological excess sludge.

5.1.4 Gas metering

The gas metering has suffered from limitations.

The following limitations are found:
- During the working days addition of biological excess sludge, the biogas production from step 1 digesters exceeds the maximum gas meter capacity
- During weekends the gas metering of gas from digester step 2, especially from digester line 1, step 2 may be below the lower measuring range of the gas meter

Calculating the gas production relative to conversion of organic matter gives unreliable variations the different digesters in between.

Thus in general it has not been possible to make a biogas balance on the system to compare with the organic matter balance. In practice the gas balance is neglected and the efficiency of the hydrolysis system is based on total solids and organic solids balances.

5.1.5 Fat trap fat handling

The digester system has to handle fat from the fat trap at the main wastewater inlet. This fat may be added each of the digesters.

The data are as follows:
- Concentrated fat amounts about 7 m^3 / week
- TS / VS content of fat 30 / 29 %
- Total fat TS amount per day about 300 kg
- Gas production from fat about 0.073 m^3 / kg TS and 0.074 m^3 / kg VS
- Total gas production from 1 batch of fat about 7 m^3 / day.

The total amount of TS added to each line is about 5,000 kg TS per day. Thus, the amount of fat solids as well as the biogas potentials from the solids may be within the variation of the solids addition.

During the project periods the fat trap fat is added the step 1 digesters. It has not been possible to observe an influence from the addition on the TS or VS balances or on the gas production. Thus the influence from addition of the fat is negligible.

5.1.6 Biological excess sludge handling

The excess sludge treatment includes, as mentioned in chapter 3.3 a sludge mineralisation plant, why only a part of the biological excess sludge is added the digesters. Still as much biological excess sludge as possible is added the digesters during the test periods 2 and 3.

Unfortunately the total amount of biological excess sludge is not known, as metering has suffered from inaccuracy. Metering the amounts added the pre-dewatering equipment seems quite reliable, why the TS and VS amounts added the digesters seems accurate.

5.1.7 **Conclusion on general conditions**

Even if the utility during the project parts 2 and 3 has invested in as well maintenance as rebuilding of the plant, the plant may suffer from parts showing limited reliability. It should be noticed, that this not uncommon as far as referring to the digester system. This actually is in contrast to the conditions at the activated sludge part of plants, as the treatment demands on water have needed ongoing adaption and investments.

Even if this is the case, indeed very good results of the efficiency of the hydrolysis system are obtained. Lab digestion experiments support the full scale results, showing a reliable, efficient system.

5.2 Sludge composition

5.2.1 **General concerns**

During the project part 1 and 2 it was concluded that the hydrolysis effect on biological excess sludge is substantially higher than on primary sludge. The efficiency may be as follows:

- Primary sludge, part 1 / 2: + 5 to 10 / 10 % turnover
- Biological excess sludge, part 1 / 2: + 40 / > 50 % biogas production

as recognised levels. During one test period the efficiency on biological excess sludge reached more than 60 % higher biogas production.

Thus the content of primary sludge to biological excess sludge has special interest, and it has been a special purpose of this project phase 3 to stabilise the relative amount of biological excess sludge during the experimental period 2 and 3.

5.2.2 **Experimental results**

The table below shows the relative amounts of primary sludge and biological excess sludge during the experimental periods. As mentioned above some of the biological excess sludge is added a sludge mineralisation plant, which should be kept at least partly loaded during the experimental period.

Sludge composition	% primary sludge	% biological excess sludge	Total daily amounts M^3 / 24 h
Period 1	80	20	157
Period 2	76	24	180
Period 3	59	41	207

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

It is common that the sludge amounts vary with the season and with weather conditions. Especially precipitation may enhance the amounts of primary sludge, as high water amounts more or less wash the sewer system.

However the load conditions vary quite much, which may influence the hydrolysis efficiency.

5.3 Heat balances

The heating system includes the following heat exchangers:

- Heat exchanger 1: cools digester step 2 outlet counter current to digester step 1 inlet
- Heat exchanger 2: cools hydrolysis outlet counter current to digester step 1 inlet after heat exchanger 1
- Heat exchanger 3: cools hydrolysis outlet before heat exchanger 2 counter current to hydrolysis inlet from digester step 1
- Heat exchanger 4: heats up sludge from digester step 1 after heat exchanger 3 to hydrolysis temperature counter current to hot water.

It is concluded that the heat exchangers keeps the dimensioning figures which implies the following heat recovery efficiency:

- Heat exchanger 1: Primary side 41°C, secondary side 12°C, 45 % heat recovery (sludge / sludge)
- Heat exchanger 2: Primary side 52°C, secondary side 29°C, 50 % heat recovery (sludge / sludge)
- Heat exchanger 3: Primary side 75°C, secondary side 40°C, 70 % heat recovery (sludge / sludge)
- Heat exchanger 4: Primary side 92°C, secondary side 65°C, 50 % heat recovery (water / sludge)

The temperature in the hydrolysis tanks is controlled at temperatures between 70 and 82°C; during the experimental period between 74 and 77°C. Looking at the above temperature data this comply a heat recovery rate better than 70% heat recovery. It should be kept in mind, that heat exchanger 1 and 2 secondary side is reduced relatively to the primary side as the biological excess sludge is passed directly to the digesters.

As mentioned above there have been problems with pumping the cold, untreated sludge trough the heat exchanger 1 and 2, secondary sides. Thus actually during periods the heat recovery has been reduced relatively to the information in chapter 4.1.2. It has been necessary to maintain the temperature in digester step 2 if using hydrolysis, as the heat loss here is high during winter time. The observed heat recovery rate is about 40 to 45%.

5.4 Total and organic solids balances

5.4.1 **General concerns**

Total and organic solids are the easiest variables to analyse and easy to compare with gas production. The variables are used as a general turnover parameter in the literature and thus the easiest figure to use comparing different digester systems.

The method has its limitations at high concentrations of VFA, where the evaporation temperatures of the light VFA's are at the same level as water, thus underestimating the amount of organic matter. The data below, filtered COD besides VFA, chapters 4.4.2.2 and 4.5.2 shows this not to become a problem in this case.

5.4.2 **Experimental results**

The table below shows the concentrations of TS and VS downstream the plant during the experimental periods.

TS / VS	Inlet	Inlet	Line 1,	Line 1,	Line 2,	Line 2,

% matter	Line 1	Line 2	step 1	step 2	step 1	step 2
Period 1	4.09 / 3.26	4.07 / 3.27	2.03 / 1.29	1.81 / 1.05	1.95 / 1.21	1.83 / 1.17
Period 2	4.13 / 3.33	4.02 / 3.23	1.91 / 1.24	1.48 / 0.90	1.67 / 1.03	1.68 / 1.04
Period 3	4.47 / 3.30	4.52 / 3.31	2.02 / 1.27	1.59 / 0.90	1.86 / 1.10	1.64 / 0.95

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

The data show as follows:

- The TS and VS content reflects the rise in the content of biological excess sludge given in chapter 5.2.2 showing a TS rise for period 3 with high biological excess sludge addition and near to unchanged VS concentration
- The stabilisation period 1, line 1 operating hydrolysis show lower outlet concentrations from line 1, step 2 after hydrolysis and digestion than line 2
- During test period 2, line 1 operating hydrolysis show even lower outlet concentrations from step 2 than during the stabilisation period
- During test period 3, both lines operating hydrolysis, line 2 step 1 shows lower outlet concentrations than line 1 step 1; still outlet from line 2, step 2 shows higher concentrations than found from line 1, step 2 outlet.

Thus the hydrolysis process stabilises fast and brings a higher turnover of TS and VS than obtained during common operation.

The figures show as follows:

- The inlet VS concentration varies only to a limited extent. The value is about 3.30 % VS
- Without hydrolysis the VS out of step 2 is about 1.11 % VS, complying a VS turnover of 66 %
- With hydrolysis the VS out of step 1, the digestion step upstream the hydrolysis is about 1.26 % VS, complying a VS turnover of 62 %
- With hydrolysis the VS out of step 2 is about 0.90 % VS, complying a VS turnover through the hydrolysis line of about 73 %.
- It is expected that the line 2, step 2 is not completely adapted during phase 3.

This implies a total VS conversion of about 2.2 %-points VS without hydrolysis. With hydrolysis the VS conversion is 2.4 %-points. Thus the VS based hydrolysis efficiency is about 9 %.

In any case the turnover as well without hydrolysis as with hydrolysis is unexpectedly high. A VS turnover level of 50 % is, according to our experience a general figure for well-functioning sludge digesters added primary and biological excess sludge. To compare the VS conversion in line 1, step 1 is 62 %.

5.5 Biogas production

5.5.1 **General concerns**

The biogas production is proportional to conversion of organic matter. It may become measured as TS or VS. Most often the gas production is given relative to added amounts of wet substance, TS and / or VS.

Obtained results may theoretically be controlled according to general stoichiometric composition of the organic matter constituting the sludge.

5.5.2 Experimental results

The table below shows the gas production results of the 2 lines relative to added mass during the experimental periods.

M^3 biogas each line	M^3 / m^3 wet sludge		M^3 / kg TS added		M^3 / kg VS added	
	Line 1	Line 2	Line 1	Line 2	Line 1	Line 2
Period 1	33	39	0.813	0.961	0.996	1.200
Period 2	35	36	0.888	0.893	1.092	1.060
Period 3	42	50	0.966	1.162	1.256	1.461

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

First it should be mentioned that the stoichiometric conversion of sludge organic matter may be in the order of 0.9 m^3 biogas / kg VS. As this complies a total conversion of organic matter to biogas, it is impossible to reach. The above data for m^3 biogas / kg VS added surpass the stoichiometric values, why the gas metering and / or metering of variable relating to sludge amounts and gas production may suffer from inaccuracy.

The new gas engine is mounted with a gas meter including a methane analyser which meters the gas consumption. The gas meter shows a gas consumption corresponding to about 70 % of the sum of gas from the individual gas meters at the digesters. Thus we face the individual gas meters to be too inaccurate for a balance calculation.

Whatever, the table below shows the biogas production relative to converted TS and VS.

M^3 biogas each line	M^3 / kg TS converted		M^3 / kg VS converted	
	Line 1	Line 2	Line 1	Line 2
Period 1	1.462	1.744	1.454	1.873
Period 2	1.415	1.542	1.509	1.533
Period 3	1.530	1.873	1.724	2.023

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

Again the data shows influence from inaccurate gas metering, as the VS specific gas production cannot exceed the stoichiometric value at about 0.9.

Thus it may be concluded, that at the high gas production rates, which are found for the digester step 1 and for the low gas production rates from step 2 of hydrolysis lines, the gas metering exceeds the measuring range. Still, the conversion rates of organic matter given in chapter 5.4.2, shows a higher VS conversion of lines operated with hydrolysis. As the organic matter turnover is proportional to the biogas production, the biogas metering is insufficient.

5.5.3 Biogas composition

During the 2 last periods of experiments it has been possible to control the methane content of the biogas added the gas engine.

During the whole period the concentration of hydrogen sulphide is negligible, still the concentration of methane has varied as follows, as the methane metering is mounted before period 2:

- Period 2: 60 – 63 % methane
- Period 3: 63 – 65 % methane.

This shows that, even if the VS turnover is higher using hydrolysis, the conversion of organic matter results in a general rise of the methane content of the produced biogas.

It should be mentioned, that gas resisting from the hydrolysis process is cleaned in a gas scrubber and passed to the surroundings. Thus a given gas production from the hydrolysis process tanks is not included in the total gas production. It is not possible to meter the gas production from the hydrolysis tanks. The gas from the hydrolysis tanks is expected to include almost only carbon dioxide produced during hydrolysis of mainly bacterial cell wall constituents and complex carbohydrates.

5.6 COD balances

5.6.1 **Total COD**

5.6.1.1 General concerns

The total COD gives a figure for the digestible part of the organic solids. Just to mention, stoichiometry calculations on organic matter brings a general value of about 1.6 kg COD / kg organic matter as far as the matter include mostly carbohydrates and proteins besides smaller amounts of fat.

To complete the information VFA oxidation using COD analyse is limited. Normally about 60 % efficiency should be expected.

Finally 1 kg of COD is equivalent to 0.35 m^3 methane at STP or, at 62 % CH_4 about 0.56 m^3 biogas.

5.6.1.2 Experimental results

The table below shows the concentrations of COD downstream the plant during the experimental periods.

COD kg per m^3	Added Sludge	Line 1, step 1	Hydrolysis	Line 1, step 2	Line 2, Step 1	Line 2, step 2
Period 1	51	23	23	19	22	21
Period 2	48	19	20	15	17	18
Period 3	49	24	19	16	-	17

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

The table data shows as follows:

- The concentration of COD in added sludge is in the order of 50 kg COD / m^3 sludge
- Without hydrolysis the COD out of step 1 respectively 2 is at the same level, namely 17 – 22 kg COD / m^3 sludge
- With hydrolysis the concentration in step 1 amounts 19 – 24 kg COD / m^3 sludge
- With hydrolysis the concentration is step 2 amounts 15 – 17 kg COD / m^3 sludge

The data show a COD turnover of about 60 % without hydrolysis and about 68 % with hydrolysis. This comply a hydrolysis efficiency of 13 % on COD.

Whatever it is difficult to measure the COD of particle and SS containing masses as undigested sludge. This is the case for primary sludge as well as biological excess sludge.

Referring to chapter 5.4.2 concerning VS conversion, COD and VS conversion show similar levels. The ratios COD / VS are found to 1.7 for added sludge and about 1.8 for outlet from both digester lines. This is within the accuracy that may be expected.

5.6.2 **Filtered COD**

5.6.2.1 General concerns

The filtered COD gives a figure for fine SS and dissolved organic matter. Fine SS and dissolved organic matter normally is easily digestible. Just to mention the VFA's show a general value of 1,1 to 1,5 kg COD / kg organic matter with increasing concentrations of VFA.

5.6.2.2 Experimental results

The table below shows the concentrations of filtered COD downstream the plant during the experimental periods. As the filtered COD show left over concentrations of easily digestible organic matter, the data are only of interest to what concerns outlet concentrations.

COD_f kg / m^3	Hydrolysis	Line 1, step 2	Line 2, step 2
Period 1	-	-	-
Period 2	4.6	1.0	0.8
Period 3	4.5	1.4	1.1

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

In general the values for the hydrolysis plant are higher than for the step 2 digesters. Note especially that:

- Without hydrolysis the COD_f value is lower than for values for line 1, operating with hydrolysis
- After starting hydrolysis on line 2 during period 3, the COD_f value is within the span of results for line 1 operating with hydrolysis.

Relative to the calculated digestion efficiency on VS and COD, a higher turnover of organic matter, as by using hydrolysis may introduce higher concentration of fine SS in the digested sludge.

5.7 VFA balances

5.7.1 **General concerns**

Volatile Fatty Acids normally are characterised as fatty acids having 1 to 5 C-atoms. The most common metabolic product of the carbon cycle is acetic acid, C_2H_5OH having a value of 1,07 kg COD / kg acetic acid.

Volatile fatty acids are easily digestible and the concentration shows the efficiency of the digestion. As such a low concentration is equal to a high mineralisation level of the sludge. On the other hand, the fatty acids having uneven number of C-atoms and not the less branched fatty acids may be slowly digested. Especially propionic acid $C_3H_6O_2$ is inhibiting to the process. Some of the methane forming bacteria cannot distinguish between acetic and propionic acid and undergo irreversible enzyme blockage reacting with propionic acid.

5.7.2 Experimental results

The table below shows the VFA concentrations downstream the plant during the experimental periods.

VFA kg / m^3	Line 1, step 1	Line 1, step 2	Line 2, step 1	Line 2, step 2
Period 1	0.4	0.4	0.3	0.3
Period 2	0.4	0.3	0.3	0.3

Period 1 and 2: hydrolysis on line 1.

In any case the data show a very stable digestion in all digester steps and quite uniform data whatever operating with hydrolysis or without hydrolysis. Whatever, the concentrations are low and show an indeed very well-functioning digester system.

Referring to the above chapter 5.4.2 regarding VS turnover, the low VFA-values verifies a very efficient digester system even without using hydrolysis.

5.8 Alkalinity and bicarbonate alkalinity

5.8.1 General concerns

The alkalinity shows the concentration of basic components. During anaerobic digestion the most important ones are ammonia and bicarbonate. Besides ortho-P may play a role.

5.8.2 Experimental results

The table below shows the alkalinity and bicarbonate alkalinity downstream the plant during the experimental periods.

Alk / BiC alk kg / m^3	Line 1, step 1	Line 1, step 2	Line 2, step 1	Line 2, step 2
Period 1	2.9 / 2.6	4.0 / 3.7	3.7 / 3.5	3.1 / 2.9
Period 2	3.9 / 3.6	5.3 / 5.1	4.2 / 4.0	4.2 / 4.0

Period 1 and 2: hydrolysis on line 1.

By far, line 1 step 2 shows the highest total alkalinity and bicarbonate alkalinity. In any case the bicarbonate alkalinity level includes 80 to 95 % of the total alkalinity. It is expected that the elevated bicarbonate alkalinity of line 1, step 2 digester represents a reaction with ammonium producing a higher concentration of ammonium bicarbonate. This is the general picture and complies a higher pH value, as seen from the below chapter 5.9.

5.9 pH

5.9.1 General concerns

For short the pH shows the balance between acid and basic components in the mixture. Relating to anaerobic conditions the level is normally within a range of 7.5 to 8.2. A relatively high pH indicates a well-functioning digester.

The most important components influencing the pH are the VFA's, ammonia and bicarbonate. Under normal conditions the concentration of bicarbonate is sufficient to balance the pH whatever concentrations of VFA's.

5.9.2 Experimental results

The table below shows the pH values measured downstream the plant during the experimental periods.

pH	Line 1, step 1	Line 1, step 2	Line 2, step 1	Line 2, step 2
Period 1	7.5	7.9	7.6	7.7
Period 2	7.5	7.9	7.6	7.6

Period 1 and 2: hydrolysis on line 1.

The data are few; still it seems obvious that line 1 step 2 shows higher pH than the others. Referring to the below chapter 4.8 this may coincide with possible higher concentration of ammonium bicarbonate according to the alkalinity and bicarbonate alkalinity results.

5.10 Nitrogen balances

5.10.1 Total nitrogen

5.10.1.1 General concerns

During the digestion of sludge, total nitrogen should not change to any extent unless the sludge mass includes substantial concentrations of nitrate and / or nitrite.

5.10.1.2 Experimental results

The table below shows the concentrations of Tot-N downstream the plant during the experimental periods.

Tot-N g / m^3	KC-2	Bio-sludge line 1 / 2	Line 1, step 1	Hydrolysis	Line 1, step 2	Line 2, step 2
Period 2	1,100	4,200 / 4,700	1,700	1,800	1,700	1,600
Period 3	1,400	3,200 / 4,000	1,900	1,600	1,900	1,800

Period 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

The concentrations of total N show stable levels during the system. There is no noticeable difference in the data for the different downstream operations, just a tendency for period 3 to show a higher concentration than for period 2. This may be a result of concentration differences of de-watered biological excess sludge including a possible deviation of the concentration the 2 lines in between.

5.10.2 Ammonia nitrogen

5.10.2.1 General concerns

During anaerobic digestion ammonia is produced from components, mainly proteins containing organic nitrogen. Thus, everything else equal a high ammonia concentration relative to Tot-N shows a high mineralisation level of the sludge.

5.10.2.2 Experimental results

The table below shows the concentrations of ammonia-N downstream the plant during the experimental periods.

Amm-N g/m^3	KC-2	Bio-sludge line 1 / 2	Line 1, step 1	Hydrolysis	Line 1, step 2	Line 2, step 2
Period 2	200	700 / 800	1,000	1,400	1,300	1,000
Period 3	400	200 / 200	1,100	1,300	1,400	1,200

Period 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

The concentration of ammonia-N shows enhancement of the concentration in line 1 relative to line 2. This indicates for short as follows:

- Digestion of nitrogen containing components is higher using hydrolysis than using common digester technology
- By far the highest de-ammonification finds place during the anaerobic digestion in general and the hydrolysis adds about 20 % ammonia hereto, accounting for about 200 g ammonia-N / m^3 sludge.

During period 3, where line 2 also use hydrolysis, the ammonia concentration is enhanced from the lower level comparable with line 1, step 1 to a level near line 1 step 2 concentration.

5.11 Phosphor balances

5.11.1 **Total phosphor**

5.11.1.1 General concerns

In wastewater treatment phosphor is bound as well as a constituent in bacterial mass in the biological sludge as to added metals to precipitate excess phosphorous.

Under conditions, where the levels of VFA increase, precipitated phosphor may dissolve. Too, as biological excess sludge is digested, organic bound phosphor may become dissolved. As such the content of dissolved phosphor may increase during digestion and leave dissolved phosphor.

5.11.1.2 Experimental results

The table below shows the concentrations of Tot-P downstream the plant during the experimental periods.

Tot-P g/m^3	KC-2	Bio-sludge line 1 / 2	Line 1, step 1	Hydrolysis	Line 1, step 2	Line 2, step 2
Period 2	260	660 / 650	580	660	660	560
Period 3	330	1,100 / 1,100	600	580	610	540

Period 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

The concentration of total P indicates a rather stable addition of biological excess sludge to the digester system. Besides line 2 show a lower level of Tot-P, which might indicate a lower amount of biological excess sludge than added to line 1.

5.11.2 **Dissolved phosphor**

5.11.2.1 General concerns

As mentioned above dissolved phosphor may form during digestion of sludge. An efficient digestion may elevate the pH value of the digested sludge, and under such conditions the reaction of phosphor with metals may increase. Thus an efficient digestion and mineralisation of sludge may not markedly influence the content of dissolved phosphor.

5.11.2.2 Experimental results

The table below shows the concentrations of Ortho-P downstream the plant during the experimental periods.

Ortho-P g/m^3	KC-2	Bio-sludge line 1 / 2	Line 1, step 1	Hydrolysis	Line 1, step 2	Line 2, step 2
Period 2	53	6 / 6	55	58	57	44
Period 3	58	1 / 2	44	49	60	50

Period 2: hydrolysis on line 1. Period 3: hydrolysis on both lines.

The concentration of Ortho-P indicates a limited enhancement resisting from the hydrolysis process. The enhancement is low and might level until about 10 g Ortho-P / m^3 digested sludge. This enhancement may be uncertain as the total variation the figures in between is high. Thus it might be concluded, that a very low production of Ortho-P could occur.

5.12 Post digestion experiments

5.12.1 **General concerns**

Post digestion experiments are made to show the digestibility of left-over organic matter in the digested sludge. Anything else equal the content of digestible matter should be lower in hydrolysed, digested sludge than in the not hydrolysed sludge as far as the hydrolysis function is efficient and produces easily digestible matter, which is converted to biogas in the step 2 digesters.

In general 1 m^3 biogas represents the conversion of about 1.2 kg organic matter conversion besides more or less biochemical water consumption.

5.12.2 **Experimental results based on sludge wet weight**

Below the results of the post digestion experiments are given:

M^3 / t	Gas production m^3 / t after 4 days				Gas production m^3 / t after 9 days			
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 1, starting hydrolysis on line 1								
Mean	0.485	0.160	0.411	0.288	0.765	0.211	0.575	0.380
Maximal	0.594	0.248	0.555	0.397	0.778	0.390	0.715	0.504
Minimal	0.296	0.109	0.328	0.239	0.750	0.137	0.464	0.267
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 2, stable operation of hydrolysis on line 1								
Mean	0.618	0.115	0.381	0.304	0.917	0.130	0.585	0.468
Maximal	0.886	0.288	0.581	0.385	1.199	0.328	0.816	0.628

Minimal	0.363	0.043	0.215	0.177	0.665	0.050	0.336	0.374
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 3, using hydrolysis on both lines								
Mean	0.538	0.069	0.467	0.129	0.785	0.108	0.662	0.186
Maximal	0.690	0.090	0.633	0.317	0.981	0.205	0.962	0.494
Minimal	0.352	0.039	0.358	0.063	0.352	0.064	0.376	0.088

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines. L = line. L 1 = line 1. S = step. L 1 = line 1. L 2 = line 2.

The data shows a quite clear picture of the biogas potential with or without hydrolysis:

- During period 1 the 4 days results does not differ much the two lines in between whatever mean, maximum or minimum values; still line 2, step 2 values are higher than equivalent figures for line 1
- During period 1 the 9 days results already differ to what concerns production from step 1 and 2, where line 1 step 1 show higher values and line 1 step 2 show lower values than found for the line 2 digesters
- During period 2 as well for 4 as for 9 days values line 1 step 1 exceeds line 2 step 1 and line 1 step 2 is lower than line 2 step 2 digester results
- During period 3, where hydrolysis on line 2 is started, the results for line 2 become similar to the results from line 1.

None of the lines produce more than about 1.1 m^3 biogas / ton wet weight. This comply a VS conversion of about 1.3 kg VS / m^3 sludge or 0.13 %-point VS. Referring to chapter 5.4.2 the turnover on line 1 and 2 may be about 2.4 and 2 %-point TS, why the rest-gas production accounts for less than 6 % of the VS conversion.

5.12.3 **Experimental results based on sludge TS weight**

Below the results of the post digestion experiments are given:

M^3 / t	Gas production m^3 / t after 4 days				Gas production m^3 / t after 9 days			
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 1, starting hydrolysis on line 1								
Mean	0.024	0.009	0.022	0.015	0.039	0.011	0.031	0.019
Maximal	0.030	0.012	0.029	0.021	0.042	0.018	0.038	0.027
Minimal	0.015	0.006	0.016	0.012	0.036	0.008	0.026	0.015
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 2, stable operation of hydrolysis on line 1								
Mean	0.033	0.007	0.024	0.019	0.050	0.008	0.036	0.029
Maximal	0.047	0.019	0.036	0.024	0.065	0.021	0.051	0.040
Minimal	0.020	0.003	0.013	0.011	0.036	0.003	0.021	0.021
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 3, using hydrolysis on both lines								
Mean	0.027	0.004	0.027	0.008	0.040	0.007	0.038	0.012
Maximal	0.035	0.006	0.036	0.019	0.049	0.013	0.052	0.030
Minimal	0.018	0.002	0.020	0.004	0.018	0.004	0.022	0.006

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines. L = line. L 1 = line 1. S = step. L 1 = line 1. L 2 = line 2.

By nature the TS based gas production results follows the wet weight results, as the solids content is a result of the biogas production, inversely proportional. In general hydrolysis brings high gas production from step 1 and low gas production from step 2. The low production from step 2 amounts about 0.005 m^3 biogas / kg TS added the step. Relative to a turnover at about 2 to 2.4 %-points or 20 to 24 kg / m^3 sludge, 0.005 m^3 biogas complies a TS conversion of about 0.1 m^3 biogas / ton wet weight added the step 2 from the hydrolysis plant, which is not extracted during the processing in the full scale plant. This certainly represents a limited amount.

5.12.4 **Experimental results based on sludge VS weight**

Below the results of the post digestion experiments are given:

M^3 / t	Gas production m^3 / t after 4 days				Gas production m^3 / t after 9 days			
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 1, starting hydrolysis on line 1								
Mean	0.038	0.015	0.035	0.025	0.060	0.019	0.050	0.033
Maximal	0.047	0.019	0.047	0.035	0.065	0.030	0.060	0.044
Minimal	0.024	0.011	0.026	0.020	0.057	0.014	0.042	0.024
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 2, stable operation of hydrolysis on line 1								
Mean	0.052	0.013	0.039	0.031	0.077	0.015	0.059	0.047
Maximal	0.072	0.032	0.059	0.039	0.100	0.037	0.083	0.069
Minimal	0.032	0.005	0.022	0.017	0.058	0.006	0.034	0.036
Mass	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2	L 1, S 1	L 1, S 2	L 2, S 1	L 2, S 2
Period 3, using hydrolysis on both lines								
Mean	0.044	0.008	0.044	0.014	0.064	0.012	0.062	0.020
Maximal	0.056	0.010	0.057	0.033	0.077	0.023	0.086	0.052
Minimal	0.030	0.004	0.032	0.007	0.030	0.007	0.036	0.010

Period 1 and 2: hydrolysis on line 1. Period 3: hydrolysis on both lines. L = line. L 1 = line 1. S = step. L 1 = line 1. L 2 = line 2.

As the TS and VS contents are consistent and proportional, we refer to the comments in the above chapter 5.12.4.

5.12.5 **Conclusion on post digestion experiments**

It is concluded, that line 1 using hydrolysis efficiently digests organic matter, and that the rest gas amounts are quite limited. Actually the rest gas sum of line 1 results does not deviate that much from the rest gas sum of line 2. This indicates that the reduction in organic matter from hydrolysed sludge consists of organic matter that is non-digestible without using hydrolysis. Thus the hydrolysis step may make inaccessible organic matter available for further digestion during the digestion step 2.

Thus, a very important conclusion of this intense research shows that the effect of the hydrolysis treatment in the plant may be a mobilisation of inaccessible organic matter for further conversion.

It is also of special importance, that period 3, when both digester lines operate with hydrolysis not affects neither the 4 days nor the 9 days results of line 1. Actually the rest gas from line 1, both digester steps is further reduced while the results of line 2, now operating with hydrolysis like line 1 to a higher extent equal line 1 results.

5.13 Settling of digested mass

5.13.1 General concerns

Separation and settling of sludge solids are tested using Imhoff cones.

In general the settling efficiency may influence the de-watering of the digested sludge, as poor settling conditions may indicate an unstable sludge.

Still in this actual project the digested and hydrolysed sludge shows very low post digestion biogas production regardless of setting results. This implies, everything else equal, that the sludge is very well digested and thus ought to be objected as very stable after the combined hydrolysis and digestion treatment.

5.13.2 Experimental results

The settling characteristics of hydrolysed as well as not hydrolysed and digested sludge has been extensively analysed and the solids distribution controlled by TS and VS analyses. The below table show the results of the settling experiments.

The below table show the general settling conditions when settling for 2 and 24 hours respectively.

	Settling 2 h		Settling 24 h	
Line x, step 2	Line 1, hydrolysis	Line 2	Line 1, hydrolysis	Line 2
Clear zone, ml	0	10	60	100

Generally, the non-hydrolysed sludge shows best settling characteristics as seen by the bigger clear zone results.

To characterise the settling samples at top, at half settling volume level and a mixture of the lowest ½ litre volume is analysed for TS and VS for the 24 hours settling result. The results are given below.

Settling results	Top % TS / % VS / % ash	Middle % TS / % VS / % ash	Bottom % TS / % VS / % ash
Line 1, hydrolysis	0.76 / 0.50 / 0.26	1.62 / 0.97 / 0.66	1.70 / 0.96 / 0.74
Line 2, no hydrolysis	0.44 / 0.34 / 0.10	1.90 / 1.18 / 0.72	2.06 / 1.22 / 0.84

The analyses show as follows:

- TS, VS and ash from non-hydrolysed, digested sludge settle more efficient than ash from hydrolysed and digested sludge
- Settled sludge, as here analysed as the concentration at half the amount of test sludge and the lower ½ litre sludge mixed, is more uniform for hydrolysed, digested sludge than from non-hydrolysed, digested sludge.

These data further confirms that the non-hydrolysed sludge settles more efficient since less organic matter is left in the upper zone of the sludge and water mixture. Referring to chapter 5.6.2 for filtered COD there seems to be proportionality between filtered COD and settling characteristics.

Actually this condition has been unforeseen; still it is in accordance with the explanation that the hydrolysis may result in production of a higher concentration of fine SS as more organic matter is converted to biogas. This may leave back a higher concentration of fine SS which show poor settling capacity.

5.13.3 **Conclusion on settling experiments**

The data shows that hydrolysis reduces the settling efficiency of digested sludge. The digested, hydrolysed sludge disperse more uniformly throughout the water column than the non- hydrolysed sludge.

5.14 De-watering results for digested sludge

5.14.1 **General concerns**

The de-watering result of the digested sludge may depend on the concentration of fine SS and thus the COD_f concentration besides the settling characteristics.

Everything else equal the total amounts of de-watered sludge may depend on the TS concentration, and as the TS and VS concentrations are reduced using hydrolysis, the de-watering might result in lower sludge amounts and / or higher sludge concentration than without hydrolysis treatment.

5.14.2 **Experimental results**

The below results show the mean results of de-watering sludge.

Period	1. Starting hydrolysis on line 1	2. Line 1 stable	3. 2 lines hydrolyse
Matter as % TS / % VS	20.0 / 11.7	19.7 / 11.4	20.0 / 11.2

The results seems quite uniform, and aside from a possible reduction of the content of VS during the period, which may be a result of the hydrolysis process, the total solids of the de-watered sludge is near to constant.

5.14.3 **Conclusion on de-watering**

De-watering of sludge seems to be independent of the hydrolysis process. However, The data variation within each period is large and other factors than the physical chemical conditions, such as polymer age, equipment and staffing may influence on the result.

However, as the TS content of the de-watered sludge is stable even if the VS content seemingly fall, the resulting amount of de-watered sludge may be reduced.

6 Balance calculations

6.1 TS and VS mass balances

The below TS and VS mass balances are based on experimental period 1 and 2 for line 2 without hydrolysis and period 2 and 3 for line 1 using hydrolysis. During these periods the plant has showed high and stable hydrolysis efficiency and stable operating conditions.

The mass balances are as follows taking into account that about 10 % of the produced biogas resists from chemical bound water.

For TS:

Hydrolysis	100 kg TS sludge	+	6.4 kg water	=>	70.7 kg biogas	+	35.7 kg TS sludge
Standard	100 kg TS sludge	+	5.6 kg water	=>	62.1 kg biogas	+	43.5 kg TS sludge
Difference	0 kg TS sludge	+	0.8 kg water	=>	8.6 kg biogas	-	7.8 kg TS sludge

For VS:

Hydrolysis	100 kg VS sludge	+	7.3 kg water	=>	80.1 kg biogas	+	27.2 kg VS sludge
Standard	100 kg VS sludge	+	6.7 kg water	=>	73.3 kg biogas	+	33.4 kg VS sludge
Difference	0 kg VS sludge	+	0.6 kg water	=>	6.8 kg biogas	-	6.2 kg VS sludge

Even if there always may be come variation on analyses of full scale systems the balance data are comparable. Actually the VS based data might be the most correct as certain sedimentation of ash is observed through the digester steps 1. Thus the TS reduction may be a bit overestimated.

As such the VS based data might be more reliable than the TS based data.

It should be mentioned that CO_2 gas weight is 2.75 times heavier than methane gas as the molar weight respectively is 44 and 16 g / mole. Thus the in chapter 5.5.3 mentioned higher methane concentration during phase 3 everything else equal represents a lower weight of produced biogas.

All in all the TS balance represents hydrolysis efficiency for TS at about 18 % and for VS at about 19%.

It should be mentioned that during phase 2, line 2 was added relatively lower amounts of biological excess sludge than line 1. The reason for this deviation is a short period for repair of one of the impellers in a hydrolysis tank. Thus the biogas production and VS turnover from the “Standard” may be a bit overestimated, as the primary sludge is easier digestible than the biological excess sludge.

6.2 Calculation of full sludge load data

The above mass balance accounts for periods 1, 2 and 3 for the system referring to period 1 and 2 for line 2 without hydrolysis and line 1 for periods 2 and 3using hydrolysis. Especially during period 2 and 3 a lot of effort is done to enhance the utilisation of biological excess sludge for biogas production.

It is expected that biological excess sludge VS amounts account for 40 % of the total available VS amounts. For the above calculations covering periods 2 and 3, biological excess sludge accounts for respectively about 32 and about 40 % of the total sludge VS. Thus, during phase 3 all the biological excess sludge may be added to the digester system.

It is not possible from the experimental results to evaluate the hydrolysis effect on primary sludge and biological excess sludge separately. Using data from project part 1 the effects may become elucidated:

- Effect on primary sludge 5 to 10 %. Below 10 % effect is used
- Balance calculations may give the effect on biological excess sludge
- The mean hydrolysis effect on VS according to the above chapter is 9 %.

Thus the VS balances may be as follows using the data for phase 2:

100 kg VS input	Primary sludge		Biological sludge		Water		Biogas
VS amounts	68 kg VS	+	32 kg VS	+	7 kg	=>	80 kg
Hydrolysis effects	+ 10 %		+ 39 %				+ 9 %

Thus the hydrolysis efficiency on biological excess sludge might be in the order of 40 %.

For phase 3, having full load with biological excess sludge the following data may be calculated:

100 kg VS input	Primary sludge		Biological sludge		Water		Biogas
VS amounts	53 kg VS	+	47 kg VS	+	10 kg	=>	115 kg
Hydrolysis effects	+ 10 %		+ 39 %				+ 13 %

Relative to the project part 2 results the found efficiency is reduced. During part 2 the mineralisation of biological excess sludge VS was found to be above 50 %. Still, taking into account all the possible uncertainties that might be at a full scale plant, the result should be objected as being equivalent to the results of the project part 2 experimental data.

6.3 Hydrolysis plant based energy production

The produced biogas is converted to heat and power with a Jennbacher 312 gas engine. The yields of the engine are as follows at full load:

- input effect: 1.500 kW
- power yield: 38 % or 570 kW
- heat yield: 40 % or 600 kW

The heat system is coupled to the district heating network to buy as well as sell heat.

The energy production and conversion data are based on utilisation of the full amount of biological excess sludge. The biogas production is given as a rounded figure as the influence from fat trap fat and the fact, that the variation in addition of biological excess sludge has been minimal makes it impossible to calculate the actual biogas production.

Besides the gas engines most often operate at half load implying a reduced power yield and an enhanced heat yield. The used yields are as follows:

- power yield: 36 %
- heat yield: 42 %

Besides the methane content of the biogas from the hydrolysis based plant is higher than from the standard plant. The figures used are 64 and 60 % methane respectively. The basis for this evaluation is the measured rise in methane content from period 2 to period 3, where the rise is about 2 %-points. Presuming the biogas production is near to uniform the 2 lines in between, the basic "standard" methane content may be in the order of 60 %.

This brings the following calculated results.

Element	Without hydrolysis	With hydrolysis	Change
Biogas production m^3 / year	1,050,000	1,190,000	140,000
Energy production MWh / year	6,300	7,620	1,320
Power production MWh / year	2,270	2,740	470
Heat production MWh / year	2.650	3,200	550

The table shows a substantially higher energy production using the hydrolysis technology. Still this project part 3 shows lower efficiency enhancement than found during project part 2. Especially expected amounts of biological excess sludge and the here calculated lower efficiency of hydrolysis on biological excess sludge may cause this reduction. Still the high hydrolysis efficiency cannot be put in doubt.

6.4 Hydrolysis plant energy consumption

The energy consumption for the hydrolysis plant is estimated as follows, where the heat consumption in parenthesis refers to the total heat consumption of the digester system. The calculated heat consumption refers to the heat loss from the hydrolysis tanks, as the energy necessary for heating up the sludge to the hydrolysis temperature is recovered using heat exchange.

Position	MWh / year
Consumed power…………………………………………………..	300
Consumed heat…………………………………………………….	250 (1,270)
Sum, consumed energy………………………………………….	550

The data for heat consumption is based on the heat recovery rate of 75 % which might be possible at digester plants in general taking the temperature span of near to 65°C into account. Thus the poor insulation of digester step 2 of each line is not valuated.

It should be noticed that the heating of the sludge for the hydrolysis accounts for the main part of the total heat consumption to heat up and maintain temperature of the sludge in the digesters.

6.5 Reduction of power for nitrification

The power consumption for nitrification is based on the following assumptions:

- 2 moles of oxygen to oxidise 1 mole of ammonia
- Power specific oxygen transfer rate 0,8 kg O_2 per kWh

why the power consumption to oxidise 1 kg of ammonia is 4,5 kWh.

The ammonia stripping system has not been effective in evaporating ammonia, especially as it has been concluded impossible to a combination of temperature and humidity of the stripper air to selectively evaporate ammonia.

According to chapter 4.10.2.2 there is a net production of ammonia through the hydrolysis system of about 20 % relative to a common digestion.

This implies as follows:

Status, without hydrolysis: 60 t ammonia á 4.5 MWh / t => 270 MWh / year.
Operating with hydrolysis: 72 t ammonia á 4.5 MWh / t => 325 MWh / year.

To reduce the ammonia load at the aerated plant a treatment plant to treat reject water from final de-watering of digested sludge might become necessary. This may include either a nitrate producing de-nitrifying plant or an air and soda based ammonia stripper plant.

6.6 Energy consumption for transport of sludge

The energy consumption is based on the actual handling of the sludge and on general figures from the transport sector for transport and reload of sludge.

The basis is as follows:

- 210 m3 digested sludge / day
- 1.7 % TS in digested sludge and 1.5 % TS in the digested, hydrolysed sludge
- 95 % sludge yield in the final de-watering
- 20 % total solids in the de-watered sludge
- 35 km transport distance from wastewater treatment plant to sludge storage
- 15 km transport from sludge storage to farm
- 2 km from storage area on farm to fields
- Diesel consumption 2,5 km / litre for transport
- Diesel consumption 0,25 litres / ton of sludge for loading onto truck
- 30 tonnes of load for transport on road
- 8 tonnes of load for transport at farm
- Empty return
- Energy content 10 kWh / l diesel.

This brings on the following diesel consumption as MWh per year:

Element	Without hydrolysis	With hydrolysis	Change
WWTP to sludge storage	51.7	45.5	6.1
Sludge storage to farm	22.1	19.5	2.6
Farm to field	11.1	9.8	1.3
Reload sludge storage	13.8	12.2	1.6
Reload farm	13.8	12.2	1.6
Total consumption	112.5	99.1	13.4

The table shows, that as the total amounts of sludge at the plant is used for biogas production using hydrolysis, the energy consumption for handling of de-watered sludge is reduced to 88 % relative to the standard consumption. It should be mentioned, that during the project part 2 it was found, that the higher efficiency of the hydrolysis found here referred to 77 % reduction relative to the standard consumption. The reduction in diesel consumption equals respectively 1.3 and 3.3 m^3 / year.

6.7 Energy balances

Based on the above results the energy balance may be as calculated below. All values are in MWh per year using rounded figures:

Incoming energy:		
Power production	470	
Heat production	550	
Power savings from reduced nitrification	- 55	
Power savings from reduced transport	15	
Sum, incoming energy	980	980 MWh
Outgoing energy:		
Power consumption for hydrolysis plant	300	
Extraordinary heat consumption, hydrolysis plant	250	
Sum, outgoing energy	550	550 MWh
Net energy production:		430 MWh

Taking the benefit from the sanitation into account, the balance may be a follows:

Sanitation plant power consumption	300	
Extraordinary heat consumption, sanitation plant	200	
Sum, energy demand of sanitation plant	500	500 MWh
Net energy production		930 MWh

7 Cost benefit analysis

7.1 Establishment costs for hydrolysis plant and connections

The establishment costs for the plant are given below. The costs are based on a detailed going through of the plant, simplifications to the experimental plant besides build-up and a cost estimation made by a turn-key supplier. All costs are excl. VAT.

It is expected that the mechanical installations may be placed in existing building.

The establishment costs are specified as follows using rounded figures:

Element	Cost DK ex. VAT
Soil and concrete works	100.000
Hydrolysis tanks including equipment	1.000.000
Mechanical equipment, pipes including mounting	800.000
Heat exchangers including mounting	1.600.000
Scada, signals and power system	300.000
Sum 1. Erection costs………………………..	…………………3.800.000
Design, consultancy, starting operation	250.000
Sum 2. Total establishment costs………………….	………………………4.050.000
Unforeseen costs 10 %	400.000
Sum 3. Total project costs………………………..	……………………....4.450.000

Thus it is found, that the establishment costs for the plant established in Denmark may be in the order of 4.5 mills. DKK excl. VAT including unforeseen costs.

As the hydrolysed sludge is sanitised to a very high level of sanitation, it may be of interest to face the alternative costs for establishing a sanitation plant that sanitises the sludge according to the demands to controlled sanitation.

These establishment costs are sketched to the following level using analogue input, again using rounded figures:

Sanitation plant including 3 parallel sanitation tanks and heat exchangers…… 4.000.000 DKK

Thus the costs for establishing sanitation plant amounts about 90 % of the costs of the hydrolysis plant. It should be mentioned that sanitation not contributes to the other benefits of the hydrolysis. It should be mentioned that the main part of the cost difference refers to cost for tank volume.

Still, from a legal veterinary point of view a sanitation plant makes the system comparable with the plant including the hydrolysis system.

7.2 Benefits from establishing hydrolysis plant

7.2.1 Qualitative and non-valued quantitative benefits

The qualitative benefits from establishing hydrolysis system are as follows:

- The sludge is sanitised; the efficiency is exceeds the legal demands to controlled sanitation which especially implies a profound effect on viability of some temperature resistant virus, spores and parasite eggs
- The need for power to de-water the hydrolysed and digested sludge is expected to become reduced. This value is not added the quantitative benefits
- The need for polymer to the de-watering of sludge is expected to become reduced. This value is not added the quantitative benefits
- The smell emission from the sludge is reduced. The smell resembles more or less a combination of "diesel oil" and "old wooden house"
- Even during long time storage in closed container the sludge emission does not change character
- Emission after spreading is transient

On the other hand it is experienced, that the need for power to nitrify and de-nitrify reject water from final de-watering of hydrolysed, digested sludge may become enhanced with some 20.

7.2.2 **Quantitative benefits**

The below table show the values of establishing the hydrolysis system.

Position	DKK / year
Produced biogas / power…………………………………………..	540.000
Produced biogas / heat…………………………………………….	110.000
Reduced sludge amounts…………………………………………..	190.000
Reduced power consumption for nitrification……………………..	- 30.000
Sum, quantitative benefits	810.000

The sales price for power is set to 1.150 DKK / MWh while the price for buying is 550 DKK / MWh. The sales price for heat is 200 DKK / MWh. Final disposition of sludge is 255 DKK / t.

7.3 Costs for operating hydrolysis plant

The costs for operating the hydrolysis system are:

Position	DKK / year
Power consumption………………………………………………....	165.000
Heat consumption………………………………………………...	50.000
Maintenance and repair of machinery equipment…………………..	20.000
Yearly operation and maintenance costs……………………………...	235.000

Besides and to compare the system sanitation rate the alternative cost for operating a sanitation plant treating sludge according to the demands to controlled sanitation:

Position	DKK / year
Power consumption……………………………………………….	135.000
Heat consumption………………………………………………...	40.000
Maintenance and repair of machinery equipment…………………...	20.000
Yearly operation and maintenance costs…………………………….	195.000

Thus the energy costs to operate a sanitation plant amounts about 80 % of the similar costs for the hydrolysis plant.

It cannot be expected, that a sanitation plant may have any influence on the biogas production or change nitrogen balances, why it is not comparable to the hydrolysis plant from a processing point of view.

Now, sanitation in itself does not imply easier disposal or reduced disposal costs. Still the sanitised sludge may become used even for root-fruits, why the customer group may become larger, competition for getting sludge higher and thus the disposal costs lower. We still await a market for sanitised sludge.

7.4 Fees for handling of sludge

Esbjerg Renseanlæg Vest uses a contractor to take care of the produced sludge. As long as the sludge keeps the demands to content of organic priority pollutants and heavy metals the sludge is used for fertiliser.

For the calculations we assume, that all sludge is used for fertiliser. The contractor cost is 255 DK per tonnes. This implies that the costs without and with hydrolysis plant are as follows:

Position	Without hydrolysis	With hydrolysis	Change DKK / year
Total fee	1.560.000	1.370.000	190.000

For information, the on-going changes to the de-watering system have made it possible to pass the normally found 20 % TS in de-watered sludge. The disposal costs are 255 DK / ton in all.

7.5 Payback calculations

7.5.1 Standard conditions

The simple payback time based on the above calculations may be as follows excl. VAT:

Investment, DKK		4.500.000
Yearly balance in DKK / year:		
Power production	540.000	
Heat production	110.000	
Reduced power consumption for nitrification	- 30.000	
Reduced fee for sludge disposing	190.000	
Sum, ingoing	810.000	810.000
Power consumption	165.000	
Heat consumption	50.000	
Maintenance and repair	20.000	
Sum, outgoing	235.000	235.000
Yearly balance excl. man-hours		575.000
Simple payback time		7.8 years

The pay-back time may be objected as being within an acceptable level.

7.5.2 Plant added the value of sanitation

The simple payback time based on the above calculations may be as follows excl. VAT:

Investment, DKK	4.500.000
Investment in sanitation plant, DKK	4.000.000
Marginal investment for hydrolysis plant	500.000

Comparing with the above balance result the following result is found using rounded figures:

Yearly balance excl. man-hours	500.000
Simple payback time	1 year

Whatever this simple payback time is quite acceptable.

We still await a market for digested, sanitised sludge.

New hydrolysis tanks and simplified gas system after rebuilding the plant. Photo Niels Oestergaard

8 Conclusion

The results included in this report are based on operating a sludge hydrolysis plant in full scale. The project test period includes 3 phases of more than 1 month.

The 3 phases includes starting the hydrolysis plant, a stable period of operating the hydrolysis plant at one digester line parallel to operating another digestion line without hydrolysis and a third period of operating both lines with hydrolysis to test the possible loading limits

The results tell as follows:

- Hydrolysis efficiency on primary sludge about 10 % on VS basis
- Hydrolysis efficiency on biological excess sludge about 40 % on VS basis. During project part 2 a 50 % efficiency was found
- (ammonium + ammonia)-N reduction - 20 %, i. e. a net ammonia production.

Thus the balances may be changed as follows at the plant as is:

- Sludge dry matter reduction 150 tonnes of TS per year (project part 2: 330 tonnes of TS per year) or 730 tonnes of dewatered sludge (project part 2: 1,650 tonnes of dewatered sludge)
- Enhancement of biogas production 140.000 m^3 per year (project part 2: 370.000 m^3 per year)
- Nitrogen N production 12 tonnes per year or about 2 % of the total N load at the plant (project part 2: 25 to 35 tonnes per year or 4 to 6 %)

The energy balances are found to be influenced as follows:

- Power demand for nitrification is enhanced with 55 MWh per year (project part 2: 110 to 160 MWh per year)
- Diesel oil demand for transportation is reduced with 15 MWh per year (project part 2: 33 MWh per year)
- Power production from enhanced biogas is 470 MWh per year (project part 2: 630 MWh per year)
- Heat production from enhanced biogas is 550 MWh per year (project part 2: 620 MWh per year)

It should be mentioned, that the plant line operating without hydrolysis shows efficiency on VS conversion of about 60 %. This figure is uncommon high, where the normal level is in the order of 40 to 50 %. Too, during project part 2 the VS conversion was lower than this report part 3 shows. The reason for the change is not known.

Power and energy reduction from enhanced circulation of wastewater for de-nitrification and from reduced amounts of sludge for dewatering are not included in the energy balances.

The hydrolysis processing also sanitises the sludge. If the energy consumption from a standard sanitising plant is included in the calculations to value this secondary benefit, the energy balances becomes even more advantageous.

The cost-benefit analyses show, that:

- The simple pay-back time of the system is in the order of 8 years (project part 2: 5 years)
- If the value of sanitising is included the simple pay-back time is about 1 year (project part 2: 0.4 years).

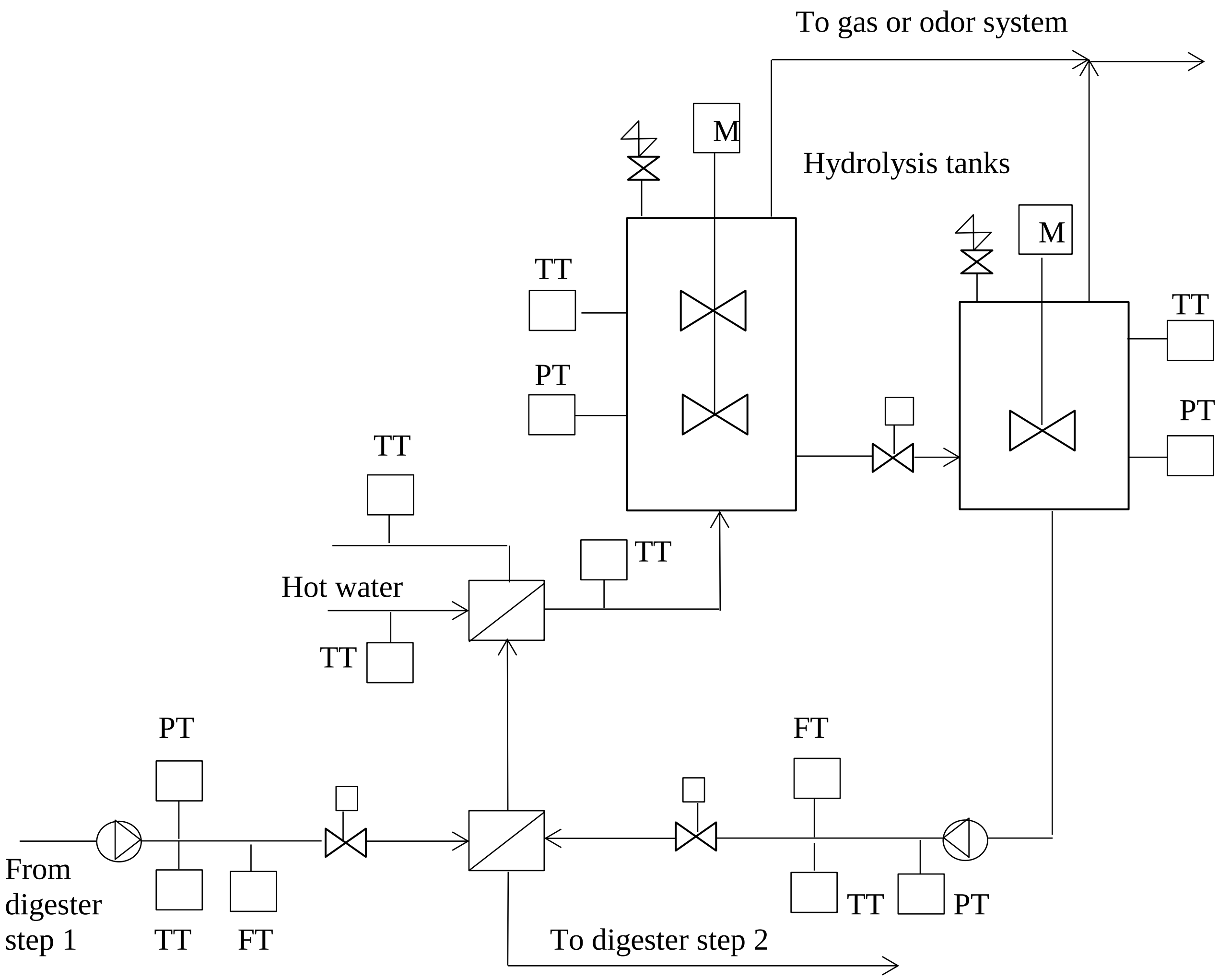
These calculations do not take the on-going changes of the sludge handling into account. Whatever the case the, changes may result in further advantages from utilising the hydrolysis system relating to especially sludge amounts.

Based on the obtained results the participants of the project continue the corporation and operation of the full scale plant at the Esbjerg Renseanlæg Vest waste water treatment plant.

Odour gas scrubber including acid cabinet. Photo Niels Oestergaard

Appendix 1

P & I diagram for the hydrolysis plant



Appendix 2

SWOT analysis

Strengths	**Weaknesses**
Optimal utilisation of organic matter in sludge for production of enhanced amounts of biogas with higher energy content Reduced costs for sludge de-watering and final disposal whatever including drying, incineration or farmland application Simple construction and equipment, comparable with well-known equipment at wastewater and agricultural biogas producing plants Processing comparable with general processing of sludge and agricultural residues No special training or education required for operating staff Processing also providing controlled sanitation at a level that exceeds the applicable requirements	Only 2 plants until now. One of these closed down for other reasons Only one person has worked with the plant details Large companies in the branch have not shown interest in the technology Universities have not shown interest in the technology Still the info level is reduced. The final report may change this condition No process protection possible The process needs a 2-step digestion complying a total treatment time at about 40 days which a relatively low number of plants may include
Opportunities	**Threats**
About 30 of about 60 large wastewater treatment plants in Denmark have the setup necessary for implementation of the technology Quite considerable export potential for wastewater and agriculture; presumably proportional to the potential in Denmark Continued process optimization towards greater efficiency and lower investment Courses, lectures and marketing, also in neighbor countries may develop the market Might introduce a new economically advantageous market for sanitized, digested and de-watered wastewater sludge	New technical set-up. Copying on insufficient basis may provide marketing problems Other, more well documented processes might be easier to market regardless of relative effect Cheaper process equipment regardless of relative effect Analogue pre-treatment regardless of relative effect Insufficient marketing capacity Possible problems with holders of analogue patents or utility model protected processes