Increased Biogas Production at the Henriksdal WWTP

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Abstract: Stockholm Vatten VA AB (Stockholm Water Company) participates in a European project, Biogasmax, the overall goal of which is to reduce the usage of fossil fuels for transportation in Europe by increasing the use of biogas. The technical and process related possibilities to introduce different methods to increase the biogas production at the Henriksdal WWTP are reviewed. Combinations of these methods that are expected to yield at least 10 % increase of the total biogas production include pre-thickening of primary sludge in combination with increased production of primary sludge and serial operation; pre-thickening of primary sludge in combination with increased production of primary sludge; and pre-thickening of primary sludge in combination with serial operation. It is recommended that precipitation tests as well as digestion tests (serial operation) are carried out to verify the assessments of the biogas increase and the potential effects on the processes at the wastewater treatment plant. Addition of enzymes, electroporation and ozone treatment are three interesting methods with great potential that are under development. Thermal hydrolysis yields the greatest gross gas increase, and the method becomes more cost-effective if greater amounts of EOM are received.

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Summary

Stockholm Vatten VA AB (Stockholm Water Company) participates in a European project, Biogasmax, the overall goal of which is to reduce the usage of fossil fuels for transportation in Europe by increasing the use of biogas. As part of its commitment to the project, Stockholm Vatten has undertaken to demonstrate how the biogas production may be increased by 10 % at the Henriksdal wastewater treatment plant.

This plant is the largest wastewater treatment plant in the City of Stockholm, with a load of 870 000 pe (population equivalents) and an average flow of about 240 000 m3/d during the years 2000-2005. At the Henriksdal plant, there are seven digesters with at total volume of about 38 400 m^3. During the years 2000-2005, these received an average 27.9 tonnes of VS (volatile solids)/d (day) from primary sludge, 10.6 tonnes of VS/d from pre-thickened excess biological sludge, and 3.3 tonnes of VS/d from external fatty sludge, i.e., a total of 1.35 kg VS/(m^3 digester volume · d). The corresponding biogas production was 1054 Nm^3 biogas/h, with a methane concentration of 65.6 %.[12] (Nm^3 = normal cubic metre, the quantity of gas that takes up the volume of one cubic metre at a pressure of 1 atm and a temperature of 0ºC)

The purpose of this study is to describe the technical and process related possibilities to introduce different methods to increase the biogas production at the Henriksdal WWTP (wastewater treatment plant).

Initially, a number of prospective methods that generally would be expected to result in an increased biogas production were described. The description included for example the technical feasibility of each method, the predicted effect on the biogas production and the exergy balance for the method. The methods that were described include

- increased production of primary sludge
- increase of the hydraulic retention time (preferably through pre-thickening of primary sludge)
- thermophilic digestion
- conversion to serial operation
- collection of biogas from existing sludge tanks
- disintegration of the biomass through mechanical treatment
- pasteurisation
- thermal hydrolysis
- chemical hydrolysis
- thermo-chemical hydrolysis
- ozone treatment
- ultrasound treatment
- treatment with electrical impulses
- addition of enzymes
- addition of deficient substances
- increased reception of external organic material.

A selection was made of methods that were assessed as technically feasible; that would result in at least 5 % increase of the total biogas production; and show a positive exergy balance (i.e., the gas production exceeds the increased consumption of exergy).

The selected methods included pre-thickening of primary sludge, increased production of primary sludge, serial operation, addition of enzymes, thermal hydrolysis, and increased reception of organic material. Chosen methods were finally combined to a number of alternatives that can be expected to yield at least 10 % increase of the total biogas production. These alternatives are presented in the table below.

Process	Estimated increase of gas production without additional organic material %	Estimated increase of gas production with an additional 5 600 m³ fatty sludge and 20 000 m³ food waste slurry per year
Increased production of primary sludge	11	11*
Pre-thickening + increased production of primary sludge	15	30
Pre-thickening + serial operation	10	26
Pre-thickening + increased production of primary sludge + serial operation	23	39
Addition of enzymes	15	15*
Thermal hydrolysis	3 % (net)	20 (net)
Addition of another 5 600 m³ fatty sludge per year	3	15

* No futher anaerobic digester volume was available since the hydraulic retention time is less than the reference value of 20.1 days already at the case without addition of external organic material.

Costs were estimated for the different alternatives, with and without the addition of 25 600 m³ external organic material per year. The estimates include both investment costs and operational costs, and are presented in the table below. Pre-thickening of primary sludge together with serial operation seem most economically advantageous, followed by pre-thickening of primary sludge in combination with increased production of primary sludge and serial operation. The third best alternative with respect to cost effectiveness is pre-thickening of primary sludge combined with increased production of primary sludge.

Process	Gas increase %	Net gas increase Nm^3 CH_4/yr	Investment cost MEUR	Change in annual cost MEUR/yr	Cost effectiveness, Change in annual cost per Nm^3 CH_4 net increase (EUR/Nm^3 CH_4)
C. Pre-thickening + serial operation	10	640 000	1.1	-0.17	-0.26
C. + 25 600 tonnes EOM	26	1 700 000	1.1	-0.02	-0.01
D. Pre-thickening + increased PS production + serial operation	23	1 500 000	1.5	0.27	0.18
D. + 25 600 tonnes EOM	39	2 500 000	1.5	0.42	0.17
B. Pre-thickening + increased PS production	15	940 000	1.2	0.30	0.32
B. + 25 600 tonnes EOM	30	1 900 000	1.2	0.45	0.23

CH_4 = methane, yr = year, MEUR = 10^6 Euros, EOM = external organic material, PS = primary sludge

Prior to continuing these studies, it is recommended that precipitation tests as well as digestion tests (serial operation) are carried out to verify the assessments of the gas increase and the potential effects on the processes at the Henriksdal WWTP.

Trials with pre-thickening of primary sludge have begun. Addition of enzymes, electroporation and ozone treatment are three interesting methods with great potential that are under development, and the results can be expected to improve during the coming years. The development should therefore be monitored closely, possibly also through trials together with the different suppliers.

Thermal hydrolysis yields the greatest gross gas increase, and the method becomes more cost-effective if greater amounts of EOM are received. Thermal hydrolysis is the only one of the proposed alternatives that leads to a hygienisation of the sludge. It is, however, undoubtedly the most complex and space–demanding method of the alternatives that have been compared here, and is associated with a certain risk for operational problems. Thermal hydrolysis, however, might result in fewer problems with foaming in the anaerobic digesters.

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Preface

This study was carried out during the period of September 2008 to April 2009 as a defined project. Assessments and discussions were carried out within a project group including Agnes Mossakowska, Lena Jonsson, Daniel Hellström, Katarina Starberg, Cajsa Hellstedt and Lars- Erik Olsson.

The main part of the report writing, the process calculations and the elaboration of mass balances and cost estimates were carried out by WSP och AnoxKaldnes AB. Lena Jonsson contributed with the section on planned and completed measures at the Henriksdal WWTP after the reference period. Daniel Hellström performed the calculations regarding nitrogen balances at Henriksdal, the calculations of ratio of biogas from fatty sludge as well as the estimates of reduced amounts of excess biological sludge at increased withdrawal of primary sludge. The Stockholm Vatten staff also contributed in the identification and selection of studied methods; in elaborating the evaluation criteria for the different stages of the study; and also in structuring and reviewing the report.

1. Introduction

1.1. Background

Stockholm Vatten VA AB (Stockholm Water Company) participates in a European project, Biogasmax, the overall goal of which is to reduce the usage of fossil fuels for transportation in Europe by increasing the use of biogas. As part of its commitment to the project, Stockholm Vatten has undertaken to demonstrate how the biogas production may be increased by 10 % at existing wastewater treatment plants. This study focuses on the Henriksdal wastewater treatment plant (WWTP) in Sweden.

Within the framework of Biogasmax, the Stockholm Water Company, in cooperation with the company Svensk Biogas, Linköping, Sweden, has earlier undertaken a thorough investigation of the existing anaerobic digestion process at the Henriksdal WWTP. In addition, Stockholm Vatten has studied several methods and measures for increased biogas production at the plant.

As a continuation of these efforts, WSP was assigned to carry out a more detailed study regarding methods for increased biogas production that may be viable for the Henriksdal WWTP.

1.2. Purpose and goal

The purpose of this study is to describe the technical and process related possibilities to introduce different methods to increase the biogas production at the Henriksdal WWTP.

The goal of the study is:

- To identify and describe the three most cost-effective and technically feasible process solutions that will result in a 10 % increase of the biogas production at the Henriksdal WWTP.

The cost effectiveness is calculated from the cost (operations + investment) expressed as EUR/Nm^3 of increased methane production.

1.3. Methodology

The study was carried out in three stages. The selection of appropriate methods was made through step-wise elimination of possible measures, based on a number of selection criteria specified by Stockholm Vatten.

Stage 1 comprised a review of a number of prospective methods that generally would be expected to result in an increased biogas production. The description includes for example the technical feasibility of each method, the predicted effect on the biogas production and the exergy balance for the method.

This survey of methods then constituted the basis for the selection of methods in subsequent sections.

In Stage 2, a first selection of the methods in Stage 1 was made. The selection was based on the assessment that each selected method could by itself fulfil the following criteria:

- technically feasible
- will result in at least 5 % increase of the total biogas production
- shows a positive exergy balance, i.e., the biogas production exceeds the increased consumption of exergy

Selected methods were then combined to a number of alternatives that were investigated further. Each of these alternatives consisted of one or more methods. The selection criteria that were applied onto the chosen alternatives were that each alternative should:

- be technically feasible
- result in at least a 10 % increase of the total biogas production
- show a positive exergy balance

In Stage 3, rough cost estimates of the different alternatives were made, including investments and cost of operation. The annual cost was also estimated for each alternative.

Stage 3 was completed by selecting the three alternatives that were assessed as the most cost-effective alternatives for the Henriksdal WWTP. The cost effectiveness was based on the change in annual cost induced by each method related to the increase in gas production, expressed as EUR/Nm^3 of methane (the increase in methane production). The rate 10.20 SEK/EUR valid for October 2009 was used.

1.4. Limitations

Potential costs for extending the biogas piping system have not been included, nor have potential costs or fees associated with the reception of external organic material (EOM). These aspects are currently being handled within other projects in progress at Stockholm Vatten.

Especially in food waste the content of nitrogen is high,which result in an increased concentration of ammonium nitrogen in the reject water from the centrifuges. Potential costs that may occur for extended nitrogen removal in the biological treatment at Henriksdal have not been considered in the cost calculations.

Revenues have not been included at all in this study (i.e., revenue from the sale of vehicle fuel) due to the contractual confidentiality with the current buyer.

2. Current Situation

2.1. The Henriksdal WWTP

The Henriksdal WWTP is the largest wastewater treatment plant in the city of Stockholm, with a load of 870 000 pe (population equivalents) (based on 70 g BOD/person and day) and an average incoming flow of about 240 000 m^3/d.

The treatment consists of mechanical, chemical and biological treatment, and in a final stage the water passes a filter filled with crushed ceramic material and sand before it reaches the recipient waterway. The sludge from the wastewater treatment is utilised as a soil conditioner. The biogas that is produced in the anaerobic digestion stage is collected in a gas dome and utilised as a fuel for the heat production in the heating system of the plant; for the production of electricity; and for the upgrading to vehicle fuel (biomethane). Since further biomethane is expected to be utilized by busses, district heating for heating of the anaerobic digesters was installed during 2007. In the near future, nearly all biogas is expected to be used for the production of biomethane.

Digestion is an anaerobic biological process that takes place in three steps:

- hydrolysis of complex organic compounds
- production of volatile organic acids
- production of biogas

All the steps take place in the anaerobic digester but rely on different groups of micro-organisms. Each step has a different optimum for its specific process, and functional synergy for the entire chain requires that the process operates under stable conditions that work well for all the micro-organisms involved.

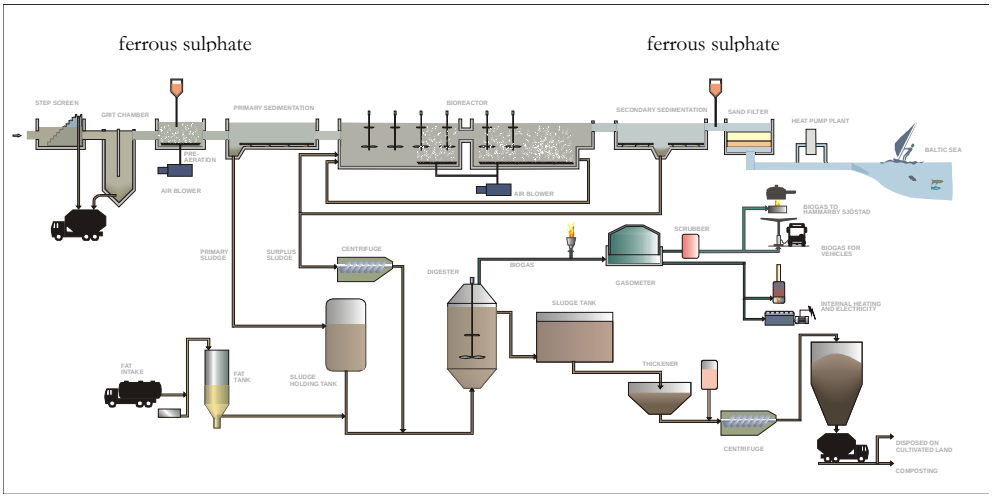

Figure 1. Overview of the treatment processes at the Henriksdal WWTP. The figure is from Stockholm Vatten's Biogasmax project report D2.15_SVAB_v1[12].

2.1.a. The existing anaerobic digestion process at the Henriksdal WWTP

Information about the anaerobic digestion system at the Henriksdal plant has been obtained from the first Biogasmax project report by Stockholm Vatten, report D2.15_SVAB_v1[12].

At the Henriksdal plant, there are 7 anaerobic digesters operated parallel as continuously stirred tank reactors (CSTR) with a total volume of 38 400 m^3. The volume differs among the anaerobic digesters. Table 1 shows the data for each tank. The anaerobic digesters are situated below ground, cut into the rock, with the rock surfaces functioning as chamber walls. Incoming material is fed into the bottom of the tanks and extraction of digested material takes place through overflow at the top of each anaerobic digester. Mixing is achieved by mechanical

mixers consisting of two or three pair of rotor blades fastened on a long mixer shaft; and a top mixer aimed at eliminating any potential foam in the anaerobic digester.

The supplied power to the mixers is 30.1 kW for the central mixers (9.4 revolutions/minute) and approximately 26.5 kW for the anti-foam mixers (174 revolutions/minute), totally about 56.6 kW. A certain mixing action is also achieved via the circulation of sludge through external heat exchangers.

Table 1. Data for the 7 anaerobic digesters at the Henriksdal WWTP. The volume refers to the liquid volume in each anaerobic digester.

Digester no.	Volume (m^3)	Mixing
1	5 070	2 blades
2	5 068	2 blades
3	5 036	2 blades
4	5 035	2 blades
5	6 687	3 blades
6	6 688	3 blades
7	4 855	2 blades

The anaerobic digesters are emptied at a rate of approximately one per year, in turn, according to an established schedule for inspection and cleaning. This usually results in about a 10 week shut-down for the anaerobic digester in question.

Three different fractions are treated in the anaerobic digesters, primary sludge (PS), excess biological sludge (EBS) and external organic material (EOM).

Primary sludge is chemically precipitated sludge that is gravimetrically separated in the primary sedimentation basins. Sludge is pumped from the sludge hoppers at the bottom of the basins to two sludge silos. From these silos, the different anaerobic digesters are fed consecutively through an inlet pipe at the bottom of each anaerobic digester. Excess biological sludge consists of active sludge from the biological stage. This type of sludge is difficult to degrade compared with primary sludge, since the suspended solids that have entered the anaerobic digesters via the supernatant from the primary sedimentation basins has already been consumed by the bacteria and incorporated into the cell structures. Excess biological sludge is dewatered (thickened) in centrifuges prior to entering the anaerobic digesters in order to reduce the amount of water and thereby increase the hydraulic retention time. From the centrifuges, excess biological sludge is pumped to the inlet pipe.

EOM has been received at the Henriksdal WWTP since March, 2000. EOM is received at a separate receiving station and is introduced into the feeding line. To avoid clogging, EOM is always pumped together with primary sludge to maintain a high level of flow in the pipe. Today, about 96 % of the supplied EOM consists of sludge collected from grease separators in the food and beverage industry and restaurants, here called fatty sludge. EOM is supplied to the plant during the whole year, with somewhat lesser amounts during the 3rd quarter each year.

After anaerobic digestion, the digested sludge is pumped to the sludge dewatering stage at a separate plant in the area of Sickla, located approximately 2 km from Henriksdal. The sludge passes two holding tanks (5 000 m^3 each) at the Henriksdal plant, and two hydraulically overloaded gravimetric thickeners (660 m^3 each) at the Sickla plant prior to dewatering. Recently, one of these thickeners has been taken out of operation and in the other a mixer has been installed.

The biogas that is produced in the anaerobic digesters was earlier utilised for electricity production and heating. In 2004, the first gas upgrading plant was installed at Henriksdal for the production of vehicle fuel (biomethane). In this plant, carbon dioxide, hydrogen sulphide, and ammonia are separated from the methane through water pressure absorption in a water scrubber process. The purified gas contains about 96-98 % methane. Another

water scrubber plant was put into operation in 2006, and the total biogas purification capacity is now 1 400 Nm^3 biogas/h.

The biogas that for different reasons cannot be utilised (e.g. due to operational disruption) is led to a flare for destruction.

2.2. Reference data

Assessment and evaluation of the different methods that were investigated in this study were carried out through comparison with the present load on the anaerobic digesters and the present production of biogas at the Henriksdal plant. The years 2000-2005 were chosen as reference period, partly since this period was previously used within the Biogasmax project.

Table 2 below shows the incoming load to the anaerobic digesters during the reference period.

The measured concentration of dry solids (DS) for the EOM varied greatly during this period, most likely due to difficulties with the sampling of received fatty sludge. The table shows the median value for the period, as this was considered to best represent the actual DS concentration.

Organic material, VS (volatile solids) is presented in the table as incoming load in tonnes per day (24 h) to the anaerobic digester. The VS % of DS were during the reference period 73.5% for primary sludge, 59.1% for excess biological sludge and 94.6% for EOM. The average reduction of VS was 51.0% or 28.0 tonnes/day during the same period, see Table 3.

Table 2. Compiled data on incoming substrate to the anaerobic digestion process during the years 2000-2005. The table is obtained from the Biogasmax project report D2.15_SVAB_v1[12].

	Primary sludge[1)]			Excess biological sludge[1)]			EOM[2)]		
Year	Amount (m^3/d)	DS (%)	VS (tonnes /d)	Amount (m^3/d)	DS (%)	VS (tonnes /d)	Amount (m^3/d)	TS (%)	VS (tonnes /d)
2000	1 466	3.4	38.1	391	4.9	10.6	39	5.2	1.9
2001	1 443	3.3	36.3	358	4.7	10.5	65	5.2	3.2
2002	1 452	3.8	40.7	330	5.8	11.8	70	5.2	3.4
2003	1 388	3.6	36.2	400	3.7	8.7	69	5.2	3.4
2004	1 560	3.6	40.0	393	4.6	10.9	78	5.2	3.8
2005	1 411	3.6	36.3	468	4.0	11.1	79	5.2	3.9
Mean	**1 453**	**3.6**	**37.9**	**390**	**4.6**	**10.6**	**66.8**	**5.2**	**3.3**

1) The values for primary sludge and excess biological sludge are calculated annual mean values.

2) The values for DS of the EOM are based on the median value of the total number of analyses (n=35) performed on fatty sludge during the trial period. The other values for EOM are calculated annual mean values.

Table 3 shows the biogas production for the reference period year 2000-2005. Data is obtained from the first Biogasmax report D2.15_SVAB_v1[12] and presented as annual mean values. For more details of the raw data, please consult the Appendix VII in the first Biogasmax report.

Table 3. The gas production from the anaerobic digestion process during the years 2000-2005 (annual mean values). The table is obtained from the Biogasmax report D2.15_SVAB_v1[12].

Year	Production of biogas (Nm^3/h)	Concentration of methane (%)	Production of methane, (Nm^3/h)	VS reduction (%)
2000	1 021	64.7	661	48
2001	975	65.1	635	49
2002	1 029	65.2	672	57
2003	1 087	65.8	716	52
2004	1 085	66.5	722	50
2005	1 125	66.5	749	49
Mean	**1 054**	**65.6**	**693**	**51**

The biogas production varies over the year, with lower production during the summer months, and shows the same pattern during each of the years of the reference period. The reason is that the load to the entire plant decreases during the summer, and despite that the VS concentration increases at somewhat lower flow rates, the organic load to the anaerobic digesters is on the whole lower during June-August each year.

During the reference period, the measured biogas production at Henriksdal thus approximates 25 300 Nm^3 biogas/d (24 h) as shown in the table above. This is based on values from the years 2000-2005. During this period the temperature in the anaerobic digesters was 35.5 °C on the average.

2.3. Planned and completed improvement measures at Henriksdal after the reference period

After the reference period 2000-2005, a number of improvement measures in the anaerobic digesters and biogas piping system were undertaken at Henriksdal. These are described below.

2.3.a. By-pass biogas pipe

For quite some time the safety valves released repeatedly at elevated pressure in the anaerobic digesters due to the biogas production exceeding the capacity of the biogas piping system. If the biogas production increases, this will occur more often. The possibility to increase the biogas flow capacity from the anaerobic digesters to the gas dome was investigated by calculating the pressure losses in the biogas piping system (Ø 200 mm). At present there are sections of biogas piping with inadequate dimensions. For the calculations it was assumed that the biogas piping system should be able to handle biogas flow velocities up to 34 m/s, which occurs at 3500 Nm^3/h (84 000 Nm^3/d) in the outlet pipe from the gas dome.

Existing safety valves each consist of a receptacle filled with water covered by a gas dome. The valves release above an elevated pressure of 40-44 mbar depending on the amount of water in the receptacle. Refilling of water takes place automatically after a valve has released, when water and biogas are released to the surrounding air. A cut-off valve between an anaerobic digester and its gas flow meter closes when the meter shows an abnormally low or high value. This prevents most of the biogas from passing from one anaerobic digester to another. During 2006, the security valve at anaerobic digester 7 was replaced by a mechanical valve that releases at overpressures exceeding 50 mbar, which increased the capacity of the biogas piping system. There are now plans to replace all the safety valves. In order not to disturb operations, emptying of a maximum of two anaerobic digesters yearly can take place. However, Hellström *et al.* (2008)[12] suggest that no more than one anaerobic digester at a time is taken out of operation in order to maintain a sufficient hydraulic retention time in the system as a whole.

Mattsson och Stegberg[17, 18, 19, 20] suggested various measures to increase the capacity of the piping system. The narrowest sections with the greatest pressure losses were identified in the section between the point where anaerobic digesters 6 and 7 intersect, up to the point where the common biogas pipe for all the anaerobic digesters begins, see Figure 2 below; and from the common biogas pipe to the gas dome. It was suggested that a new biogas pipe should be drawn in parallel with the existing pipe and that the existing Ø 200 pipes be replaced with Ø 300 pipes; or a combination of these alternatives on one or several of the narrow sections. Installation of fans was also mentioned in the investigation as a possible alternative.

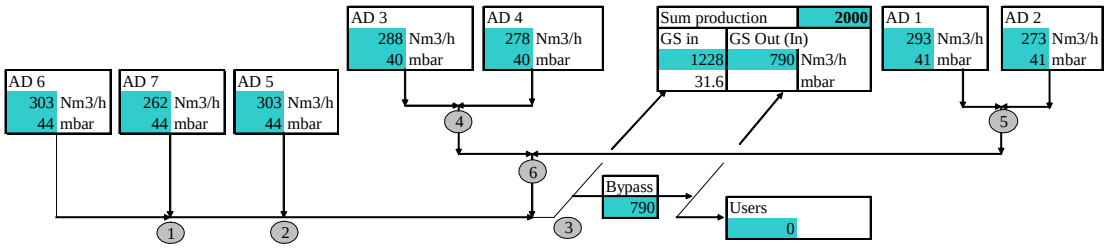

Figure 2. Flow schematic of the anaerobic digester system including the new bypass for the biogas dome, drawing by Stefan Mattson FVB Sverige AB. AD = Anaerobic Digester. GS = Gas Storage dome.

The solution that was finally chosen was the installation of a pipe Ø150 mm in parallel with the existing inlet and outlet biogas pipe of the gas dome with a dimension of Ø200 mm. The cost associated with this was approximately 12 000 EUR. The bypass pipe was taken into operation on 15 February 2007 and the pressure loss was immediately reduced by 2 mbar across the biogas dome. The capacity has thereby been increased from approximately 1700 Nm^3/h (40 800 Nm^3/d) to 2000 Nm^3/h (48 000 Nm^3/d). If the anaerobic digesters had been operated as a two-stage digestion process, calculations indicate that the corresponding increase in capacity would have been from 1600 Nm^3/h before 2007 to about 1800 Nm^3/h. Figure 3 shows a photo of the new parallel pipe that bypasses the biogas dome.

Figure 3. The new pipe bypassing the biogas dome, photo by Thorbjörn Rydén.

2.3.b. Heat exchangers

During quite some time, the heat exchangers at Henriksdal have not been able to heat the sludge in the anaerobic digesters to the desired set point temperature. Hellström *et al.* (2008)[12] show the temperature in the seven anaerobic digesters between 2000 and 2005. The temperature often declines below the set point temperature, particularly in winter (during melting of the snow) when the temperature in the anaerobic digesters can decline to below + 30ºC.

In March 2000, the Henriksdal WWTP started to receive fatty sludge from grease separators. An increase in biogas production was then obtained. In October 2001 the set point temperature in the anaerobic digesters was raised from + 35ºC to + 37ºC. This meant that a more optimal temperature for mesophilic digestion could be maintained. However, the capacity of the heat exchangers was still too low. The sludge flow also increased and the temperature declined more often far below the set point temperature of + 37ºC.

The Henriksdal WWTP was connected to district heating in November of 2007. After this, the gas boilers required less biogas to heat the anaerobic digesters. Instead, this amount of biogas could be made available for generation of electricity in the gas engines, or for production of biomethane in the upgrading plant. Two new parallel heat exchangers have been installed for each anaerobic digester. These heat exchangers were chosen for the purpose of managing to keep the temperature in the digesters at the set point value and having capacity enough to operate with the low feed temperature originating from district heating during summer. If anaerobic digesters can be maintained at the set point temperature, more biogas can be produced. A conservative assessment made by Hellström *et al.* (2008)[12] was that a 1ºC increase in temperature results in an increased biogas production in the anaerobic digesters of approximately 1 %. The average temperature in the anaerobic digesters was 35.5 ºC during the years 2000-2005.

During the period mid-January to the end of September 2008, the existing heat exchangers were replaced by new ones with a larger heat exchange surface and therefore higher capacity (Figure 4). The new heat exchangers can manage a smaller temperature difference between the sludge and the feed water. This is important since the feed water from the district heating system has a lower temperature than the water from the heating boilers. The feed water temperature may decline to + 60 ºC, usually during summer. The anaerobic digesters were shut off one at a time to replace the heat exchangers, but did not have to be emptied. Since the replacement, the temperature has remained at its set point value + 37ºC even though the outer temperature has occasionally dropped to -11ºC (January 5, 2009). A conservative estimate is that the biogas production has increased by approximately 1.5 % since the new heat exchangers were installed. The total cost of replacing these was about 2.24 MEUR.

In October 2006, the heat requirement for the anaerobic digesters amounted to approximately 18 GWh/year according to Rystedt[22]. The heat effect requirement for the new heat exchangers was estimated to 4 MW or, if no more than one anaerobic digester is shut off at a time, 4.7 MW. Assuming that only district heating is used to heat the anaerobic digesters, all the biogas that is currently used in the gas engines and heating boilers is made available for the production of biomethane in the upgrading plant. During 2000-2005, this amounted to an average of 6.8 MNm^3 biogas/yr (gas engines), and about 590 000 Nm^3 biogas/yr (heating boilers). However, electricity production is lost, which equalled about 15 600 MWh/yr during 2000-2005.

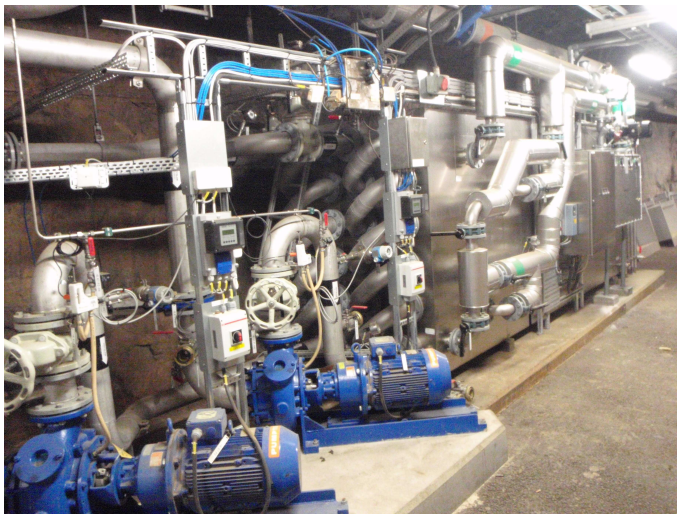

Figure 4. Two new tube heat exchangers installed in parallel below one of the anaerobic digesters, photo by Ulf Jansson, BYAK AB.

3. Stage 1 – Description of methods to increase biogas production during anaerobic digestion

In this chapter, a number of methods to increase the biogas production from anaerobic digestion are presented:

- methods that entail changes in existing plant operations
- methods that entail disintegration of the biomass to be digested
- methods that entail an additive to the anaerobic digestion stage

3.1. Methods to increase biogas production through changes in existing operations

This group includes five methods that involve some kind of change to existing operational procedures. For each method a general technical description; the operational experience and references; and required measures for the potential introduction of the method at Henriksdal are presented.

3.1.a. Increased production of primary sludge

3.1.a.i. General description

The primary sedimentation basins at Henriksdal have not been optimised with respect to precipitation and flocculation since the installation of the chemical treatment around 1970. Since primary sludge yields more than twice the biogas production than excess biological sludge does, the level of solids separation should be as high as possible in the primary sedimentation basins. At present, the dosage is 16 g Fe/m^3 wastewater, as ferrous sulphate heptahydrate ($FeSO_4 \cdot 7H_2O$). The iron is thus in divalent form, and aeration and dosage takes place simultaneously in the pre-aeration basins to oxidise a smaller part of the iron to Fe^{3+}. It is very likely that the efficiency of the separation process can be increased. However, the majority of the Fe^{2+} is oxidized to Fe^{3+} in the aeration tanks.

There are several methods available for precipitation of primary sludge:

1. *Addition of precipitation agents, such as iron- and aluminium based precipitation agents*

   By this method, suspended material, parts of dissolved organic compounds and a large part of the phosphorous content are all precipitated. The disadvantage is that too much of the phosphorous and possibly dissolved compounds may be precipitated, which in turn may cause a phosphorous deficit in the BOD reduction and/or a carbon deficit in the denitrification stage.

2. *Addition of precipitation agent in combination with polymer*

   By this method, the amount of precipitation agent can be decreased and thus be primarily directed towards precipitation of particular matter. The purpose of the polymer is to replace the precipitation agent and prevent too much of the phosphorous and dissolved compounds to precipitate. A greater amount of particular matter flocculates compared to the simple precipitation in 1.

3. *A combination of lower dosage of precipitation agents and low-molecular cationic polymer followed by a high-molecular anionic polymer.*

   This technique can be considered the most sophisticated. In this case, nearly all the particular and colloidal matter is precipitated and flocculated. Only relatively small amounts of dissolved material and phosphorous precipitate, and thus there will be no risk of a phosphorous or carbon deficit. However, the particular matter that otherwise is degraded to dissolved material in the beginning of the aeration tanks will not be available as a carbon source for the biological treatment.

3.1.a.ii. Experience

To simply increase the dosage of ferrous sulphate or of another metal salt will precipitate a large part of the phosphorous and an even greater amount of COD. This may cause problems in the subsequent nitrogen removal stage, both in the denitrification and aeration processes. Increased precipitation of dissolved COD may lead to a deficit of available carbon in the denitrification process, and precipitation of too much phosphorous may lead to problems with the biological treatment where phosphate phosphorous must be available for the growth of micro-organisms. Deficit of phosphate phosphorous often lead to a sludge with filamentous bacteria.

At the Bromma WWTP (which has a similar precipitation process as Henriksdal), full scale trials have been carried out that indicate that the precipitation process may be improved significantly through a change of precipitation agents.[34] The trials were performed during a period of one month with the addition of PIX-111. Compared with the period before the trial, the withdrawal of primary sludge was increased by approximately 3 tonnes DS/d (from about 16 to 19 tonnes DS/d). However, during this time, the Bromma WWTP received a high organic load from a large brewery. This means that the results are not directly applicable to Henriksdal.

The triple dosage method is being used at several wastewater treatment plants. First, a trivalent metal salt is added, e.g., polyaluminium chloride, which pre-coagulates colloidal matter and also precipitates part of the phosphorous. Then, a smaller amount of low molecular cationic polymer is added, followed finally by a high molecular anionic polymer. The formed flocks turn out compact, and the sedimentation process thus improves. The DS concentration in the separated sludge is usually higher, and the amount of sludge increases.

3.1.a.iii. Required measures at the Henriksdal WWTP

The measures for increased primary sludge production through optimising the addition of precipitation chemicals do not require an extensive overhaul and consist of retrofitting or extending the chemical dosage equipment. A change of precipitation agents will lead to an estimated decrease in dosage from 16 to 10 g Fe/m^3 wastewater since this includes a change from the current precipitation agent with divalent iron to an agent with trivalent iron. This will increase the reduction of particulate matter and the precipitation of phosphorous will also increase dramatically. In addition, dissolved organic compounds might precipitate to smaller or greater extent.

If the precipitation chemical is combined with a polymer, more particular matter flocculates, however, not to the extent that can be achieved by triple dosage. Consequently, the increase in biogas production cannot be expected to be as large.

Using a triple dosage with ferric chloride (trivalent iron) and two polymers, the dosage of ferric chloride can be further decreased from the current 16 g Fe/m^3 to 6 g Fe/m^3 wastewater. The dosages are estimated to be:

Ferric chloride (13.7 % Cl)	30 ml (6 g Fe)/ m^3 wastewater
Polymer 1	2 ml/ m^3 wastewater
Polymer 2	0.2 g/m^3 wastewater

This will maximise the precipitation of particulate matter, while precipitation of phosphorous decreases compared with usage of metal salt only. If the amount of primary sludge (VS) increases by 20 %, an estimated increase in energy of about 20 000 kWh/d (based on 0.343 Nm^3 methane/kg VS_{in}) will be produced in the form of biogas. Additional large cost reductions will result in other parts of the wastewater treatment plant as the air consumption and amount of excess biological sludge will be reduced.

Reduced amounts of BOD and phosphorous will naturally be the result even if only ferric chloride is used. The reduction of suspended solids, biologically degradable COD, and total COD today are 59 %, 47 %, and 48 %, respectively, in the primary sedimentation basins.

3.1.b. Increasing hydraulic retention time

3.1.b.i. General description

There are two different retention times that are of interest, SRT (solids retention time) and HRT (hydraulic retention time).

SRT is the average time the biomass and other solid material spend in an anaerobic reactor (digester). This time period is of significance to the growth of the micro-organisms in the anaerobic digester and it is important that the SRT is long enough to ensure sufficient bacteria growth.

HRT is defined as digester volume divided by volume flow fed to the reactor, i.e., the time that the liquid spends in the reactor. In an ideal continual CSTR (completely stirred tank reactor) process, SRT = HRT. In continual CSTR processes it is generally assumed that 95 % of the material in the reactor has been exchanged after 3 retention times.

To ensure bacteria growth, it is important that the material remain for a sufficient time in the anaerobic digester to allow for the micro-organisms to grow and multiply. Different organisms have different multiplying times, and methane-producing micro-organisms are those that grow the slowest.

Increased retention time allows the degradation in the anaerobic digester to proceed for a longer period and in this way increase the biogas production. The longer the original retention time, the smaller the relative increase due to prolonged retention time will be.

The most obvious way to increase sludge retention time in an anaerobic digester is to thicken the sludge through pre-dewatering, which results in a reduced sludge flow. However, thickening may lead to great pressure loss during the pumping of sludge. The concentration of DS to which the sludge can be thickened is limited primarily by practical concerns, such as difficulties during pumping and mixing, and is approximately 5-7 % DS for excess biological sludge. Primary sludge can often be thickened to a very high concentration of DS through mechanical dewatering. Also in this case the handling is limited by practical aspects, such as design of the pumping system. A generally accepted practical "limit" is usually 5-6 % DS, but higher DS concentrations do exist.

3.1.b.ii. Experience

The experiences of thickening sludge through pre-dewatering are generally good. As the digester volumes at many older plants are very generous (low load systems) and the retention times are already very long, it is usually not longer retention times that is the purpose but rather savings in the cost of heating. This is currently where the greatest savings can be made through sludge thickening. Naturally, a reduced sludge flow is also advantageous for the dimensioning and operation of subsequent stages (result in smaller systems and lower operational costs).

Due to the increased demand for biogas and generally increased energy costs, sludge thickening has been brought to the fore at many wastewater treatment plants in recent years, not least in the larger plants:

- At the Rya WWTP in the city of Gothenburg, new mechanical pre-dewatering equipment (belt thickener) was installed for extensive thickening of the entire sludge flow
- At the Gässlösa WWTP in the city of Borås, there is the same type of installation as in Gothenburg.
- At the Käppala WWTP on Lidingö (greater Stockholm area) excess biological sludge is thickened in centrifuges, and primary sludge is withdrawn directly from the primary sludge hoppers at 7-9 % DS.
- At the Sjölunda WWTP in Malmö, pre-dewatering equipment is being installed.

Experiences are generally very satisfactory, with few operational problems, and the staff at most plants are very pleased with the results. Investment costs are relatively low and generate proportionally large savings in energy.

Figure 5 illustrates how the DS concentration of the sludge affects the heat requirement for the anaerobic digesters.

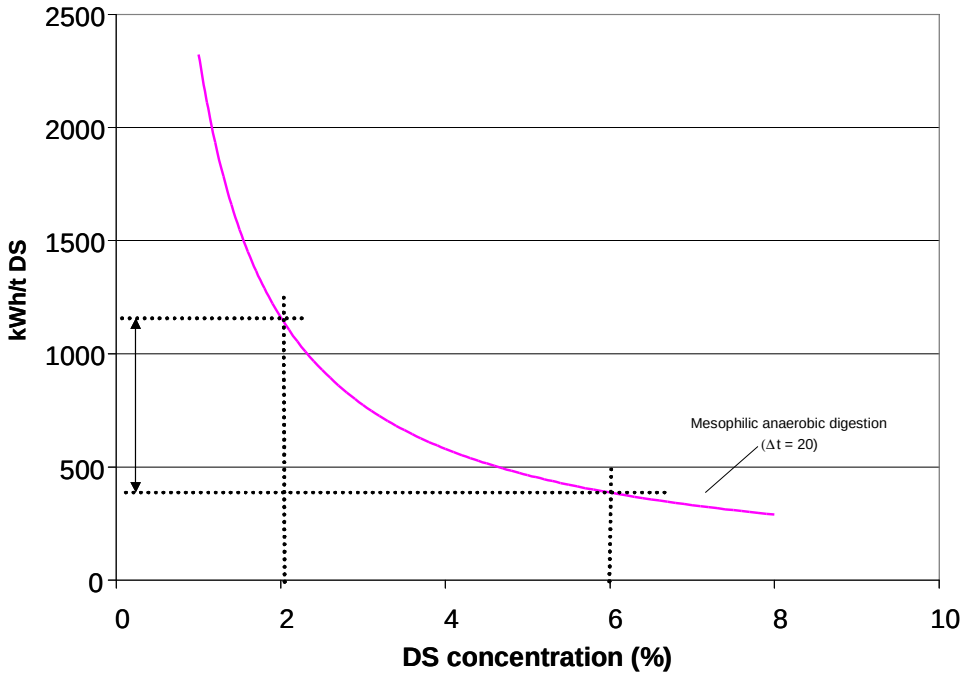

Figure 5. Heat requirement for the anaerobic digesters as function of the DS concentration in the sludge. The figure shows that the heat savings amount to 800 kWh/tonne if the sludge is thickened from 2 % to 6 % DS.

3.1.b.iii. Required measures at the Henriksdal WWTP

At Henriksdal, tracer studies have shown that the mixing in the anaerobic digesters is very good and it is assumed that the anaerobic digesters are completely stirred. Therefore, it has been assessed that no measures are required in this area. Retention times are relatively long, approximately 20 d, and the effect of prolonging the retention time is relatively limited. According to the previous Biogasmax project report[12], an increase in retention time from 20 to 30 days would yield an increase in biogas production of about 4 %.

As mentioned earlier, excess biological sludge at Henriksdal is pre-thickened in centrifuges prior to anaerobic digestion, and further thickening to higher concentrations of DS than the current 4-6 % DS is, based on experience, difficult in practice. However, trials with mechanical treatment (knives "cutting" the sludge) of the sludge indicated that the DS concentration could be increased by one percent without the viscosity (pumpability) deteriorating compared to non-treated sludge.[33]

For primary sludge though, there is a possibility to raise the DS concentration to increase the retention time. In this area, Stockholm Vatten plans to review the primary sludge withdrawal and reconstruct the primary sedimentation basins to allow for withdrawal of primary sludge of a higher DS concentration. Tests will be run with a new mixer for thickening in one of the primary sludge hoppers and a new pump will be installed close to its basin. It is believed that this will raise the DS concentration from 3.6 % to 5 % DS. If the result proves satisfactory, all the basins will be retrofitted in this way.

The DS concentration of the sludge could also be increased through mechanical thickening. In addition to potential problems with the pumping of sludge at very high DS concentrations, there is also a potential problem in terms of available space. In addition, the installation of mechanical thickeners in rock and long pumping distances may prove to be challenging. The equipment is compact and strictly in terms of space it is probably possible to find a place for it. The primary difficulty is likely to be in the area of ventilation. For reasons of odour control, the ventilation must be very carefully designed, and achieving a satisfactory solution at a reasonable cost will most likely be complicated.

Further mechanical thickening of primary sludge from such a high DS concentration as 5 % is significantly more complicated than treating unthickened sludge, since the feeding of the sludge and the polymer addition are considerably more difficult and require special design. Our assessment is therefore that the thickening of the primary sludge in the primary sedimentation basins according to the description above is the most cost effective way to thicken the sludge and therefore only this alternative is investigated further henceforth.

A significant, indirect effect from thickening is that available anaerobic digester volume increases. In the above mentioned case with thickening of primary sludge to 5 % DS the available digester volume is expected to increase by a total of 8 500 m^3. Instead of using this volume to increase retention time, it can be utilised to receive more EOM.

The energy consumption for anaerobic digester mixing may increase somewhat as the sludge is thickened. The assessment of such effects has not been made in this study.

3.1.c. Thermophilic digestion

3.1.c.i. General description

In thermophilic digestion, the temperature in the anaerobic digester is maintained between +50 and +55°C. The growth rate of the micro-organisms is higher in thermophilic reactors than in mesophilic reactors, which means that the rate of degradation increases. The substrate does not have to spend as much time in the anaerobic digester in thermophilic digestion compared with mesophilic digestion. Operation at a higher temperature thus leads to a shorter retention time compared with mesophilic conditions.

Aside from degradation of organic material, thermophilic digestion also leads to a change in the bacterial composition. The microbial flora in thermophilic and mesophilic processes differ. In mesophilic cultures, the microbial flora is more diverse than in thermophilic cultures, i.e., at higher temperatures there are fewer types of micro-organisms[16]. For example, salmonella bacteria are eliminated very efficiently during thermophilic digestion, but to a much lesser degree in a mesophilic process. Thus, the thermophilic process accomplishes an efficient hygienisation[24]. In addition, the viscosity of the material in the anaerobic digester decreases, and the process can thus be operated at a higher DS concentration.

Thermophilic digestion is more sensitive to disturbances, such as temperature differences and certain chemical compounds that may interfere with the process.

The dewaterability of the sludge changes after thermophilic digestion. However, the direction in which this change occurs cannot be predicted. Both improved and deteriorated dewaterability have been reported from plants that have increased the digestion temperature.

Different opinions also prevail regarding the effect of temperature on biogas production. Experience has shown that when changing from mesophilic to thermophilic conditions with unchanged retention time, the degree of degradation and the biogas production increase in certain cases, but not in others. There is no complete explanation for this yet. If the temperature is raised to a thermophilic level in an anaerobic digester where the load is very high or the retention time is short, the biogas production normally increases, since the degradation process becomes more efficient.

In the thermophilic temperature span, the load on the anaerobic digester can normally be approximately 4 kg VS/m^3 digester volume and the retention time about 15 days.

3.1.c.ii. Experience

Experience of anaerobic digester constructions made of concrete has shown that an increase in digestion temperature usually is possible without risk for crack formation or other problems.

In several cases, the increase in anaerobic digester temperature from mesophilic to thermophilic operation has been carried out in full scale as well as in pilot and laboratory scale, with good results. The temperature has then been raised approximately 0.5°C or less per day, without problems and without interruptions of the inlet flow. For instance, at the WWTP in the city of Lund, the temperature has been raised to a thermophilic level during 6 months, without incidents. No investigations of the constructions were conducted. In a high load anaerobic digester, the concentration of organic acids may temporarily be very high, which may cause some difficulty during the recovery of the anaerobic digester. The load on the anaerobic digesters at Henriksdal is currently very low, which means that a transition from a mesophilic to thermophilic process can be expected to be uneventful.

Since the sludge would be heated to a higher temperature, the risk of odour problems increases when the digested sludge comes in contact with the surroundings. After passing the anaerobic digesters, the digested sludge releases methane, in sludge holding tanks and at the dewatering stage. A potential conversion to a thermophilic process will require an extension of the heat recovery from the digested sludge, not only due to the increased heating demand but also to reduce (the risk of) methane release from the sludge.

3.1.c.iii. Required measures at the Henriksdal WWTP

There are several reasons why thermophilic digestion may be interesting at Henriksdal:

- Faster degradation of the organic material takes place, which means that the load on the anaerobic digesters can be increased.
- Digester volume is made available through a higher rate of degradation, and may be utilised to increase the amount of EOM to the anaerobic digesters.
- Thermophilic temperatures may in certain cases lead to an increased degree of degradation, which in turn results in a higher biogas production and decreased amounts of sludge.
- Hygienisation of sludge and organic material is achieved.

The existing heating system for the anaerobic digesters is currently not designed for thermophilic operation. A thorough analysis of the capacity of all system parts is required to assess the possibility to carry out a conversion. The following should be considered:

- Is there enough capacity
  - In the existing heat exchangers?
  - In the district heating pipe and sub-sections; external and internal feed?
- How should the heating be achieved?
- Is the existing equipment compatible with the elevated temperature?
- Is the capacity of the biogas system sufficient for a potential increase in the biogas production?
- How and when will the conversion to the higher temperature occur?
- How should the process be run to meet potential requirements for hygienisation?

District heating is currently used to heat the digester sludge. During summer, the feed temperature decreases to approximately +60°C, which is insufficient to heat the sludge to the required +55°C. Therefore, the system would require an additional amount of heat from the boilers during several months each year, i.e., a part of the produced biogas would be utilised for the heating.

By pre-heating the sludge, the amount of energy required to heat the sludge to optimal thermophilic temperature will not be greater than at the normal mesophilic operation, and the existing circulating heat exchangers may be used. (However, the exergy consumption is increased as biogas is required for the heating). It should be noted that the comparison is not quite accurate since pre-heating of the sludge does not take place at the current mesophilic operation. However, at thermophilic temperatures, heat recovery is more important since the energy consumption otherwise becomes too high and for this reason the comparison can still be considered relevant. To pre-heat sludge, existing heat exchangers need to be extended by additional heat exchangers (of sludge/water/sludge type) that pre-heat incoming sludge to the anaerobic digesters with exiting sludge. At installations of sludge/water/sludge heat exchangers, the heat of the exiting sludge is utilised, by which the sludge is cooled by about +20 to +25°C, i.e., from +55°C to +30°C or +35°C. However, pre-heating the sludge can often be very problematic with thick deposits on the heat exchanger surfaces and difficulties to pump the primary sludge through the heat exchangers, particularly at elevated temperatures and DS concentrations. For these reasons, pre-heating is avoided at many plants today.

Potential additional heat exchangers require space that is currently not available at Henriksdal but that space must somehow be made. Today, the existing space for the heat exchangers is already very limited, and to prepare more space through blasting or splitting near the area of the existing anaerobic digesters is assessed to be very complicated. A possible alternative could be to place the heat exchangers elsewhere in the rock, but this would require extensive piping. The heat in the digested sludge is currently utilised to heat the ventilating air. If sludge pre-heating was chosen, a completely different solution for heating the plant would have to be found.

The Swedish Environmental Agency's proposed regulation on sludge treatment[1] includes requirements for sludge hygienisation. The proposed regulation specifies for instance a 6 h retention time when no material are added to or removed from the reactor. Final requirements are not yet determined.

If a conversion to thermophilic digestion is carried out, retention time is estimated to be reduced to about 15 days, and the "released" digester volume becomes approximately 9 800 m^3.

3.1.d. Conversion to serial operation

3.1.d.i. General description

A pair of anaerobic digesters can be operated in mainly two ways, in parallel or in series. In parallel operation, anaerobic digesters are operated completely independently of each other, and the retention time should be at least 18 days for a mesophilic process and 15 days for a thermophilic process. Shorter retention times are possible, but there may then be greater risk of process disruption.

During operation in series, the anaerobic digesters are used one after the other, in turn. In this case, digester operations depend on one another. If both anaerobic digesters have approximately the same volume, the total retention time should also be about 18 days for a mesophilic process. This means that the retention time in the first anaerobic digester is about 9 days, which may seem a very short time. It has been shown that about 70-75 % of the degradation takes place in stage 1 and the remainder in stage 2. The total result is a higher biogas production and a higher VS reduction since the anaerobic digestion has been split in two volumes and a longer retention time (SRT) is therefore accomplished for all the sludge particles. There is, however, a great risk of overload in stage 1. Many of the anaerobic digesters that were built at small and medium sized wastewater treatment plants were – and are still – operated in series where the anaerobic digesters have the same volume. However, it is not a disadvantage if the first stage in a serial system is of a slightly larger volume (proportion 60:40).

If the digester system instead is operated with the first volume corresponding to 3-4 days retention time and the other anaerobic digesters afterwards are run in parallel, a system with pre-hydrolysis is obtained. During the first stage, only hydrolysis and acidification takes place, while the formation of methane occurs in the second stage without being limited by the rate of hydrolysis.

If a smaller anaerobic digester is instead placed *after* the other anaerobic digesters, so-called post-digestion will result. In this way, about 5-10 % of the biogas is formed here and the methane emissions to the atmosphere will be reduced if this biogas is collected.

3.1.d.ii. Experience

The supplier AnoxKaldnes AB has evaluated serial anaerobic digesters in the towns of Helsingborg and Klippan. Both plants were evaluated with respect to load for the purpose of establishing whether it is possible to introduce food waste together with the sludge. Results showed that it was possible to increase the load on the first anaerobic digester to over 8 kg DS/(m^3·d), with a retention time of 7-8 days. The explanation for the surprising results is probably that the hydrolysis stage – and not the methane forming stage – is the rate-determining stage. Therefore, the concentration of organic acids is not increased significantly.

If a pretreatment method that increases the rate of hydrolysis is introduced, such as the addition of enzymes or mechanical treatment, there is a risk of overload of the methane stage in the first anaerobic digester. It is then not the hydrolysis stage that is rate-determining, but the methane stage. If the methane forming bacteria are not able to produce methane from the organic acids at a sufficient rate, there is a risk of acidification of the anaerobic digester.

Experience from trials at the Helsingborg WWTP showed that a system with a three day retention time followed by an anaerobic digester with a retention time of 9-10 days functions almost as well as two stages with 10 days retention time each.

3.1.d.iii. Required measures at the Henriksdal WWTP

Today, the seven anaerobic digesters are operated in parallel, see Figure 6.

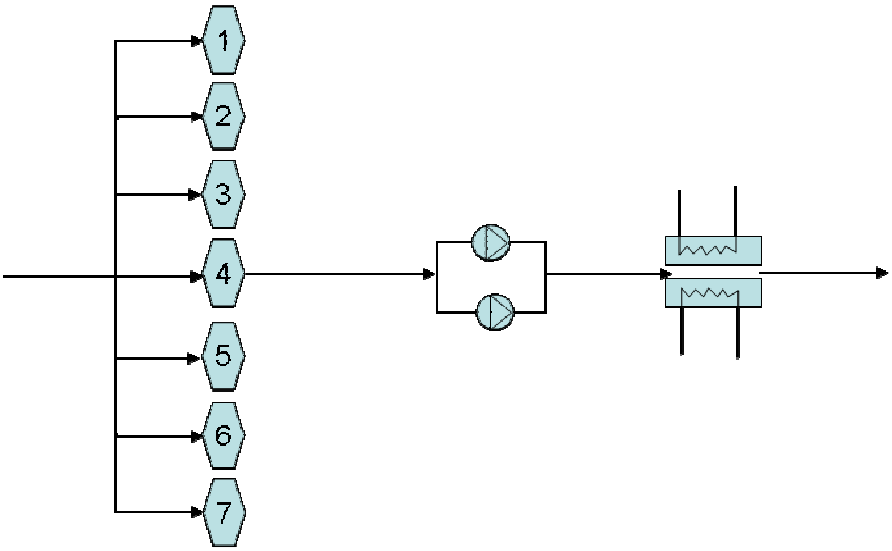

Figure 6. Schematic of the anaerobic digester process at Henriksdal showing the current parallel operation. From left to right; the seven anaerobic digesters, two parallel connected pumps and a heat exchanger.

The most usual type of serial operation is two anaerobic digesters connected in series. At Henriksdal this would mean four anaerobic digesters in stage 1 and three anaerobic digesters in stage 2, or vice versa. However, an installation with three anaerobic digesters in stage 1 requires significantly larger heat exchangers than existing equipment since almost the entire amount of heat is added to the anaerobic digesters in stage 1. There is no room for larger heat exchangers in existing areas, and more rock would have to be blasted. The rock in this area is generally of poor quality and it is uncertain whether it is practically feasible to increase the space.

An alternate solution would be that anaerobic digesters no. 4-7 are used as the first stage and digesters no. 1-3 as a second stage in the serial process (see Figure 7). The volume in the first stage would then be about 23 300 m^3 and the volume in the second stage about 15 200 m^3. More than 60 % of the total volume is thus involved in the first stage. The retention times are 12.2 and 7.9 days, respectively, for the two stages. Our assessment is that a large first stage is only advantageous and reduces the risk of acidification if a pretreatment method is introduced (so that the rate of hydrolysis is increased). The existing heat exchangers have a relatively large excess capacity and if the primary sludge is thickened, the heat exchanger capacity may be sufficient. Alternatively, the excess biological sludge may be fed directly to stage 2 to offload the heat exchangers connected to anaerobic digesters 4-7.

Earlier estimates for a conversion to serial operation at Henriksdal indicate an increase in biogas production of up to 7 % while keeping the current retention time[12]. However, in conclusion, our estimate is that a conversion to serial operation would result in an increase in the biogas production by 8-10 %, based on the experience from the AnoxKaldnes evaluation of the serial operation at Helsingborg and Klippan.

Digested sludge is currently exited from the anaerobic digester by gravimetric flow (i.e., overflows at the anaerobic digester top and is collected in a common sludge pipe). During winter the heat content of the sludge is utilised to heat the plant interior through heat exchange with incoming air. Two pumps are therefore installed to feed the sludge through the heat exchangers. These pumps are in operation during the winter months.

Switching to serial operation of the anaerobic digesters, the pumps could still be utilised for pumping the sludge from anaerobic digesters 4-7 to anaerobic digesters 1-3, see figure 7. Thus the system requires additional pumps and piping to and from anaerobic digesters 1-3 (stage 2). To evacuate the sludge from anaerobic digesters 1-3, new pumps are required for each anaerobic digester.

In terms of detailed design, there are several alternate solutions for the implementation of this version of serial operation, for instance specific locations for inlet and outlet flow. This report describes only schematically how the stages are constructed. Details shall be worked out later, if the method proves interesting for Henriksdal.

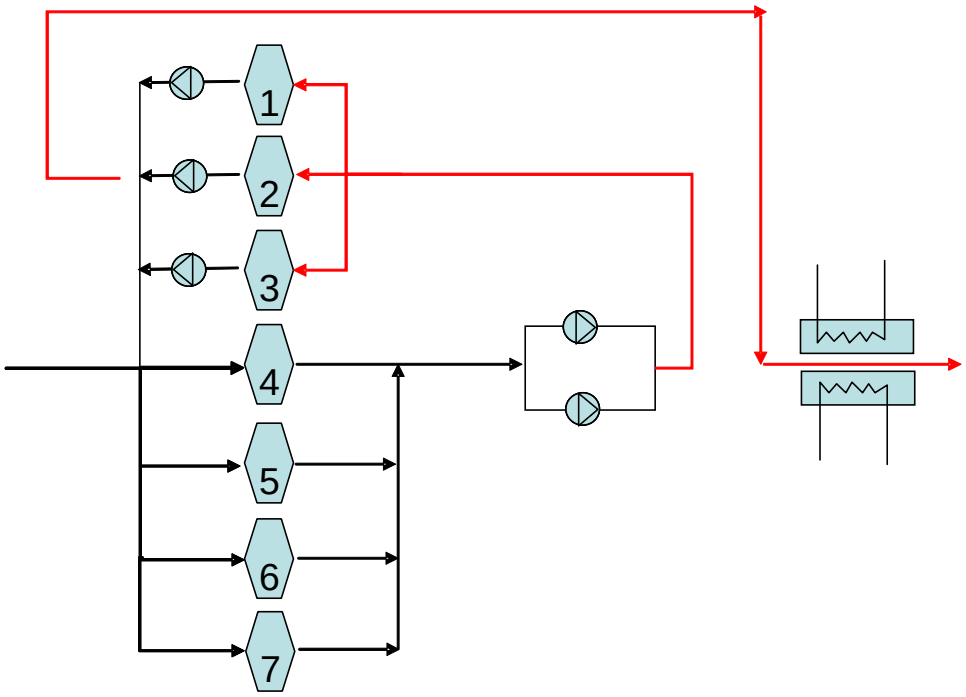

Figure 7. Switching to serial operation, with anaerobic digesters 4-7 as stage 1 and anaerobic digesters 1-3 as stage 2.

The piping is placed in the existing path to the current pump room for heat exchange (see Figure 8).The pumps for evacuation from anaerobic digesters 1, 2 and 3 should be mounted very near each anaerobic digester.

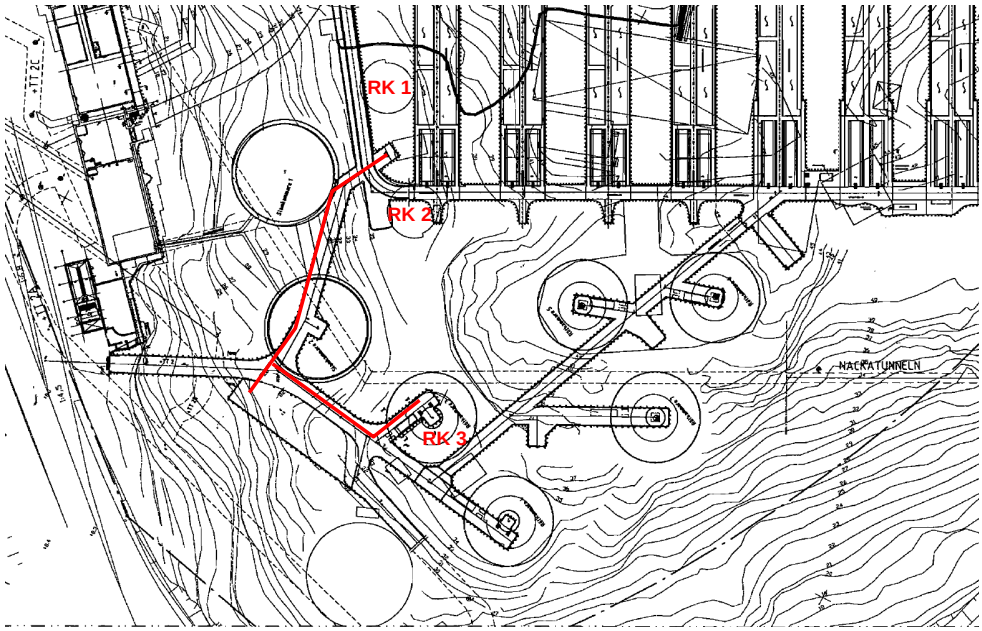

Figure 8. Overview of anaerobic digester location and new pipeline for conversion to serial operation.

As a special case of serial operation, it is possible – as mentioned above – to consider some kind of pre-hydrolysis, i.e., very short retention time in the first stage.

In combination with thickening the primary sludge, this alternative utilises one of the anaerobic digesters as a hydrolysis stage (in the calculations anaerobic digester 1, volume approximately 5 100 m^3) prior to feeding the sludge to the other six anaerobic digesters (2-7), which are operated in parallel as today. The maximum available volume in the anaerobic digesters will then be 33 400 m^3 and the sludge flow about 1 500 m^3/day. The hydrolysis in itself is not estimated to result in an increased biogas production. However, the reaction rates in the digester

process will increase when the sludge is hydrolysed and therefore the retention time can be shortened and space is made available in the anaerobic digesters. If the retention time is set to 17.0 days in the anaerobic digesters, a volume of about 8000 m^3 is created. The retention time in the hydrolysis stage will then be 3.4 days.

This alternative in itself will probably not result in a great increase in biogas production, but the volume made available can be utilised for large amounts of EOM and therefore increase the biogas production. However, it should be noted that in this case the entire sludge flow is heated to +37 °C prior to the hydrolysis stage, which will cause problems in terms of the heat exchanger capacity.

3.1.e. Collection of biogas from existing sludge tanks

3.1.e.i. General description

This method entails that the digested material is stored in some kind of gas tight tank that is used for the collection of the biogas. The tank, which should be insulated, does not require heating and the post-digestion can take place at the resulting temperature that is obtained, about +30°C.

3.1.e.ii. Experience

There are examples that indicate that 5-10 % of the biogas production takes place in the post digestion stage. For example, plant managers at the waste company Nordvästra Skånes Renhållning AB's co-digestion plant for organic waste fractions in Helsingborg estimate that approximately 10 % av the produced biogas comes from the post-digestion stage. Digestion tests on sludge from the Öresund WWTP in Helsingborg indicate about 5 % biogas production during post-digestion. The proportion depends on the retention time in the anaerobic digester. If the sludge is well digested (degraded), the proportion will not be as large.

During the period 2007-2008, the consulting firm Sweco Environment conducted an investigation monitoring the methane leakage from the holding tanks for digested sludge at Henriksdal.[31] The investigation showed that the estimated leakage of methane amounted to about 4.5 % of the total methane production at Henriksdal (about 210 tonnes per year). Sweco believes that this result underestimates the real value since the methane concentrations periodically exceeded the measurement limit of the monitoring equipment. The investigation showed a clear relation between the amount of sludge in the holding tanks and the methane concentration, and therefore the size of the leakage. An estimate of the methane leakage for continually completely filled holding tanks of 5000 m^3 was made, and the total emission of methane was calculated to be 596 tonnes per year, which is more than 10 % of the total methane production.[31]

The post digestion stage is particularly important when the load on the anaerobic digesters is high and the concentration of organic acids is about 500-1 000 mg/l. A reduction of acids may then occur in the tanks.

The post digestion tank can also be heated to the same temperature as the anaerobic digesters, possibly then converting a part of the sludge to biogas. If the temperature is allowed to decrease in the post digestion tank, the production of biogas decreases, and the biogas that is released consists mainly of dissolved gas.

3.1.e.iii. Required measures at the Henriksdal WWTP

Post-digestion could be accomplished through reconstruction of existing holding tanks for digested sludge and collection of the biogas. According to measurements at Henriksdal there is today a methane leakage of about 10 %[31].

3.2. Methods for increased biogas production through disintegration of biomass

Organic compounds can be degraded to smaller compounds and become more easily degradable, and thereby the biogas production may be increased. The availability of the particles for degradation depends on the particle surface area exposed. Disintegrating larger particles to smaller ones increases the exposed surface area and thus also the rate of hydrolysis. In addition, if the cell membrane is destroyed, the cell content is made available for degradation. There are several methods to disintegrate biomass. The most common ones are presented in this chapter.

3.2.a. Mechanical treatment of sludge

3.2.a.i. General description

Mechanical treatment of sludge means that sludge is treated mechanically so that cell membranes break and intra cellular material dissolves. The treatment also disintegrates filamentous bacteria, which means that the risk of potential foaming problems appears to decrease[13]. The effects in terms of increased degree of degradation and increased biogas production are also obtained. Studies have shown an increase in biogas production in the order of magnitude of 10 %[28]. Mechanical treatment can be accomplished by different disintegrating equipment such as mills and high pressure homogenisers.

A high pressure homogeniser consists of a high pressure pump in combination with a homogenising valve. The high pressure pump exposes the sludge to a pressure of several hundred bars, which forms cavitation bubbles (gas bubbles). The pressure suddenly drops in the valve, which causes the cavitation bubbles to collapse. When this occurs, high temperature and strong forces are created, which in turn tear apart particles and cells. The principle is the same as in ultrasound treatment (see Chapter 3.2.h.).

Other ways to mechanically treat sludge include milling or treatment with rotating knives.

A type of disintegration equipment, that is relatively new in sludge applications, has been installed in full scale at several Swedish wastewater treatment plants (e.g., Käppala WWTP in Lidingö and the Himmerfjärd plant in Södertälje). The equipment originates in the pulp and paper industry, where it is used to disintegrate recycled paper.

Figure 9. Disintegration equipment. To the right, the mill casing has been opened (Jönköping biogas plant).

Today, the technique is applied on waste fractions such as screening solids and food waste, which are disintegrated prior to anaerobic digestion. The material is fed to the centre of the mill casing and is there forced outward between the grinding plates. The material can be recirculated several times through the machine and very small particle sizes can be obtained (<1 mm).

3.2.a.ii. Experience

In a Masters' thesis by Anna Åkerlund[33], a method to disintegrate excess biological sludge from the Henriksdal WWTP was evaluated, which comprised rotating knives in a centrifuge for sludge dewatering. The result showed that the degree of disintegration for a centrifuge equipped with disintegrated knives was on the average 1.6 % for EBS with DS concentrations between 6 and 7 %. This should be compared with an average degree of disintegration of about 0.4 % from a centrifuge without knives or other disintegration equipment. In the study, the treatment also showed a positive effect on the viscosity and pumpability of the EBS. While no increase in specific methane potential could be detected, the rate of degradation in the EBS increased somewhat. The effect on biogas production was marginal. Certain gains in energy could possibly be obtained as the study showed that the decrease in heat requirement was larger than the increase in required electricity consumption.

The report states that high pressure homogenisation theoretically is the most efficient mechanical technique for pretreatment of sludge[5, 13], but in practice, the method is actually not implemented much.

At the Käppala WWTP, a German pilot plant for high pressure homogenisation was installed in 2005 for the purpose of treating excess biological sludge. However, the plant suffered from many operational problems and did not deliver the desired results[35].

Regarding the specific disintegration technique, laboratory trials have been carried out at JTI (the Swedish Institute of Agricultural and Environmental Engineering in Uppsala, Sweden) entailing the anaerobic digestion of untreated and treated sludge (i.e., sludge that has passed a disintegration machine). The biogas production increased by 33 % for disintegrated excess biological sludge, while the primary sludge was not notably affected[29]. In full scale tests at Käppala WWTP sludge viscosity appeared to change during treatment and result in a more easily pumped sludge. A new smaller machine is studied at present but results are not yet available[35].

3.2.a.iii. Required measures at the Henriksdal WWTP

At the Henriksdal WWTP, the intake section for the wastewater will be moved to a different location. In connection with this change, equipment for disintegration will be installed for the treatment of screening solids, similar to the installation at the Käppala WWTP. Potential disintegration of sludge is, based on the results above, only interesting for excess biological sludge. The capacity of the disintegrating machine equipment is very large and assessed to be sufficient for both sludge and screening solids. The pumping of sludge to and from the disintegrating equipment is the more difficult issue. The pumping may be challenging due to the high viscosity of the thickened sludge and to the greater pumping distances.

It can be expected that the biogas production will increase. Based on the results from Käppala WWTP, an approximate 30 % biogas increase from the excess biological sludge could be expected, which means about 3.5 % biogas increase in total.

3.2.b. Thermal and chemical treatment of sludge

Sludge can be pre-treated thermally through treatment at high temperature:

- Pasteurisation, temperatures up to 100°C
- Thermal hydrolysis, temperatures up to 200°C

Trials have indicated that biogas production increases by about 10 % after treatment at temperatures above approximately 60°C. Degradation of hydrophobic structures require about 70°C.[28] During heating of the sludge to 160-180°C, organic compounds, primarily proteins and starch are degraded to organic acids. The cells in the sludge burst and the energy-rich organic material is dissolved. This extends the degree of degradation of sludge and higher biogas production is thereby obtained. Since the cells have burst, the dewaterability of the sludge is improved and DS concentrations of about 40 % can be reached by centrifuge.[10]

Thermal treatment often results in fewer problems with foaming in the anaerobic digester, decreased sludge production, increased biogas production and most likely improved sludge dewatering. Through treatment at high temperature, sludge is also hygienised[5]. The reason for decreased foaming is that both filamentous and hydrophobic structures are degraded. During degradation of filamentous structures, intra-cellular material dissolves, which leads to an increased biogas production.

Similar effects can also be obtained by the addition of chemicals, so called chemical hydrolysis. Also in this case, the cell walls are destroyed and the cellular content released.

3.2.c. Pasteurisation

3.2.c.i. General description

Pasteurisation is a type of heat treatment that involves heating to 70°C during 1 h. Micro-organisms that cause illness, pathogens, are eliminated to such a degree that the material is considered hygienised, which is usually the primary purpose of the treatment.

3.2.c.ii. Experience

Pasteurisation is a well established method and is common in certain areas, such as the food and beverage industry. For sewage sludge, legal requirements for hygienisation are expected eventually, but not necessarily by method of pasteurisation.

Many anaerobic digestion plants for organic waste are equipped with a pasteurisation stage for incoming material, sometimes in combination with thermophilic digestion. The incoming slurry of waste is fed to insulated tanks with a retention time of 1 h. Heating often takes place by steam. To fit this batch process into the

continuous digestion process, 3 consecutively operated tanks are usually used, where one tank is filled, one is treated and one is emptied simultaneously. Figure 10 shows the pasteurisation tanks at the Uppsala biogas plant.

Figure 10. Pasteurisation tanks at the Uppsala biogas plant.

The heat treatment always takes place before the digestion stage, since a pasteurised sludge becomes relatively "dead" and therefore vulnerable to pathogens that can grow in an uninhibited manner without the competition of other bacteria cultures. The sludge therefore always needs stabilisation after heat treatment to ascertain a sufficient presence of benign bacteria.

The pasteurisation process reduces the viscosity of the sludge and it is reasonable to expect positive effects on the subsequent pumping and mixing. These effects have been observed in the majority of digestion plants for organic waste, e.g. the Uppsala biogas plant.

Regarding potential effects of heat treatment on the biogas production, the trials that have been carried out are considered insufficient as a basis for definite, general conclusions. Experiments made at KTH[28] indicated a 10 % biogas increase during anaerobic digestion of heat treated excess biological sludge. AnoxKaldnes AB has earlier also performed similar experiments on mixed sludge, but without detecting any significant increase of biogas. However, there are experiments that indicate a higher increase of the biogas production during anaerobic digestion of heat treated mixed sludge, up to 20 % increase compared with non-treated sludge. In some experiments that have been reported to lead to a higher biogas production, the sludge has been heated for approximately 2 days before anaerobic (thermophilic) digestion but these results are not completely comparable to those of the pasteurisation method.

3.2.c.iii. Required measures at the Henriksdal WWTP

Pasteurisation entails, as mentioned above, heating to 70°C during 1 h. The heat treatment can be accomplished in several ways, but all the methods require that a certain part of the produced biogas is used for the heating.

For practical reasons, direct heating using steam can be an advantageous alternative since the sludge does not have to pass any heat exchangers. To pasteurise the sludge at Henriksdal then requires the installation of a number of pasteurisation tanks, with a total volume of about 3 x 100 = 300 m^3, at current sludge flow. A biogas-fuelled steam boiler is installed and the steam contacts the sludge directly when passed through nozzles mounted at the bottom of the tanks. Pre-heating of the sludge can take place by district heating to minimise the steam requirement. From the tanks, the sludge is then pumped to the anaerobic digesters.

The sludge must be cooled to the current digestion temperature before entering the anaerobic digesters. Alternatively, the pasteurisation is accomplished by district heating throughout the entire year. During summer, additional heat will then be required from biogas-fuelled boilers to reach a sufficiently high temperature.

If the heat treatment aims to hygienise the sludge to meet future requirements, all the fractions that are fed to the anaerobic digester should be included, such as disintegrated screening solids and organic waste.

3.2.d. Thermal hydrolysis

3.2.d.i. General description

The most common commercial method for thermal hydrolysis of sludge is the CAMBI method. In addition to being exposed to high heat, the sludge is here also exposed to high pressure.

The main effects from thermal hydrolysis are:

- increased degree of degradation and thereby increased biogas production and reduced need for anaerobic digester volume
- reduced amounts of sludge through improved dewaterability and increased degree of degradation
- hygienisation

The CAMBI method includes heating the sludge to about 160-170°C under pressure (12 bar) using steam, in several reactor tanks. While the process in each reactor is a batch process, a number of reactors overlap in time to make the process as a whole continuous. The retention time is about 30 minutes. The pressure is then released gradually. Steam that is released is utilised to pre-heat the sludge. When the pressure reaches 2-3 bars, the sludge is finally released to a flashtank where the last amount of steam is boiled off. Extensive heat exchange takes place. The sludge, which is thickened to a large extent (about 14-16 % DS) is pre-heated in two tanks. In the first tank, the sludge is pre-heated to about 90°C by recycling steam from the flashtank. In the other tank, the sludge is heated further to about 130°C by recycling steam that is released from the reactor tanks during the reduction of the pressure. Finally, the temperature and pressure is raised to 160°C/12 bar through the addition of steam.

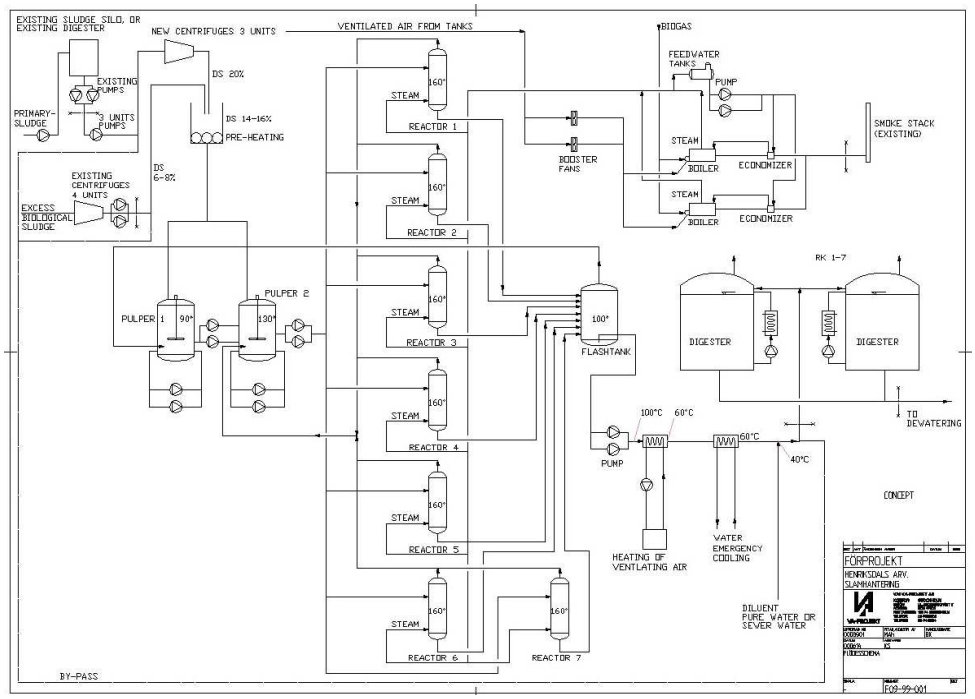

Figure 11. Flow schematic for thermal hydrolysis (from the Stockholm Vatten report no. 26, June 2000).

After the sludge has been hydrolysed, it is cooled and diluted before being pumped to the anaerobic digestion stage. Since the sludge is pre-hydrolysed, the anaerobic digestion time can be reduced without affecting the biogas production. The sludge also flows more easily and is more homogenous, which makes it possible to maintain a higher DS concentration. For a normal municipal activated sludge, the biogas production can be expected to be about 30 % greater than during conventional anaerobic digestion. In addition, the sludge is sterile as it has been heated to >120°C[10].

District heating cannot alone be utilised for thermal hydrolysis, since approximately 160°C is required and the feed water temperature normally only reaches about 95°C (maximum) during winter and may drop to around 60°C during summer. However, district heating can be utilised to pre-heat the sludge to approximately 35-50°C. Heating the sludge to higher temperatures require, as in the case of pasteurisation, primary heat from a carrier such as steam.

3.2.d.ii. Experience

Stockholm Vatten has earlier studied the possibilities to treat the sludge at the Henriksdal WWTP by thermal hydrolysis.[27]

In an additional sludge hydrolysis study[11], which was completed by Stockholm Vatten and the company Purac in 1999, hydrolysis tests on a laboratory scale were performed on sludge from Henriksdal. Sludge samples containing mixed sludge were sent to CAMBI in Norway for treatment where the sludge was heated to 165°C during 20 min and then cooled. The treated sludge was then sent to the CENOX laboratory in the city of Lund for anaerobic digestion. The degree of degradation was measured to be 65 %, which may have been slightly overestimated, but in any case was assessed to at least 60 %. The degradation of organic material increased by 45 %. Thus, the degree of degradation was considerably lower during the time of the test than during the reference period 2000 - 2005 used in this report. This led to an increase in the biogas production, according to Purac, between 30 and 40 %.[11] Theoretically, however, an increase in the degree of degradation of the organic material should give an increase in the gas production of the same magnitude.

Thermal hydrolysis has been implemented in full scale at the wastewater treatment plant in Hamar in Norway. The sludge is removed from the plant as a mixed sludge and thickened in a centrifuge to about 16 % DS before being treated in the hydrolysis plant. The retention time in the subsequent anaerobic digester is about 14 days. The degree of degradation has been 60 %, the biogas production about 550 l biogas/kg added organic substances (VS), and the methane concentration in the biogas about 65 % [11].

At the Aarhus wastewater treatment plant in Denmark, comparative trials with conventional anaerobic digestion were carried out in cooperation with CAMBI. The trials were carried out as continuous experiments during a relatively long time. Using sludge from wastewater treatment plants with primary sedimentation and subsequent nitrogen removal stages, an increase in the degree of degradation was obtained, from 45 % to 62 % based on COD. The biogas production increased by 22 % to 450 l biogas/kg added COD[11]. The increases in degree of degradation and in biogas production do not correlate. This is further discussed in an article by Sørensen *et al.*, published in the journal Vatten, 1999.[30]

3.2.d.iii. Effects on the processes at the Henriksdal WWTP

The effects of thermal hydrolysis on the different processes at the Henriksdal WWTP were investigated within a project regarding preliminary design for sludge handling at the plant[27]. In conclusion, the risk of upsetting the digestion and nitrification processes was estimated to be low, but there is a risk that disturbances in the denitrification process may occur:

- The nitrogen concentrations in the supernatant from sludge dewatering will increase since the degradation of the sludge will be more extensive and organic nitrogen will be dissolved. The concentrations of nitrogen in the supernatant increase greatly and the amount of ammonia nitrogen from the supernatant will be about 20-25 % of the total amount of ammonia nitrogen in primary sedimented wastewater, instead of the normal 10-13 %.
- The increased amount of nitrogen will cause an increase in the nitrogen concentration in the effluent from the plant by an estimated 1 mg/l. This will probably require improved nitrogen removal at the plant.
- Addition of methanol may be required for the denitrification process due to the lack of carbon for the increased nitrogen load from the supernatant.
- Increased nitrogen load will increase the reduction of alkalinity during nitrification and thus decrease the pH value. If the concentration of alkalinity becomes much too low, the pH value decreases abruptly, and the nitrification process is inhibited to a large extent.
- The concentration of ammonia nitrogen in the anaerobic digester will reach 2 000 mg/l with hydrolysis compared to the current 650 mg/l[27], well below the limit concentration that is generally considered inhibitory (approximately 3 000 mg/l).

3.2.d.iv. Required measures at the Henriksdal WWTP

Within the preliminary design for sludge handling at Henriksdal, different sludge handling alternatives to decrease the amount of sludge were investigated (hydrolysis and drying)[27]. In this context, a proposed technical solution was elaborated that involved placing the hydrolysis system in one of the two existing tanks for digested sludge, which would then be reconstructed for the purpose.

Primary sludge and excess biological sludge was assumed to be pumped and treated in mainly the same way as today, with the addition of a new pipe for excess biological sludge placed in a new shaft. The evacuated sludge tank was partitioned in three levels, where pre-dewatering of the primary sludge would take place on the top level, a mixing tank would be installed on the mid-level, and the actual hydrolysis system on the bottom level. The extensive thickening was thus planned to occur directly adjacent to the hydrolysis system, which thus would enable the implementation (after hydrolysis, the sludge is much more easily pumped). The considerations that have earlier been made here in connection with mechanical thickening (see Chapter 3.1.b.iii.) are thus not relevant in the same way for the case thermal hydrolysis.

3.2.e. Chemical hydrolysis

3.2.e.i. General description

Chemical hydrolysis aims at destroying the cell walls of the bacteria and thereby releasing the cell content. The chemicals used may be for instance a strong acid, a base, or an oxidation agent. Common chemical compounds that are used are sodium hydroxide (NaOH), magnesium hydroxide ($Mg(OH)_2$), potassium hydroxide (KOH), calcium hydroxide ($Ca(OH)_2$), ozone (O_3), hydrogen peroxide (H_2O_2) and a variety of acids. Acids have proven most efficient to dissolve the inorganic material from the sludge, while bases may dissolve a significant part of the organic content of the sludge, about 30-40 %[13].

Certain chemicals dissolve or oxidise the components of the cell walls so that the cell contents will be made available for biological degradation. These include for instance sodium hydroxide and certain inorganic acids.

Methods for chemical pre-treatment include:

- acids and bases for dissolution of different components in sludge
- oxidising chemicals as hydrogen peroxide and hypo chlorite

Addition of sodium hydroxide may require neutralisation before feeding the sludge to the anaerobic digester.

Patent issues should be investigated prior to the use of chemicals for sludge hydrolysis.

3.2.e.ii. Experience

In a report by Svenskt Vatten (the Swedish Water and Wastewater Association) on methods for sludge hydrolysis[7], reference is made to the fact that studies on the addition of various basic compounds have shown that mono-hydroxides result in a higher ratio of dissolved COD than di-hydroxides. Sodium hydroxide and potassium hydroxide have the greatest effect on the ratio of dissolved COD (40 % and 37 %, respectively).

Sodium hydroxide dosage to biological sludge was tested by the company Purac during the 1990's. A large part of the sludge (the micro-organisms) were dissolved and thus made available for the anaerobic bacteria. However, the sludge dewaterability deteriorated after anaerobic digestion and in addition, the chemical costs of hydroxide and then acid for neutralisation became unreasonably high.

No other studies on solely chemical hydrolysis have been found here. However, chemical hydrolysis occurs in combination with thermal hydrolysis and is then called thermo-chemical hydrolysis, which is described below in Chapter 3.2.f.

3.2.e.iii. Required measures at the Henriksdal WWTP

The method is most cost-effective in combination with heat treatment, which is described below.

3.2.f. Thermo-chemical hydrolysis

3.2.f.i. General description

Thermo-chemical hydrolysis is a combination of the above chemical method with heating, which leads to a faster and more complete degradation of the bacteria cells.

3.2.f.ii. Experience

Bengt Hultman and Erik Levlin[13] describe two cases where NaOH is used in combination with heat to dissolve organic material. In the first study, NaOH was added to reach pH 12 during heating to 30°C and 60°C, respectively. Comparison was then made with heating alone to 100°C. The study shows that both cases of base addition and heating resulted in a larger dissolution of organic material than heating alone.

The other case includes a study at the Bayer AG wastewater treatment plant at the factory in Dormagen, Germany, where hydrolysis with NaOH was used in combination with the heating of excess biological sludge. The sludge was heated with steam to 95°C, and a sodium hydroxide solution with 25 % NaOH was added. This treatment resulted in the dissolution of 55-60 % of the organic material. The treated sludge was then mixed with primary sludge and could, after conditioning with lime and ferric chloride, be dewatered to 43 % DS in chamber filter presses.

A combination of chemical and thermal techniques has in the literature been considered more cost effective, than to use only one of the methods for treatment of excess biological sludge. However, this entails a more complex plant, which might possibly still be interesting for a wastewater treatment plant of the size of Henriksdal.

3.2.f.iii. Required measures at the Henriksdal WWTP

Required measures for the installation of thermo-chemical hydrolysis at Henriksdal are estimated to be similar in scope to the measures for installation of thermal hydrolysis, which have been described above. It thus entails a complex plant, which requires extensive reconstruction and intricate operation. Furthermore, a chemical treatment plant includes installations that entail consideration of extensive safety and work environment aspects.

3.2.g. Ozone treatment

3.2.g.i. General description

Ozone (O_3) is a very powerful oxidation agent, and this characteristic is utilised during a number of applications, not the least in the treatment of water and wastewater. During sludge treatment, the cell walls of the bacteria are destroyed through chemical oxidation.

Ozone is unstable and decomposes after a short while. It cannot be stored but must be produced on site by an ozone generator and utilised immediately. In larger applications, generation through electrical charges in air or oxygen is the most common method. Only some of the oxygen molecules form ozone. The produced mix contains about 1-1.5 % ozone (pure ozone is explosive). A typical ozone system includes air or oxygen compressors, particle filter, gas dryer, ozone generators, contacting units, and equipment for the destruction of the off-gases.

Ozone treatment of sludge results in that the part of dissolved COD in the sludge increases and thereby becomes available for digestion.

Ozone treatment of digested sludge that is recirculated back to the anaerobic digester has been carried out at a smaller full scale plant in Japan[32] (digester volume about 1000 m^3). The recirculation flow was about 1-1.5 times as high as the inlet flow to the anaerobic digester. Very good results are reported, such as a great increase in the biogas production by about 30 %, and improved dewaterability for the sludge. Simultaneously with the ozone addition, sludge dewatering without the addition of polymer was attempted, by which according to Yasui *et al.* (2005) the heavier sludge particles were concentrated in the withdrawn sludge, and the supernatant which contained a higher content of organic material was returned to the reactor (Figure 12). There is no information about the electrical energy consumption or detailed information on the ozone addition (specified to 24 kg O_3/d).

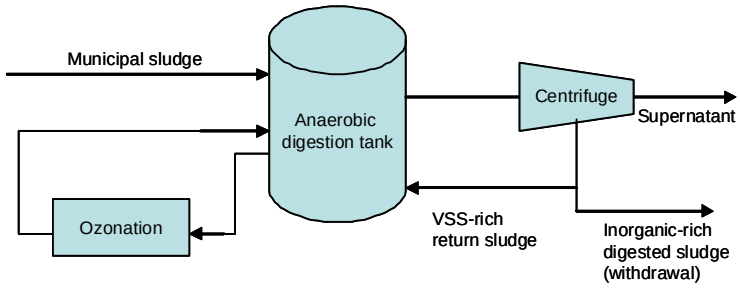

Figure 12. Ozone treatment of digested sludge (Yasui *et al.*)[32].

The commercial method for ozone treatment of sludge that is available on the market has been developed by Ondéo Dégrémont, who has a world patent on ozone treatment of sludge. However, the method aims at reducing the excess biological sludge through inhibition of the sludge growth, which thus leads to a decrease in biogas production. Any commercial method of sludge treatment prior to anaerobic digestion has not been developed by the company, referring to the practical difficulties of contacting the thickened sludge with the ozone.

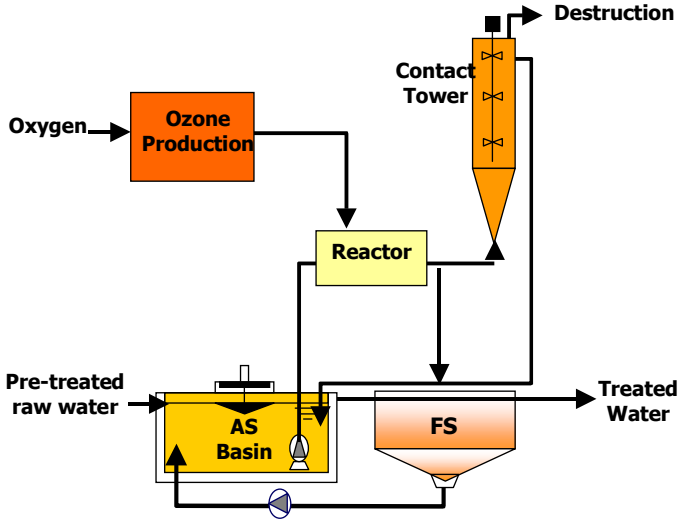

Figure 13. Schematic showing the principles for ozone treatment of sludge (Ondéo-Dégrémont). Please note that this method does not aim at increasing the biogas production, but at reducing the amount of sludge.

3.2.g.ii. Experience

Few have experience of using ozone on sludge for the purpose of increase the biogas production during anaerobic digestion, and today there is no ozone plant for sludge treatment in Sweden. This is not a common method in other countries either, mainly due to high costs. Operational costs are very high, especially due to the electrical energy consumption for the ozone production.

The method should generally be considered under development and is by no means established yet. The Japanese method described above is mainly aimed at decreasing the amount of digested sludge.

The Swedish environmental research institute IVL in Stockholm is currently planning a project on ozone treatment of sludge, in which Stockholm Vatten also will be involved. As the project is in the planning stage, there are not yet any results.

3.2.g.iii. Required measures at the Henriksdal WWTP

Currently, there is thus limited experience of ozonation of sludge before anaerobic digestion for the purpose of increasing the biogas production. Therefore, this method is not considered for Henriksdal at the moment.

3.2.h. Ultrasound treatment

3.2.h.i. General description

Ultrasound is sound with a frequency above 20 kHz and cannot be detected by the human ear since it is beyond our tonal register. When ultrasound is applied into a liquid, pressure variations are formed which leads to the formation of small gas bubbles in the liquid. These gas bubbles are called cavitations and grow in size during each cycle until their eigenfrequency/resonance frequency coincides with the frequency of the ultrasound. When this occurs, the cavitation oscillates strongly and reaches immediately a critical stage where it implodes, i.e., the bubble is compressed and reconverts very quickly to water. This is shown schematically in Figure 14.

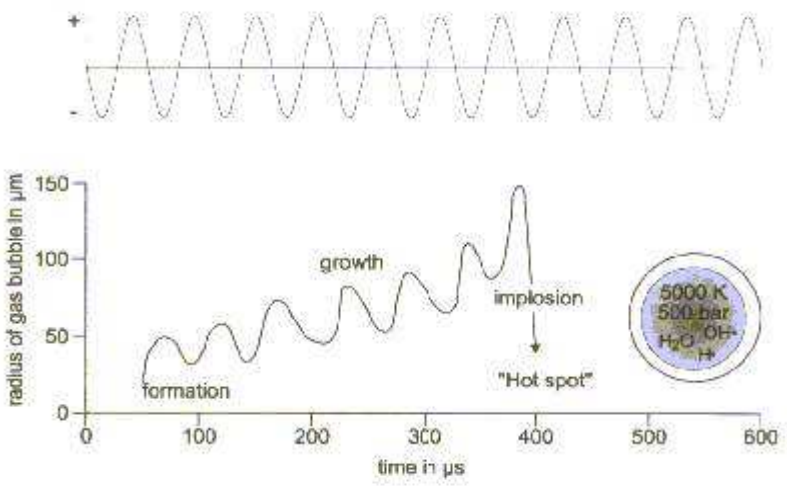

Figure 14. A cavitation increases gradually in size to finally implode.

During the implosion, the temperature and pressure increase to approximately 5 000 K and 500 bars, respectively, in the cavitation. When the cavitation implodes near a wall, a jet flow is sent toward the wall at speeds up to 100 m/s. The extreme temperature and pressure that are formed lead to specific sono-chemical reactions caused by the creation of higher active radicals and a thermal degradation of the substance.

When excess biological sludge is exposed to ultrasound treatment, filamentous bacteria are separated and disintegrated, which leads to a reduction of the concentration of filaments. Problems with foaming are expected to decrease through this action. The sludge is also disintegrated by the ultrasound treatment, and the cell structure is partly disintegrated. In consequence, the total surface area of the sludge increases, and the degradation of the organic material is improved. When the cell structures are disintegrated, nutrients and active enzymes are released. This also contributes to an improved degradation of the organic material. The improved decomposition leads to a higher degree of degradation and thus lesser amounts of digested sludge, more biogas and improved dewaterability of the digested sludge[5].

A number of suppliers of equipment for ultrasound treatment are available on the market. In Sweden, the suppliers Sonica and Ultrasonus are represented. An ultrasound reactor consists of a piece of pipe or two parallel plates onto which several ultrasound elements are mounted. The elements generate oscillations of ultrasound frequency that penetrate the sludge when it passes through the reactor. The retention time and the frequency of the oscillations both determine the amount of energy that is supplied to the sludge.[28]

3.2.h.ii. Experience

Suppliers of ultrasound technology usually state that a 10 % increase in biogas production is obtained. This is based on treatment of excess biological sludge only, and a partial flow is usually recirculated over the reactor.

Ultrasound treatment has been introduced in full scale at two wastewater treatment plants in Sweden, located in the towns of Kävlinge and Oskarshamn. Full scale trials have also been carried out at Gässlösa WWTP in the city of Borås. An extensive evaluation of the plants in Oskarshamn and Borås has been completed and is compiled in a report by the Svenskt Vatten Utveckling (the Swedish Water and Wastewater Association's Development

program)[8]. In the evaluation, the biogas production and the concentrations of total, undissolved, and dissolved COD were among the parameters measured. The conclusions of the evaluation are that direct effects of the ultrasound treatment on the excess biological sludge were difficult to show, and that an increase in the biogas production could not be detected. The amount of dissolved COD increased by about 1-3 % after ultrasound treatment, which is in agreement with other studies. The report indicates that it is unclear whether the ultrasound enables degradation that otherwise would not have taken place, or if it is only the rate of degradation that is increased. The study refers to other reports that show that degradation at short retention times in the anaerobic digester (<16 d) increase after ultrasound treatment.

The Gässlösa WWTP reports[7] that operational problems were extensive during trial operations, but if these are resolved, the method may be warranted for the purpose of reducing the foaming problems.

The report also shows that the wastewater treatment plant in Helsingør in Denmark has purchased an ultrasound plant of a different type than those that exist in Sweden. In Denmark there are fewer complaints of the technology and the biogas production has increased by 15 %. Data of dissolved COD is not available.

In Kävlinge, effects of the ultrasound on the biogas production were not studied since the installation was made at the same time as the anaerobic digestion process was switched from mesophilic to thermophilic digestion.

Lately, many WWTPs have considered the introduction of ultrasound technology. For instance, the Käppala WWTP carried out a study of different pretreatment techniques for excess biological sludge, including ultrasound. In short, the conclusion was that the ultrasound treatment was too costly (high electrical energy consumption), particularly compared with mechanical treatment. In addition, at the time of the study, there were no other relevant and reliable reference data for the biogas production before and after ultrasound treatment.

To investigate the effect of ultrasound treatment on sludge, trials were performed by Anox AB[21]. Trials were carried out during three weeks with sludge from the Frederica WWTP in Denmark. Sludge was sent from the plant to the laboratory once a week. The sludge was supplied to a 5 litres anaerobic digester once daily. The amount of added DS and VS was calculated and the biogas production measured. The retention time was 20 days and the temperature 37-38ºC in the anaerobic digesters. The DS concentration in the sludge from Frederica was 1-1.5 % and was thickened to 4-6 % DS prior to anaerobic digestion. The organic fraction was 55-60 % of DS. The ultrasound treatment was carried out in a unit delivered by Purac. The first 15 days, the treatment prior to the anaerobic digesters was carried out during 2 seconds, but was increased to 6 seconds during the rest of the trial time. The result is shown in Table 4.

Table 4. Results from tests on sludge treated with ultrasound at the Frederica WWTP[21].

	Untreated	Treated with ultrasound	
Methane yield	0.08	0.082	m^3/kg DS/d
Methane yield	0.128	0.131	m^3/kg VS/d
Methane concentration	64	65	%

The reason for the low increase in the concentration of methane is probably due to the fact that this was done on a laboratory scale. The experience from AnoxKaldnes AB and the experience from full scale plants supplied by Purac show that ultrasound treatment in full scale result in a higher degree of cell disintegration than batch treatment on a laboratory scale.

Altogether, this method is not considered cost effective for Henriksdal.

3.2.h.iii. Required measures at the Henriksdal WWTP

The method is generally compact, with limited space requirements. The area earlier used for heat pumps may be utilised. However, the sludge must be pumped and recirculated long distances, which require some pipe installations.

3.2.i. Treatment with electrical impulses

3.2.i.i. General description

Treatment with electrical impulses, electroporation, comprises the formation of pores in the cell membranes through short, electrical voltage impulses. For the impulses to be conducted between the electrodes and through the material, the presence of an electrical conduit such as water is required.

Electroporation has been developed mainly for two applications:

- Within medicine, to introduce molecules (DNA, medical drugs) into cells through temporary pores.
- Within the food and beverage industry, to permanently destroy the cell walls of fruits and vegetables, and thus facilitate extraction, for instance of sugar beets.

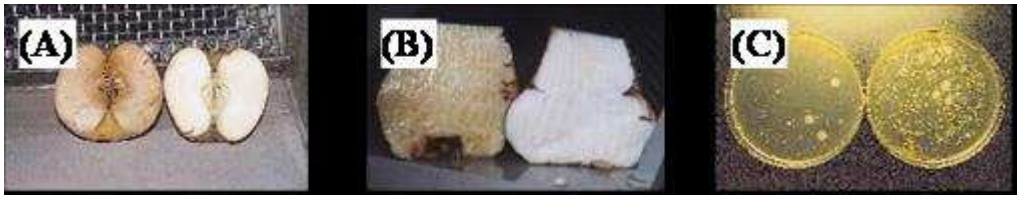

Figure 15. The effect of electroporation on (A) apples, (B) sugar-beets and (C) micro-organisms in wastewater (approved by KEA-TEC GmbH, Germany). Electroporated samples are to the left in each picture.

The optimal strength of the electrical field depends on the application and the type, size and geometry of the cell tissue. For instance, for plants an optimal strength with a span of 0.2-2 kV/cm is reported[15]. In addition to the intensity of the field, the frequency of the field and the geometry of the pulses probably have an impact on the result.

Since a few years ago, the technology has been moving forward in other areas also, such as weed control[9], disintegration of composite materials[3], and disinfection through the elimination of pathogens.[25]

The effect that can be expected during electroporation of sludge is that the bacteria cells are perforated and the cell content is made available for digestion. The reduction of organic material increases, as does the biogas production.

3.2.i.ii. Experience

Trials with electroporation as pretreatment before anaerobic digestion have only been carried out on a laboratory scale. In the trials, a special construction was used, including a 1 litre polyethene reactor with an electrode distance of 10 cm. The factors that can be varied in the system include the number of pulses per treatment, the frequency and the electrical field strength. The first trials were carried out on material from the Västerås biogas plant, which treats source-separated household waste mixed with a ley (a kind of fodder-plant). The substrate was treated in an electroporation plant at different conditions. The material was then analysed and the biochemical methane forming potential was estimated through tests. The maximum applied field strength during the trials increased the conductivity by 27 % and the COD concentration by 17 %. Hereby, the initial methane formation rate was increased by 28 % and the total methane formation of the waste by 52 %. The results from the tests cannot be used to estimate the effect of electroporation on full scale anaerobic digestion, since the tests were carried out in batch, and not as a continuous operation characteristic of full scale anaerobic digestion plants. However, the experience from the trials is so far positive, and in an ongoing second phase of the project, continuous anaerobic digestion of pretreated household waste and sugar beets is being carried out. If the results prove satisfactory, a full scale treatment plant could be in place within four years.

The technology has been developed to a full scale process within the food and beverage industry. The first full scale plant with a capacity of ~10^4 tonnes per day is currently being developed for the sugar industry.[26] The specific energy consumption for the extraction of sugar beets is <10 MJ/ tonnes (<2.8 kWh/ ton).

3.2.i.iii. Required measures at the Henriksdal WWTP

The method is not yet applied to the field of anaerobic digestion and it is not a realistic assumption that the method will be introduced here within the next few years. Based on full scale treatment plants in the fruit industry and laboratory tests, an assessment of the expected energy exchange may be made. A number of two 25 kW electroporation plants, with a space requirement of 70 m^2, would be needed to electroporate the sludge at Henriksdal. If the biogas yield increases by 25 %, this corresponds to 43 000 kWh/d. The energy for the electroporation and sludge pumping is 1 440 kWh/d. Then, only 3.3 % of the additional energy is used for the operation of the electroporation plant. However, this is only a very rough assessment, since test results for sludge are not yet optimised and the electrical energy consumption is based on sugar beets.

3.3. Methods for increased biogas production through additives or changes in substrate

3.3.a. Addition of enzymes

3.3.a.i. General description

Anaerobic digestion of sewage sludge is a slow process, and a part of the organic material is not degraded during the normal retention time of about 20 d. The rate-determining stage during anaerobic degradation of particular matter is usually the hydrolysis stage. This stage of degradation is carried out by so-called exoenzymes that are released by micro-organisms. There are natural enzymes of different types in the sludge, but an addition of extra enzyme in the process has potential to increase the rate of degradation and the total degree of degradation, and thereby also the methane potential of the sludge.

As there are fats, proteins and carbohydrates present in the sludge, different types of enzymes are needed. For fats, an enzyme such as lipase is needed; for proteins, the enzyme protease; and for cellulose, cellulase.

Proteases belong to a group of enzymes that degrade proteins to amino acids. Proteases have many natural functions in the metabolism of all organisms, such as degradation of protein-rich food, where the enzymes are active in the small intestine and split short polypeptides (earlier proteins) to amino acids. In this context, the proteases are often called peptidases. Proteases may be separated in endopeptidases and exopeptidases, depending on whether they split a peptide chain on the middle, at a certain sequence, or at one of the end sections.

Lipases are enzymes that split lipides (fats, e.g. triglycerides). More specifically, it is ester bonds that are hydrolysed. Since lipids are present in all known organisms, lipases are commonly present.

Cellulases are enzymes that degrade cellulose. Most cellulases are hydrolytic enzymes, but there are also cellulose phosphorylases and redox enzymes that may degrade cellulose. Cellulases are produced by many organisms, such as bacteria, fungi, plants and some animals.

3.3.a.ii. Experience

Many full scale, pilot scale and laboratory scale tests have been carried out to evaluate the effect of an extra addition of enzymes. Positive effects have been observed, but then often from large additions of enzymes[7]. AnoxKaldnes AB has performed tests on different biological sludges, where the effect has been relatively small at reasonable dosages.

At other laboratory tests by AnoxKaldnes during 2008 involved enzyme treatment prior to anaerobic digestion of mixture of organic waste fractions and biological sludge, three types of enzymes have been added. The tests have shown a 20-24 % increase of the biogas production. This addition of enzymes has not yet been tested on a combination of primary and excess biological sludge. These test results have not yet been officially reported.

A Master's thesis by R. Beijer[2] has been carried out at Henriksdal investigating the potential effects of enzyme treatment of sludge in the presence of the cationic binder sodium citrate. The tests showed that the COD concentration in the liquid phase could be increased by 17-32 % depending on the dosage of enzymes and sodium citrate. Anaerobic digestion tests on sludge, with a total of 18.6 mg enzymes/g DS at a concentration of 5 mM of sodium citrate, increased the methane production by almost 18 %. It also resulted in a decreased amount of sludge from the anaerobic digesters. However, the increase in biogas production was not sufficient to cover the costs of enzymes and sodium citrate. The conclusion drawn by Beijer is that the addition of enzymes and sodium citrate must be decreased to achieve profitability by this method.

In another Master's thesis carried out at the University of Lund, the sludge was treated by a combination of different enzymes and the addition of citric acid[14]. The trials were performed with hydrolytic enzymes, which split substances such as carbohydrates, proteins and fats. The goal of this work was to increase the rate of the hydrolysis reaction so that the material could be converted to fatty acids quickly and to the greatest extent possible.

Each trial was carried out with 6 reactors with sludge, of which one or two constituted control reactors. Different enzymes were added to the reactors. The control did not receive any addition of enzyme. After mixing, the first samples were taken. The reactors were placed in a water bath with a temperature of 37°C for four hours while stirring the sludge continuously. After sampling again, the trials were discontinued.

The most effective combination of enzymes proved to be protease and lipase. When this combination was used together with the addition of citric acid, the greatest amount of organic matter was degraded and the highest concentration of volatile fatty acids was produced. This meant that the amount of sludge was decreased significantly and that the amount of produced biogas increased.

The chemical company Kemira has during the last year been testing the addition of enzymes to the anaerobic digestion process on a full scale at five different wastewater treatment plants. A clear, positive effect on both the biogas production and the reduction of sludge amounts could be concluded in all of the full scale trials. In one case, the increase in biogas production was estimated to at least 25 % and the amount of sludge reduced by 24 %. The sludge reduction includes both improved dewaterability and an increased DS reduction in the anaerobic digestion process.

3.3.a.iii. Required measures at the Henriksdal WWTP

Since the results of enzyme addition vary among wastewater treatment plants, tests have to be carried out in full scale to ascertain the effect. At Henriksdal, enzymes could be added to one of the anaerobic digesters during a period of time, which should be > 6 months to determine the entire effect on the biogas production, DS reduction and sludge properties.

Installation of a system for enzyme addition is relatively simple. Enzymes are fed by feeding pumps from plastic containers to the anaerobic digesters via the existing inlet pipes. It will most likely be possible to apply the addition at one location to all the seven anaerobic digesters. If the digester operation at Henriksdal is changed to a serial mode, the most suitable location for the dosage is probably anaerobic digesters 4-7, which would constitute the first stage in a serial process.

3.3.b. Addition of deficient substances

3.3.b.i. General description

In an anaerobic digester, many different types of micro-organisms cooperate to convert proteins, fats and carbohydrates that are present in the sludge to the final products methane and carbon dioxide. Micro-organisms require a large number of nutrients and trace compounds to optimise the growth of new micro-organisms.

The most important nutrients are nitrogen, potassium and phosphorous, and there is normally a sufficient amount of these compounds in primary and secondary sludge.

For trace compounds, there are certain compounds that are particularly important for cell growth, namely iron, cobalt, nickel and sulphur.

3.3.b.ii. Experience

Analysis of anaerobic digester content has shown that there may be a shortage of cobalt and nickel or that the micro-organisms have difficulty to utilise the trace compounds. In such cases, addition of ferric chloride of low pH value, in combination with nickel and cobalt can result in a positive effect in terms of improved biogas production. The purpose of the iron addition is primarily to bind sulphides (from hydrogen sulphide) as ferrous sulphide, FeS, and thereby prevent the precipitation of nickel and cobalt as metal sulphides.

3.3.b.iii. Required measures at the Henriksdal WWTP

Installation of the addition of nutrients and trace compounds can take place in a similar manner as the addition of enzymes, above.

3.3.c. Reception of additional EOM

3.3.c.i. General description

The biogas production can be increased by increasing the addition of organic material. Since March 2000, the Henriksdal WWTP receives external organic material, EOM. The major part of this material (96 %) consists of fatty sludge from the food and beverage industry and restaurants. The organic load on the anaerobic digesters is lower during mid-June to mid-August each year, which is clearly noticed as a decrease in biogas production. During these weeks with lower loads, it may be particularly suitable to receive more EOM to even the load and obtain a more consistent biogas production.

Reception of greater amounts of EOM in the form of source separated food waste will increase the nitrogen load on the wastewater treatment plant. Reduction of the additional nitrogen will increase the oxygen consumption and an external carbon source may also be required.

3.3.c.ii. Experience

Co-digestion of food waste and sludge is often beneficial to the anaerobic digestion process. A substrate mix that meets the need for trace compounds and nutrients is obtained. In addition, the high alkalinity of the sludge stabilises the anaerobic digestion of the waste fractions.

Anaerobic digestion of solid waste fractions such as food waste requires that the material is thoroughly pretreated (grinded, with the unwanted material removed). Such pretreatment is a complicated process that requires large investments. Many waste digestion plants have experienced serious operational problems.

3.3.c.iii. Required measures at the Henriksdal WWTP

For several years, Stockholm Vatten has been investigating the possibilities to receive significantly greater amounts of organic waste than those received today, and has carried out a number of studies in collaboration with the City of Stockholm Waste Department. A prerequisite for the reception of large amounts of food waste is that the City of Stockholm introduces systems for source separation and collection of food waste on a large scale. The city recently announced its plans that such source separation shall take place only in the suburban areas, and Stockholm Vatten is now awaiting further developments in this area as well as relevant political decisions.

However, Stockholm Vatten is already preparing the Henriksdal WWTP for increased waste treatment. For example, the capacity to receive liquids and slurries (pumpable waste fractions), such as pretreated food waste from restaurants and supermarkets, will be increased from about 25 000 m^3/year today to about 50 000 m^3/year.

The reception of larger amounts of EOM will lead to a higher nitrogen load on existing processes through the increased nitrogen content in the supernatant from the sludge dewatering, which in turn may result in requirements for separate treatment of the supernatant.

3.4. Exergy

An assessment of the exergy requirement for the different methods was made. (See Table 6.) The estimates are rough and carried out only for the purpose of assessing whether a certain method yields a positive or negative exergy. The electricity and heat requirement for each method were compared with the estimated increase in biogas production for each method.

In the calculations, the heat consumption for summer (May-October) and winter (November-April) were computed. The temperature of the sludge feed to the anaerobic digesters has been assumed to be 18°C in the summer and 13°C in the winter. The base data are collected from operational statistics for the wastewater at Henriksdal for the period January 2002 to October 2008, and the temperatures are mean values for the summer and winter months, respectively. It was assumed that district heating could be used for heating up to 35.5°C during summer. For methods where higher temperatures are used, it was then assumed that biogas would be utilised for the heating above 35.5°C during the summer months. Furthermore, for the winter months, it was

assumed that district heating can be used for heating up to 50°C and that biogas will be required for temperatures above 50°C. Potential heat recovery was disregarded in the calculations.

None of the methods with potential merit were assumed to cause an increase in the electrical energy consumption to an extent that would warrant consideration in these rough calculations. Neither was energy content of enzymes and the like included, as it has not been considered necessary for the calculations at this stage. The following relation in exergy among the different kinds of energy was used:

0.3*district heating = 1*biogas = 1*electrical energy

For those methods that involve the extraction of more organic material in the form of sludge (i.e. improved sedimentation) the assumption was made that no more COD shall be withdrawn than that the nitrogen reduction will not be negatively affected without the addition of an external carbon source.

Table 5 shows the net exergy for the heating, together with the estimated increase in biogas production, based on the above presented assessments, for the methods that after a first evaluation appear to be the most interesting for Henriksdal.

Table 5. Estimated net exergy for heating and biogas increase for the methods that after a first evaluation were considered the most interesting for Henriksdal. Exergy value of released anaerobic digester volume is not included in the calculations.

Method	*Required temperature °C*	*Estimated biogas increase %*	*Released volume m³*	*Estimated net exergy +/-*
Increased production of primary sludge	35.5	11-12[1]	0	+
Increased HRT/ Pre-thickening	35.5	2.5	8 500[2]	+
Thermophilic digestion	55.0	1-3	9 800	-
Serial operation	35.5	8-10	0	+
Collection of biogas from existing sludge tanks	35.5	5-10[3]	0	+
Mechanical treatment of sludge	35.5	2.5	0[4]	+
Pasteurisation	70	0-5	0	-
Thermal hydrolysis	160	30	24 000	± 0
Enzymes	35.5	15	0	+

[1] At 20 % increase in amount of PS, biogas increase is estimated to approximately 12 %. The decrease in HRT decreases this somewhat, to about 11 %.

[2] The released volume relates to pre-thickening where a possibility of increased HRT or reception of more EOM exists.

[3] The effect is expected to be slightly lower at conversion to serial operation.

[4] Test results presented by Åkerlund (2008)[33] indicate that sludge may be thickened while maintaining the viscosity, which can result in ”released volume”.

3.5. Compilation and assessment of the methods in Stage 1

Table 6 shows a summary of all the methods described in Stage 1, together with an assessment of their applicability at Henriksdal and their effect on the biogas production.

The methods were first assessed based on technical applicability and effect on the biogas production. For the methods that were then considered interesting, an assessment was made also of the net exergy, see previous chapter. A summary of the methods together with the results of the evaluation is presented in Table 6.

Based on the result, it was then decided which methods would be studied further in the next part of the study. The evaluation criteria that were applied for the selection of methods to Stage 2 were the following:

- technically feasible
- can result in at least a 5 % increase of the total biogas production
- shows a positive net exergy, i.e., the biogas production exceeds the increased consumption of primary energy

Some methods that were rejected in this stage were those that would require large and complicated reconstruction of the existing plant, which is particularly difficult at Henriksdal as the digester and sludge handling stages are situated in rock. Other methods were rejected as they were not considered sufficiently tested in full scale and therefore not possible to apply at Henriksdal at present. These methods might, however, turn out to be viable in the future, after additional trials have been performed, but are not investigated further within this study.

Tabell 6. Compilation of the methods and the result of a first evaluation for selection of methods for Stage 2.

Method	*Technically feasible at Henriksdal*	*Effect on biogas production*	*Comment*	*Selected for Stage 2*	*Net exergy[1] +/-*
Increased production of primary sludge	**Yes, reconstruction of the chemical dosage system.**	**11-13 % (at withdrawal of 20 % more PS).** **Tests at Henriksdal are required.**	**Relative effects. Increased precipitation of COD may lead to reduced air consumption. However, risk for carbon deficit for the denitrification.**	**Yes**	**+**
Increased HRT	**Yes, however the current HRT is already long.**	**Pre-thickening of PS to 5 % DS yields increased HRT to 25.8 d. Estimated biogas increase about 2.5 %.** **(Increase from 20 d to 30 d results in about 4 % biogas increase).**	**Pre-thickening of PS to 5 % DS results in 8 500 m³ released space if HRT is not increased. The energy requirement for heating is reduced.**	**Yes**	**+**
Thermophilic digestion	Yes	Possibly a small increase, 1-3 %, but greater increase if more EOM is received.	Shorter HRT, volume is released (about 9 800 m³).	No	-

Method	*Technically feasible at Henriksdal*	*Effect on biogas production*	*Comment*	*Selected for Stage 2*	*Net exergy[1] +/-*
Serial operation	**Requires additions to the current pumping and control systems.**	**8-10 % biogas increase.**	**Costly if existing equipment needs to be changed.**	**Yes**	**+**
Serial operation, pre-hydrolysis	Requires additions to the current pumping system.	About 2 % (HRT about 26 d in total).	Releases volume (about 8 000 m^3).	No	Not assessed
Collection of biogas from existing sludge tanks	Yes	5-10 %	Biogas increase depends of the HRT in the anaerobic digesters. Collection of biogas is already planned for environmental reasons.	Possible alternative if serial operation proves not favourable[2].	+
Mechanical treatment of sludge (here disintegration by grinding in equipment for screening solids)	No, difficulties in pumping.	2.5 %	Disintegration of PS has not resulted in a significant biogas increase. Disintegration of EBS not technically feasible at Henriksdal.	No	+
Pasteurisation (heating to +70ºC during 1 hour)	Yes, for instance using one of the two sludge tanks for pasteurisation.	0-5 %	Not a method for increased biogas production. May become necessary for reasons of hygienisation.	No	-
Thermal hydrolysis	**Yes**	**About 30 %**	**One of the two sludge tanks is rebuilt to house the hydrolysis system. About 24 000 m^3 released volume. Large heat requirements.**	**Yes**	**± 0**
Chemical hydrolysis	Doubtful, due to safety and work environment issues.	Insufficient references.	Safety issues.	No	Not assessed
Thermo-chemical hydrolysis	Doubtful, due to safety and work environment issues.	Insufficient references.	Expensive, large heat and space requirements.	No	Not assessed
Ozone treatment	Doubtful, refernces are lacking.	Limited full scale references. Laboratory tests indicate 9-10 % biogas increase.	Insufficient references.	No	Not assessed

Method	*Technically feasible at Henriksdal*	*Effect on biogas production*	*Comment*	*Selected for Stage 2*	*Net exergy[1] +/-*
Ultrasound treatment	Yes	Uncertain effect, 10 % according to suppliers, but experience does not show this effect.	Uncertain effect, high electricity consumption.	No	Difficult to assess. The project team could not find any reference plants that show a significant positive net exergy.
Electrical impulses	Technique not fully developed yet.	-	Method not yet applied on sludge.	No	Not assessed
Enzymes	**Yes**	**A positive effect after addition of large amounts of enzyme, 15 %.**	**Expensive due to larger amounts of enzymes. Interesting if lower dosages may be used.**	**Yes**	**+**
Addition of deficient substances	Yes	Yes, if deficit exists.	Generally costly, however depends on the type of deficit substances.	No	Not assessed

[1] The net exergy has only been calculated for the methods that were considered interesting at the first evaluation.

[2] This method is assessed as a second best alternative to serial operation since the purpose of this study is to optimise the process in the existing anaerobic digesters. The two sludge tanks are currently used as an equalisation volume during evacuation or in case of operational disruption. Therefore, it is possible to claim only one of the tanks for post-digestion. In addition, reconstruction of an existing sludge tank involves major investments.

Methods that were considered interesting and fulfil the criteria are marked in **bold**.

4. Stage 2

In Stage 2, the methods that were selected in Stage 1 were studied further. Table 6 presented which methods, of the initial methods, that were chosen for further evaluation in Stage 2. EOM was also added to the table as it is a method that Stockholm Vatten already applies today.

The 6 methods that appear interesting and meet the criteria are presented in Table 7.

Table 7. Selected methods from Stage 1. The table shows estimated biogas increase and the potential released anaerobic digester volume.

	Estimated biogas increase %	Released volume m^3
1. Thickening of primary sludge	2.5*	approx. 8 500
2. Increased production of primary sludge	11-12	increased flow, reduced HRT
3. Serial operation**	8-10	0
4. Enzyme addition	15	0
5. Thermal hydrolysis	30	approx. 24 000
6. EOM	Depends on amount of EOM	0

* Approximately 2.5 % if the HRT is increased instead of receiving more EOM. If HRT is not increased, a large volume is released and more EOM can be received and biogas production increased. The method was therefore assessed as interesting to study further despite that it does not yield 5 % biogas increase.

** Additional alternative to serial operation is the collection of biogas from existing sludge tanks, see footnote to Table 6.

4.1. Studied process alternatives in the continued evaluation

The selected methods were combined to a number of process alternatives that are described below.

The description should be read together with appended mass balances for each alternative, Appendix 1. The appendix also contains a summary of flows, volumes and retention times for each alternative, as well as constants for the calculations. The summary table in Appendix 1 presents non-rounded values from the mass balances so that the reader will be able to follow the calculations. In the text below, the values have been rounded since the calculations include assumptions and estimates, and the accuracy of the data cannot be expected to be greater than these rounded values.

The process alternatives that have been elected for Stage 2 are the following:

A. Increased production of primary sludge.
B. Thickening of primary sludge + increased production of primary sludge.
C. Thickening of primary sludge + serial operation with two digestion stages, including 4 parallel anaerobic digesters in stage 1 and 3 parallel anaerobic digesters in stage 2.

D. Thickening of primary sludge + increased production of primary sludge + serial operation with two digestion stages, including 4 parallel anaerobic digesters in stage 1 and 3 parallel anaerobic digesters in stage 2.
E. Addition of enzymes.
F. Thermal hydrolysis.
G. Existing anaerobic digester process + EOM.

The chosen alternatives were combined on the basis that they fulfil the selection criteria:

- technically feasible
- shall result in at least a 10 % increase in biogas production
- shows a positive net exergy

Increased production of primary sludge was considered interesting to study as a separate alternative (A) since the method in itself was estimated to yield more than a 10 % biogas increase.

The method including addition of enzymes is here presented as a separate alternative since it does not involve any changes in anaerobic digester operation, and may, if considered interesting, be introduced independently of the other methods.

Thermal hydrolysis is also described as a separate alternative (F) since it has been estimated to yield more than a 10 % biogas increase. Finally, the alternative (G) is presented, entailing the existing anaerobic digester process with the addition of increased amounts of EOM. This alternative can be realised if more fatty sludge and/or source separated food waste is available and can be received at Henriksdal. The term EOM commonly refers to all types of external organic material, but in this report it is only EOM in the form of fatty sludge and food waste that were considered.

For those alternatives that include a decreased inlet flow to the anaerobic digesters, the increase in available anaerobic digester volume that would be released if the retention time was maintained at 20.1 days, was calculated. This volume can be utilised to receive more EOM. The amount of EOM that could be received in this volume together with the corresponding increase in the biogas production was estimated. In the reference plant, EOM is received in the form of 24 400 m3 fatty sludge/yr. An additional 5 600 m3 fatty sludge/yr was estimated to be available (a total of 30 000 m3 fatty sludge/yr). EOM in the form of food waste can also be received. Since there is no pretreatment station for food waste at Henriksdal, it was assumed that food waste (that usually has a DS concentration of 35 %) is pretreated at another location and that Henriksdal would receive a pretreated slurry with a DS concentration of about 10 %.

There are plans to rebuild the current receiving station for EOM at Henriksdal and the capacity after the extension will be approximately 50 000 m^3 EOM per year. The anaerobic digester volume thus made available will be presented based on two assumptions:

1. Maximum utilisation of the released anaerobic digester volume. The released volume is first filled with 5 600 m^3 of fatty sludge, then food waste slurry until the volume is reached.
2. Utilisation of anaerobic digester volume that is limited by the capacity of the receiving station that is now under construction. This means reception of an additional 25 600 m^3 EOM (for a total of 50 000 m^3). The 25 600 m^3 consist of 5 600 m^3 of fatty sludge and 20 000 m^3 food waste slurry.

4.1.a. Mass balances and biogas production

Mass balances were established in Excel to compute released anaerobic digester volumes, digester loads, flows and increased biogas production for the different alternatives. These are presented in Appendix 1.

4.1.a.i. Reference model

The reference model was designed to reflect the biogas production at Henriksdal during the years 2000-2005, with input data on sludge obtained from the earlier Stockholm Vatten report to Biogasmax[12].

The methane potential for the different sludge types and fatty sludge were estimated for the purpose of computing the biogas production in the reference model. In order to compute the biogas production when food waste is received, values for food waste were also included in such alternatives. The values used in the models are presented in Table 8.

Table 8. Values for calculation of biogas production used in the mass balances and load during reference period.

	Specific gas production (Nm^3 CH_4/kg VS_{in})	Methane content (% av Nm^3 biogas)	Degree of degradation (% of VS in)	Load during 2000 - 2005 (kg VS_{in}/d)
Primary sludge	0.343	65	52.5	37 930
Excess biological sludge	0.194	65	30	10 600
Fatty sludge	0.816	70	85	3 290
Food waste	0.455	65	65	0

The specific gas production for primary sludge and excess biological sludge have been computed based on tests that Åkerlund made in her Master's thesis 2008[33]. Values of 0.39 and 0.22 Nm^3 CH_4/kg VS_{in} were then obtained for primary sludge and excess biological sludge, respectively. In the first report to Biogasmax[12], the methane potential was estimated to 88 %. By using this value, the specific gas production constants 0.343 and 0.194 Nm^3 CH_4/kg VS_{in} for primary and excess biological sludge have been calculated here (see Table 8).

AnoxKaldnes AB performed anaerobic digestion tests on fatty sludge from Henriksdal during the period 2008-12-03 to 2009-01-05, and then obtained the result 0.878 Nm^3 CH_4/ kg VS_{in}, which, together with an utilisation degree of 88 %, yields 0.773 Nm^3 CH_4/ kg VS_{in}. This was here considered too low compared with both earlier experiences and the calculation of the ratio of biogas from fatty sludge (see section 4.1.1.3). The value 0.816 Nm^3 CH_4/ kg VS_{in} has instead been chosen, since this is in better agreement with test results from other plants and also with the ratio of biogas that is likely to originate from the fatty sludge at Henriksdal. The value 0.455 Nm^3 CH_4/ kg VS_{in} is based on the experience from several full scale co-digestion plants for waste and also a recently published substrate handbook for biogas production[6].

The degree of degradation for fatty sludge and food waste are based on earlier results. In the first report to the Biogasmax project[12], the total degree of degradation in the anaerobic digesters was calculated to 50 % on the average for the reference period. Based on this value, the degrees of degradation for primary sludge and excess biological sludge were calculated in relation to the estimated proportion of sludge amounts.

The methane content in the biogas is specified in the first Biogasmax report[12] as 65.65 % for the produced biogas. The concentrations of methane in Table 8 are based on this value, and the model results in an average methane concentration of 65.71 %, which can be considered within the margin of error.

4.1.a.ii. Sensitivity analysis for the mass balances

Sensitivity analyses have been carried out to verify the consequences of any errors in the above assumptions, see Table 9.

Tabell 9. Sensitivity analysis for the mass balances, showing the results of changes in the constants for specific gas production.

	Change %	Total biogas production according to the model Nm³/d	Change in total biogas production %
Reference model	-	27 000	-
Specific gas prod. PS	+/-10 %	29 000 / 25 000	+/- 7.4
Specific gas prod. PS	+/- 5 %	28 000 / 26 000	+/- 3.7
Specific gas prod. PS	+/- 2 %	27 400 / 26 600	+/- 1.5
Specific gas prod. EBS	+/-10 %	27 300 / 26 700	+/- 1.1
Specific gas prod. fatty sludge	+/- 10 %	27 400 / 26 600	+/- 1.5

prod. = production

The table above shows variations in the specific gas production constants for the substrates in the reference model. It should be clarified that the same variation in the degrees of degradation will have equal effects on the gas production.

Since the primary sludge produces the greatest amount of gas, it is, according to the table above, the specific gas production constant for primary sludge that results in the greatest sensitivity in the model. This parameter has therefore been varied by 10, 5 and 2 %, respectively, while the other constants have been varied by 10 % only. It can thus be seen that a variation of the constant for primary sludge by 2 % gives about the same effect as a variation on 10 % for excess biological sludge and fatty sludge.

4.1.a.iii. Gas production

During the reference period, the measured biogas production was about 25 300 Nm³ biogas/d. In the reference model, the biogas production will be about 27 000 Nm³ biogas/d, i.e., 1 700 Nm³ biogas/d corresponding to 6.7 % more than the measured biogas flow. This was, however, considered reasonable, since the biogas measurements cannot be considered reliable due to the current design of the biogas system. The biogas flow measurements are probably correct in absolute terms, but the biogas flow meters also measure biogas that flows in the opposite direction. If an anaerobic digester produces too much biogas for the pipe system to receive, the safety valves, which consist of a water seal, opens and biogas blow out. This causes the anaerobic digester to lose its overpressure and biogas that has already been measured then passes the flow meter of the blowing anaerobic digester backwards and exits through its water seal. In this way, the biogas from several anaerobic digesters can be measured several times, resulting in elevated values. At the same time however, biogas that has been produced in the blowing anaerobic digester never passes any flow meter, and the values therefore become too low. The values are thus incorrect even if the meters are accurate and precise.

There is, however, a cut-off valve between each anaerobic digester and its flow meter, which shuts off when the biogas flow is too low or too high. The part of the biogas flow that passes without being measured is thus likely to exceed the part that is being measured several times. In total, the flow meters thus show values that are too low, which corresponds well with the fact that the measured biogas production is lower than the calculated.

4.1.a.iv. Ratio of biogas from fatty sludge

To estimate the part of the biogas production that has been produced from the received fatty sludge during the reference period, three separate calculations have been made (see Appendix 2).

In the first computation, the biogas production from sludge (primary and excess biological sludge) during the years 1998-1999, when no fatty sludge was received, was calculated to 11.43 Nm³ biogas/m³ sludge, independently of the amount of VS. This factor was assumed to be constant during the following years when fatty sludge was received and the biogas production from sludge was calculated. The remaining biogas was then

assumed to come from the fatty sludge. By this calculation, the ratio of biogas from fatty sludge was 15.8 % of the total biogas production for the years 2000-2005.

The other two calculations were performed in a similar way, but the biogas production for the years 1998-1999 was instead related to the incoming amounts of COD and nitrogen to the wastewater treatment plant. These calculations yield the factors 185.5 Nm^3 biogas/tonne COD och 2 193 Nm^3 biogas/tonne N for the years 1998-1999. With the same calculations as above, this yields 17.6 % biogas from fatty sludge using COD as a basis, and 14.9 % using the nitrogen amounts in the influent.

The reference model results in 14.2 % biogas from fatty sludge, which is considered to be within the margin of error for the above values.

4.2. Description of studied alternatives

The alternatives that were studied further in Stage 2 are described below.

4.2.a. A. Increased production of primary sludge

4.2.a.i. General description

At an increased production of primary sludge of 20 %, the amount of VS from primary sludge will increase by 7.6 tonnes per day, from 37.9 to 45.5 tonnes per day. This leads, however, to an increase of the COD reduction in the primary sedimentation basins from 48 to 58 %, which reduces the organic load on the biological stage in the wastewater treatment plant with about 19 % (see Appendix 3). The assumption was made that the amount of VS in the excess biological sludge is proportional to the organic load on the biological stage. This means that the amount of VS in incoming biological sludge to the anaerobic digesters decreases by 19 % compared with the reference plant. This assumption was made in all the alternatives that include an increased production of primary sludge.

An increase in the production of primary sludge also means an increase in sludge flow. At withdrawal of 20 % more DS from the primary sludge, the total flow to the anaerobic digesters increases by about 200 m^3 per day. The total flow thus increases from about 1 900 m^3/day to 2 100 m^3/day. This means that the retention time (HRT) decreases from 20.1 d to 18.3 d. The shorter retention time results in a decrease in biogas production compared to a process with maintained HRT. In a Master's thesis by Borggren[4], anaerobic digestion tests were carried out on mixed sludge from Henriksdal. These show that the decrease in HRT from 20.1 to 18.3 days result in a slightly reduced biogas production. The Biogasmax report D2.15_SVAB_v1[12] presents a diagram showing the expected biogas production at changed retention time, based on an anaerobic digestion test from the research institute JTI (Swedish Institute of Agricultural and Environmental Engineering). Based on this, the decrease in biogas production here was estimated to about 1 %. In the model, this was simulated through decreasing the degrees of degradation by 1 %. The biogas increase then amounts to 11 % (about 12 % at maintained HRT), and there are no anaerobic digester volumes for the reception of more EOM. If increased amounts of EOM shall be received, the retention time must be reduced even further which subsequently affects the degree of degradation. This last case has not been studied within this project.

4.2.a.ii. Effects on nitrogen removal

If 20 % more suspended substance is separated as primary sludge, the total separation of suspended solids increases from 59 % to 71 % (see Appendix 3). This means that the concentration of COD_{tot} to the predenitrification will be reduced from 249 to 202 mg/l. The focus here must, however, be the part of the COD that is available as a carbon source, i.e., the biologically degradable, dissolved and particular COD, so called COD_{bio}. This decreases from 176 to 144 mg/l, while only the biologically degradable, particular COD is reduced from 107 to 75 mg/l, see Appendix 3. An estimate of how efficiently the bio-particular COD is utilised in the denitrification process can be made by measuring the rate of denitrification. A rate below 1 g N/(kg VSS·h) at 15°C indicates a slow process, which means that a carbon source that is more difficult to degrade is used, while a rate above 2 g N/(kg VSS·h) indicates that more easily degraded carbon is available. If the rate of denitrification is not known, a theoretical assessment may be made through calculating the ratio CODbio/tot-N. The ratio was earlier 4.9 at Henriksdal, and would diminish to 4.2 at the above mentioned withdrawal of primary sludge, which

means that the carbon source for denitrification would still be sufficient, but that the rate of denitrification decreases somewhat.

The ratio CODtot/Ntot amounts to 5.9 at increased production of primary sludge, which may be considered slightly low, but the supply of a carbon source depends on the amount of easily degradable organic substance.

In conclusion, it is estimated that the increased withdrawal of primary sludge will not cause a shortage of carbon source in the biological stage. The calculations are presented in Appendix 3.

4.2.b. B. Pre-thickening of primary sludge + increased production of primary sludge

4.2.b.i. General description

An increase in the production of primary sludge by 20 % means, as mentioned above, that the sludge flow increases by about 200 m^3 per day. On the other hand, by thickening the sludge, the flow is reduced. Thickening of the primary sludge from 3.6 to 5 % DS results in a reduction of the flow of primary sludge by about 500 m^3/day. In total, the flow is then reduced by approximately 300 m^3/d, and the resulting total flow to the anaerobic digesters amounts to 1 600 m^3/d. By combining these two methods, the biogas production may be increased through the withdrawal of more primary sludge without an increase in the sludge flow. The retention time will here be increased to 24.1 days, which in itself will yield an estimated 1.8 % increase in the biogas production. In combination with the increased production of primary sludge, this yields a total biogas increase of about 15 %.

If the retention time is maintained at 20.1 days, the reduced flow will release about 6 400 m^3 of anaerobic digester volume. If this volume is utilised for the reception of additional EOM, it will be possible to receive a maximum of 5 600 m^3 fatty sludge per year together with about 110 000 m^3 food waste slurry, and a biogas increase of 83 % will be obtained. However, these amounts of EOM exceed the capacity of the receiving station. Using this capacity as a limitation, about 5 600 m^3 fatty sludge together with 20 000 m^3 food waste slurry can then be received, and a biogas increase of about 30 % will be obtained.

4.2.c. C. Pre-thickening of primary sludge + serial operation with two digester stages

4.2.c.i. General description

This alternative entails the conversion to serial operation, with anaerobic digesters no 4-7 as a first stage and anaerobic digesters 1-3 as a second stage. The maximum available volumes will then be about 23 300 m^3 in stage 1 and about 15 200 m^3 in stage 2. At a normal flow (about 1 900 m^3/d), this would result in a retention time of 12.2 d in stage 1 and 7.9 d in stage 2, i.e., a total of 20.1 d. If retention time is maintained, the conversion to serial operation would yield an estimated 8 % increase in biogas production, where approximately 80 % of the biogas will be produced in stage 1 and 20 % in stage 2. By thickening the primary sludge from 3.6 to 5 % DS, the flow will be reduced from 1 900 m^3/d to 1 500 m^3/d. This results in an increase in retention time to 15.6 d in stage 1 and 10.2 d in stage 2, a total of 25.8 d. This is estimated to yield an increase in the biogas production of about 10 %.

Instead of increasing the retention time, anaerobic digester volume can be released, approximately 8 400 m^3 (about 5 100 m^3 in stage 1 and about 3 300 m^3 in stage 2). If this volume is utilised for the anaerobic digestion of maximum amounts of EOM, about 5 600 m^3 fatty sludge and approximately 150 000 m^3 food waste slurry can be received, and the corresponding increase in the biogas production is estimated to be about 100 % at the maintained retention time of about 20.1 d. This requires, however, a larger receiving station. Reception of about 5 600 m^3 fatty sludge and approximately 20 000 m^3 food waste slurry will yield an estimated 26 % biogas increase, and the retention times will be 14.9 d and 9.7 d in stages 1 and 2, respectively, (a total of 24.6 d).

4.2.d. D. Pre-thickening of primary sludge + increased production of primary sludge + serial operation

4.2.d.i. General description

By combining the above alternative with an increased production of primary sludge, the sludge flow increases slightly compared with alternative C, but in the same way as in alternative B, the total flow is reduced by about 300 m^3 per day compared with the reference plant, from about 1 900 m^3/d to 1 600 m^3/d. In this alternative, the retention time is extended to 14.6 days in stage 1 and 9.5 days in stage 2, i.e., a total of 24.1 days. In total, this alternative will yield an estimated 23 % biogas increase.

If the retention time instead is maintained at 12.2 and 7.9 days, respectively, (20.1 days in total), volumes will be released in the two stages of about 6 400 m^3 (3 900 m^3 and 2 500 m^3, respectively. Maximum utilisation of these volumes means that 5 600 m^3 fatty sludge and 110 000 m^3 food waste slurry may be received yearly, yielding an increase in the biogas production of about 90 %. If the limitations in capacity of the receiving station are kept, and thus 5 600 m^3 fatty sludge and 20 000 m^3 food waste slurry are being received yearly, the estimated increase in biogas production will be about 39 %. The retention time has then increased to 14.0 and 9.1 days, respectively, (a total of 23.1 days).

4.2.e. E. Addition of enzymes

4.2.e.i. General description

Addition of enzymes was considered in Stage 1 an interesting method, provided there are ways to decrease the required dosage of enzymes to a reasonable level. This method is thus independent of the operation and is therefore presented as a separate alternative.

Based on information from the supplier Kemira, the alternative has here been estimated to yield about 15 % of biogas increase. In Stage 1, it was described how the results from trials with additions of enzymes vary among treatment plants. Therefore, tests should be carried out in full scale at Henriksdal to verify the effect.

4.2.f. F. Thermal hydrolysis

4.2.f.i. General description

The introduction of thermal hydrolysis at Henriksdal has been studied earlier at Henriksdal and was presented in a separate report.[27] Using this method, the sludge will have a DS concentration of about 8 % when it enters the anaerobic digester, which corresponds to a flow of about 900 m^3/d. This results in a retention time of 42.1 days. The retention time in the anaerobic digesters may after thermal hydrolysis be reduced to about 16 days due to the faster digestion process. The high DS concentration in combination with the shorter retention time results in the release of about 24 000 m^3 in the anaerobic digesters.

The alternative has earlier been estimated to yield a theoretical biogas increase of about 30 %. In the calculations, the degrees of degradation have estimated to increase by 30 % for primary sludge and biological sludge, 10 % for fatty sludge and 20 % for food waste. This results in a biogas increase of 27 %. The large released digester volume would receive about 5 600 m^3 fatty sludge and 430 000 m^3 food waste slurry yearly, which in theory would yield a biogas increase of more than 300 %. This requires, however, a larger receiving station. If EOM is added up to the current limit of the receiving station, 5 600 m^3 fatty sludge and 20 000 m^3 food waste slurry, the biogas increase will amount to 45 %.

4.2.g. G. Existing digester process + EOM

4.2.g.i. General description

During the reference period, an amount of about 24 400 m3 EOM was received at Henriksdal, mostly as fatty sludge. If the reception of fatty sludge is increased by 5 600 m3 /year, the biogas production is estimated to increase by 3 %. The retention time will then decrease only marginally by 0.1 days to 20.0 days.

If the amounts of EOM shall be increased, the retention time must be decreased slightly, unless another method to decrease the sludge flow is used.

If, in addition to the 5 600 m3 fatty sludge, 20 000 m3 food waste slurry is received, the retention time will decrease to about 19.4 days. In the calculations, the reduction in HRT has been estimated to cause a 0.3 % reduction in biogas production. In total, this yields an estimated 15 % biogas increase at Henriksdal.

4.3. Compilation and comparison of the alternatives in Stage 2

The data for the seven alternatives investigated in Stage 2 are compiled in the tables below. Released anaerobic digester volumes and increased amounts of biogas are calculated using mass balances for each alternative. These are presented in Appendix 1.

Table 10 shows retention times and estimated biogas increase for the seven alternatives.

Table 10. Compilation and comparison of the alternatives in Stage 2. Flow, load and other data are found in Appendix 1.

Alternative	HRT days	Estimated biogas increase %
A. Increased production of primary sludge	18.3	11
B. Pre-thickening + increased production of primary sludge	24.1	15
C. Pre-thickening + serial operation	Stage 1: 15.6 Stage 2: 10.2	10
D. Pre-thickening + increased production of primary sludge + serial operation	Stage 1: 14.6 Stage 2: 9.5	23
E. Addition of enzymes	20.1	15
F. Thermal hydrolysis	42.1	27 (3 % net*)
G. EOM (only additional 5 600 m^3 fatty sludge per year)	20.0	3

* The method requires use of biogas (or similar fuel) for heating. Net = the amount of biogas remaining after biogas consumption for heating is subtracted.

For those alternatives where the retention time is extended, digester volume may instead be released and more EOM received.

Table 11 shows the estimated biogas increase when EOM is received to the maximum capacity of the existing receiving station, i.e., another 25 600 m^3/yr are received in those alternatives where volume can be released. The resulting retention time is also shown in the table.

Table 11. Increased biogas production for the alternatives in Stage 2 with reception of 25 600 m³ EOM per year (i.e., the maximum capacity of the receiving station) for those alternatives where volume is released. Data are found in Appendix 1.

Alternative	HRT days	Estimated biogas increase % at reception of another 25 600 m³ EOM per year (maximum capacity of receiving station) (5 600 m³ fatty sludge + 20 000 m³ food waste slurry, 10 % DS)
A. Increased production of primary sludge	18.3	No released volume
B. Pre-thickening + increased production of primary sludge	23.1	30
C. Pre-thickening + serial operation	Step 1: 14.9 Step 2: 9.7	26
D. Pre-thickening + increased production of primary sludge + serial operation	Step 1: 14.0 Step 2: 9.1	39
E. Addition of enzymes	20.1	No released volume
F. Thermal hydrolysis	38.8	45 (20 net*)
G. EOM (additional 5 600 m³ fatty sludge + 20 000 m³ food waste slurry per year)	19.4	15

* The method requires use of biogas (or similar fuel) for heating. Net = the amount of biogas remaining after biogas consumption for heating has been subtracted.

Table 12 below shows the anaerobic digester volumes that are released if the original retention time 20.1 d is maintained. The table also shows the maximum amount of EOM that can be received to utilise these volumes and the estimated corresponding biogas increase.

Table 12. Maximum utilisation of theoretically released volume with EOM at retention time 20.1 d for the alternatives (16 d at thermal hydrolysis). Data are found in Appendix 1.

Alternative	Released volume m^3	HRT days	Reception of EOM for maximum utilisation of released volume		Estimated biogas increase % at maximum utilisation of released volume
			Fatty sludge m^3/yr	Food waste slurry (10 % DS) m^3/yr	
A. Increased production of primary sludge	-	18.3	-	-	-
B. Pre-thickening + increased production of primary sludge	6 400	20.1	5 600	110 000	83
C. Pre-thickening + serial operation	Step 1: 5 100 Step 2: 3 300	Step 1: 12.2 Step 2: 7.9	5 600	150 000	100
D. Pre-thickening + increased production of primary sludge + serial operation	Step 1: 3 900 Step 2: 2 500	Step 1: 12.2 Step 2: 7.9	5 600	110 000	90
E. Addition of enzymes	-	20.1	-	-	-
F. Thermal hydrolysis	24 000	16.0	5 600	430 000	340 (280 net*)
G. EOM (additional 5 600 m^3 fatty sludge + 20 000 m^3 food waste slurry per year)	-	19.4	5 600	20 000	15

* The method requires use of biogas (or similar fuel) for heating. Net = the amount of biogas remaining after biogas consumption for heating has been subtracted.

The tables above show that the alternative F, thermal hydrolysis is the alternative that yields the greatest biogas increase and the greatest released digester volume. However, thermal hydrolysis requires methane gas to be utilised as a complement to district heating for the heating of the sludge. The estimated consumption is about 4 300 Nm^3 CH_4/d, based on earlier calculations[27]. This means that the net increase of the methane production in the alternative thermal hydrolysis only amounts to about 500 Nm^3 CH_4 per day (about 3 %, see Table 10). At the addition of 5 600 m^3 fatty sludge and 20 000 m^3 food waste slurry, the gas consumption is estimated to be about 4 600 Nm^3 CH_4 /d, and the net increase in gas production 3 400 Nm^3 CH_4 per day (about 20 %), based on the same study.

The largest net increase in biogas production without the reception of additional EOM is obtained in alternative D, serial digestion with pre-thickening of primary sludge and increased production of primary sludge. Similarly, alternative D also yields the largest increase with an addition of 5 600 m^3 fatty sludge and 20 000 m^3 food waste slurry, about 39 %. However, the alternative with thermal hydrolysis yields a very large available digester volume, where a maximum of 5 600 m^3 fatty sludge and a huge amount, 432 000 m^3, of food waste slurry could be received. This would then yield the greatest net biogas increase of about 280 %, i.e., when the biogas consumption for the heating has been subtracted (a gross methane increase of about 60 400 Nm^3 CH_4/d and a heat requirement of 11 200 Nm^3 CH_4/d yield a net increase of 49 200 Nm^3 CH_4/d). The second largest available volume appear in alternative C, pre-thickening and serial operation, where 5 600 m^3 fatty sludge and about 150 000 m^3 food waste slurry could be received, yielding a biogas increase of about 100 %. Both these last two alternatives require, however, a larger receiving station than 50 000 m^3/year and the possibility to collect a large amount of food waste.

5. Stage 3

In Stage 3, investments, and operational and yearly costs were roughly estimated for the selected alternatives. The cost estimates are presented in detail in Appendix 4 and summarised below. The costs were estimated based on the descriptions of required measures that are presented in Stage 2, above.

To assess the cost effectiveness for the different alternatives, the changes in yearly costs compared with the reference alternative have been calculated. The calculations are presented in Appendix 4. The calculations do not include costs or revenue for the reception of fatty sludge and food waste. The potential additional costs for nitrogen removal at Henriksdal have not been considered either in the calculations. The change in total yearly cost for each alternative has then been divided by the net increase in methane production, yielding a measure of cost effectiveness. This is shown in Table 16.

5.1. Cost estimates for the alternatives

5.1.a. A. Increased production of primary sludge

The introduction of a new chemical dosage to increase the production of primary sludge requires the extension of the existing chemical dosage system with two tanks for dosage of polymers. It is here assumed that these are installed in the existing area. The current dosage of ferrous sulphate is replaced by the dosage of ferric chloride, while keeping the current dosage. The ferric chloride that has been a basis for the cost estimates is a pure product that does not include other metals.

The investment for a new system for polymer dosage, including auxiliary equipment is estimated to be about 0.4 MEUR.

The operational cost of chemicals for an increased production of primary sludge is estimated to increase by 0.2 MEUR/yr, based on the following assumptions.

If triple dosage is introduced, the amount of chemical dosages is calculated to be:

Ferric chloride 30 ml/m^3 wastewater with a cost of 88 EUR/m^3

Polymer 1 2 ml/ m^3 wastewater with a cost of 2.0 EUR/l

Polymer 2 0.2 g/m^3 wastewater with a cost of 2.9 EUR/kg

Based on 240 000 m^3 wastewater per day, the cost becomes 1 720 EUR/d, which should be compared with the current cost of 1 200 EUR/d (at a price of ferrous sulphate of 59 EUR/tonne). It will, however, be possible to make savings in the other processes at the plant, for instance through a lower oxygen demand in the biological stage. Another advantage gained by replacing the ferrous sulphate is that ferrous sulphate contains certain unwanted metals, which can thus be avoided.

5.1.b. B. Pre-thickening of primary sludge + increased production of primary sludge

Pre-thickening trials are currently being planned at Henriksdal. One of the primary sedimentation basins will then be reconstructed to obtain a thicker primary sludge. The reconstruction includes for instance the installation of a new gate mixer (instead of the present paddle mixer) in one sludge hopper, and a new primary sludge pump. The estimated increase from the current 3.6 % DS to 5 % DS is assumed to be the result of this reconstruction. If the results of the trial prove satisfactory, reconstruction of all the basins may ensue.

The total cost for the reconstruction amounts to about 64 000 EUR for a ”test hopper” (a basin contains two hoppers). If all of the sludge hoppers are reconstructed, the cost will be about 59 000 EUR/basin, i.e., for 13 basins, each with two hoppers, a total of 0.8 MEUR.

The investment for increased production of primary sludge is, as earlier specified, 0.4 MEUR.

Total investment: 1.2 MEUR.

5.1.c. C. Pre-thickening of primary sludge + serial operation with two digestion stages

Pre-thickening as above, 0.8 MEUR.

The costs for the conversion to serial operation are here based on the description in Stage 2, see Chapters 3.1.d.iii. and 4.2.c. The sludge is then assumed to be pumped from step 1 to step 2. At the conversion to anaerobic digestion in series, the two existing pumps could be utilised to pump the sludge from the anaerobic digesters 4-7 to the anaerobic digesters 1-3. However, the system requires the installation of additional pumps and pressurised pipeline to and from the anaerobic digesters 1-3. New pumps for each anaerobic digester will be required to evacuate the sludge from the anaerobic digesters 1-3. It is suggested that the pressurised pipeline be placed in an existing passage that leads to the existing pump room for heat exchange, as described in Stage 1. The pumps for sludge pumping from anaerobic digesters 1, 2 and 3, should be installed directly adjacent to each anaerobic digester.

The investment for the conversion to serial digestion according to the description above is estimated to be in the order of 0.3 MEUR.

Total cost of investment: 1.1 MEUR.

5.1.d. D. Pre-thickening of primary sludge + increased production of primary sludge + serial operation

Investment include:

Pre-thickening, according to above, about 0.8 MEUR.

Increased production of primary sludge: according to above, 0.4 MEUR.

Serial operation, according to the above, about 0.3 MEUR.

Total: approximately 1.5 MEUR.

The operational cost increases due to the increased amounts of precipitation chemicals.

5.1.e. E. Addition of enzymes

The supplier Kemira has performed tests with the addition of enzymes at five wastewater treatment plants. In the information that is possible to obtain from these tests, Kemira states that at an addition of enzymes at a cost of 0.1 EUR, 0.28 EUR will be returned in the form of increased biogas production and reduced sludge amounts. These numbers are based on a 25 % biogas increase.

Kemira has helped in estimating the approximate costs for a 15 % biogas increase at Henriksdal by the addition of enzymes. The company estimates that this increase corresponds to a cost of approximately 2 000 EUR/day based on unpublished supplier tests, i.e., 0.72 MEUR/yr. The cost may naturally be adjusted if trials with enzyme additions are performed at Henriksdal.

The dewatering properties for the sludge appear to improve after the addition of enzymes, and dewatering of the sludge to about 30 % DS should be possible, which would result in a cost saving of 0.221 MEUR/yr for the removal of the sludge. The polymer costs will decrease by about 0.024 MEUR/yr. In total, the cost for a 15 % biogas increase by the addition of enzymes will amount to 0.47 MEUR/yr.

The investment for enzyme dosage equipment is estimated to about 0.2 MEUR.

5.1.f. F. Thermal hydrolysis

Based on the earlier proposed technical solution with the corresponding cost assessment for the introduction of thermal hydrolysis at Henriksdal, adjusted to today's level of cost, the cost of the system is estimated to 12 MEUR. More ammonium nitrogen, that requires nitrogen removal, can be expected to be released, see Chapter 3.2.d.iii. The cost of additional nitrogen removal is not included.

5.1.g. G. Existing digestion process + EOM

As mentioned earlier, Stockholm Vatten is currently preparing to increase the reception of EOM. A decision has been made to increase the capacity of the existing receiving station from today's 25 000 m^3/yr to about 50 000 m^3/yr pumpable waste.

In the case where even larger amounts of EOM shall be received, in addition to these 50 000 m^3/yr, more extensive investments will be required. It has not been part of this study to estimate such costs, nor potential costs for treatment of supernatant from the sludge dewatering.

5.2. Investment costs

The investment costs for each investigated alternative were roughly assessed based on the above descriptions of the required measures.

The investment costs include:

- Mechanical works
- Civil works and ventilation
- Electrical works and automation
- Unforeseeable costs, 10 %
- Engineering costs (design and implementation)

The total estimated project costs including engineering are presented in Table 13, below.

Table 13. Estimated plant costs for the alternatives.

Alternative	Plant cost MEUR
A. Increased production of primary sludge	0.5
B. Pre-thickening + increased production of primary sludge	1.2
B. + 25 600 m^3 EOM/yr	1.2*
C. Pre-thickening + serial operation	1.1
C. + 25 600 m^3 EOM/yr	1.1*
D. Pre-thickening + increased production of primary sludge + serial operation	1.5
D. + 25 600 m^3 EOM/yr	1.5*
E. Addition of enzymes	0.3
F. Thermal hydrolysis	12
F. + 25 600 m^3 EOM/yr	12*
G. 25 600 m^3 EOM/yr	0*

* The costs for extension of the receiving station for EOM are not included, nor the costs for treatment of the supernatant from the sludge dewatering.

5.3. Operational costs

The change in operational costs compared with the reference alternative that each alternative will lead to are presented in Table 14, below. The operational costs include:

- Chemicals
  - Precipitation chemicals
  - Polymers for sludge pre-thickening and final sludge dewatering
  - Enzymes
- Energy consumption
  - Electrical energy
  - Heat
- Maintenance
- Personnel

Table 14. Estimated change in operational cost for the investigated alternatives, kEUR/yr.

Alternative	Chemicals	Electricity	Heat (district heat)	Maintenance	Personnel	Change in total operational cost*
A. Increased production of primary sludge	220	0	160	10	0	380
B. Pre-thickening + increased production of primary sludge	210	20	-120	20	0	120
B. + 25 600 m³ EOM/yr	230	20	-90	20	0	180
C. Pre-thickening + serial operation	-20	60	-230	10	0	-180
C. + 25 600 m³ EOM/yr	0	60	-190	10	0	-120
D. Pre-thickening + increased production of primary sludge + serial operation	190	60	-120	20	0	150
D. + 25 600 m³ EOM/yr	210	60	-90	20	0	210
E. Addition of enzymes	690	0	0	0	0	700
F. Thermal hydrolysis	-50	150	-650**	230	20	-300
F. + 25 600 m³ EOM/yr	-40	150	-620**	230	20	-250
G. 25 600 m³ EOM/yr	20	0	40	0	0	60

* costs for pretreatment of EOM are not included

** costs for utilisation of biogas are not included

5.4. Annual costs

Based on the cost assessments for investments and operations, the changes in yearly costs have been compiled. These also include changes in the costs for sludge removal, since the different alternatives affect the amounts of dewatered sludge. Assumptions for the calculations are:

- Write-off time, mechanical works and others: 15 years
- Write-off time, civil works: 30 years
- Interest rate: 5 %
- Electricity, price: 0.10 EUR/kWh
- District heating, price: 0.06 EUR/kWh
- Sludge removal: 27.9 EUR/tonne dewatered sludge (28 % DS)

Table 15. Estimates of change in annual cost for the alternatives, kEUR/yr.

Alternative	Change in total operational cost* kEUR/yr	Capital cost kEUR/yr	Sludge transports kEUR/yr	Estimated total change in annual cost kEUR/yr
A. Increased production of primary sludge	380	50	90	520
B. Pre-thickening + increased production of primary sludge	120	110	60	300
B. + 25 600 m³ EOM/yr	180	110	160	450
C. Pre-thickening + serial operation	-180	110	-100	-170
C. + 25 600 m³ EOM/yr	-120	110	-10	-20
D. Pre-thickening + increased production of primary sludge + serial operation	150	150	-30	270
D. + 25 600 m³ EOM/yr	210	150	70	420
E. Addition of enzymes	700	20	-220	500
F. Thermal hydrolysis	-300**	1110	-550	260
F. + 25 600 m³ EOM/yr	-250**	1110	-500	360
G. 25 600 m³ EOM/yr	60	0	100	160

* cost for pretreatment of EOM is not included

** cost for utilisation of biogas is not included

Table 16. Gross and net methane increase with corresponding costs for each alternative. The cost effectiveness is calculated as change in annual cost per net CH_4 gas increase, EUR/Nm^3 CH_4[1].

Alternative	Estimated total change in annual cost (kEUR/yr)	Total gas increase per day (Nm^3 CH_4/d)	Total gas increase per year (Nm^3 CH_4/yr)	Net gas increase per day (Nm^3 CH_4/d)	Net gas increase per year (Nm^3 CH_4/yr)	**Cost effectiveness Change in annual cost per Nm^3 CH_4 net increase (EUR/Nm^3 CH_4)**
A. Increased production of primary sludge	520	2 000	730 000	2 000	730 000	**0.71**
B. Pre-thickening + increased production of primary sludge	300	2 600	940 000	2 600	940 000	**0.32**
B. + 25 600 m^3 EOM/yr	450	5 300	1 900 000	5 300	1 900 000	**0.23**
C. Pre-thickening + serial operation	-170	1 800	640 000	1 800	640 000	**-0.26**
C. + 25 600 m^3 EOM/yr	-20	4 500	1 700 000	4 500	1 700 000	**-0.01**
D. Pre-thickening + increased production of primary sludge + serial operation	270	4 100	1 500 000	4 100	1 500 000	**0.18**
D. + 25 600 m^3 EOM/yr	420	6 800	2 500 000	6 800	2 500 000	**0.17**
E. Addition of enzymes	500	2 700	970 000	2 700	970 000	**0.52**
F. Thermal hydrolysis	260	4 800	1 700 000	500	190 000	**1.4**
F. + 25 600 m^3 EOM/yr	360	8 000	2 900 000	3 400	1 200 000	**0.29**
G. 25 600 m^3 EOM/yr	160	2 700	980 000	2 700	980 000	**Not estimated**

1) Data for the methane production increase are presented in the summary table in Appendix 1. Cost estimates are found in Appendix 4 and summarised in Tables 13, 14 and 15.

The cost estimates do not include costs for a receiving station for EOM. Neither is revenue from receiving fees for the EOM included or potential costs for additional nitrogen removal at Henriksdal.

5.5. Results and discussion

Table 16 shows that **alternative C, pre-thickening + serial operation**, appears to have the greatest potential in terms of cost effectiveness. In absolute numbers, however, the increase in gas production for alternative C is the lowest of the investigated alternatives, about 0.64 MNm^3 CH_4/yr (1 800 Nm^3 CH_4/d).

If the method is implemented and results in the expected gas increase, savings of 0.26 EUR/Nm^3 CH_4 net increase will be obtained immediately. The savings are primarily due to the pre-thickening, which leads to savings in cost of heating, in combination with relatively limited investment and operational costs. At the same time, the sludge amounts decrease due to the increased degradation, which leads to significant savings in the cost of sludge removal. This alternative presupposes that the cost of conversion can be kept at a reasonable level, i.e., in practice, that the installation of the required equipment can take place in the existing areas without extensions in the rock. We have here assessed that this is feasible. However, verification is required prior to continued studies.

If additional amounts of EOM are received, the savings drop to about 0.01 EUR/Nm^3 CH_4, mainly due to the increased amounts of dewatered sludge. The revenues from selling of the biomethane (not included in the calculations) will most probably increase.

The second most cost effective alternative is **alternative D, pre-thickening in combination with increased production of primary sludge and serial operation**, 0.18 EUR/Nm^3 CH_4 net increase. Increased amounts of primary sludge lead to higher cost for the removal of sludge, but this is balanced to a large extent by the effect of pre-thickening (compare alternative A, only increased production of primary sludge, where the change in annual cost per increased Nm^3 methane amounts to 0.71 EUR). The conclusion from this is that an increase in the production of primary sludge is only interesting in combination with pre-thickening of sludge (with the assumptions regarding precipitation methods that have been made here; there may be more optimal combinations of precipitation agents.).

The combination becomes even more interesting if more EOM is received. With an additional 25 600 m^3/yr EOM, the cost amounts to 0.17 EUR/Nm^3 CH_4 net increase.

Thermal hydrolysis yields the largest gross gas increase, but is associated with a high investment cost. With 1.4 EUR/Nm^3 CH_4 net increase, this alternative is significantly less cost-effective compared with the other alternatives. The main reason for this is that a large part of the obtained increase in gas production is utilised to heat the sludge in the hydrolysis process. It is, however, the method that releases the largest anaerobic digester volume and the only one of the proposed alternatives that leads to a hygienisation of the digested sludge. Thermal hydrolysis becomes a considerably more cost-effective method if the EOM potential is used, but it is still the least advantageous method of those alternatives that include the addition of 25 600 m^3 EOM/yr.

The alternative E, enzymes, obtains an estimated cost of 0.52 EUR/Nm^3 CH_4 net increase. The alternative requires a very low cost of investment and the operational costs are low in addition to the actual cost of the enzymes. However, of the assessments made here, the addition of enzymes is the method that is associated with the greatest uncertainties regarding the dosage and the costs.

The addition of EOM generally improves the cost effectiveness for the different alternatives (see B, C, D, F), but it must be noted here that the cost of investment for the reception of the food waste has not been included, which makes the comparison less relevant. However, the trend is the same for the four EOM alternatives.

6. Conclusion and recommendations

Based on the results in this study and the above discussion, the following conclusions are drawn:

- Aside from the already implemented measures, several interesting methods to increase the biogas production at Henriksdal are assessed as possible to implement.
- Extensive pre-thickening of the sludge should be carried out regardless of the method introduced. Pre-thickening of the sludge is a method that releases anaerobic digester volume, and it also has a very positive effect on the energy consumption for the heating of the anaerobic digesters. Stockholm Vatten has started full scale trials during 2009 for the purpose of increasing the DS concentration of the primary sludge.
- To increase the biogas production by at least 10 %, three alternatives are interesting for further investigation:
  - **Alternative C. Pre-thickening + serial operation**
  - **Alternative D. Pre-thickening + increased production of primary sludge + serial operation**
  - **Alternative B. Pre-thickening + increased production of primary sludge**

Table 17. Compilation of the three alternatives that were identified as interesting for further studies, and the reception of EOM for these alternatives[1].

	Gas increase %	Net gas increase Nm^3 CH_4/yr	Investment cost MEUR	Change in annual cost MEUR/yr	**Cost effectiveness** **Change in annual cost per Nm^3 CH_4 net increase (EUR/Nm^3 CH_4)**
C. Pre-thickening + serial operation	**10**	**640 000**	**1.1**	**-0.17**	**-0.26**
C. + 25 600 m^3 EOM	26	1 700 000	1.1	-0.02	-0.01
D. Pre-thickening + increased PS production + serial operation	**23**	**1 500 000**	**1.5**	**0.27**	**0.18**
D. + 25 600 m^3 EOM	39	2 500 000	1.5	0.42	0.17
B. Pre-thickening + increased PS production	**15**	**940 000**	**1.2**	**0.30**	**0.32**
B. + 25 600 m^3 EOM	30	1 900 000	1.2	0.45	0.23

1) Data for the methane production increase is found in the compilation table in Appendix 1. Cost calculations are found in Appendix 4 and summarised in Tables 13, 14 and 15 above.

The cost calculations do not include costs for a receiving station for EOM. Nor is revenue from receiving fees for EOM or potential additional costs for nitrogen removal at Henriksdal included.

- The greatest net increase of the biogas production is obtained through alternative D, serial operation in combination with an increased production and pre-thickening of primary sludge, about 23 %. Alternative D also yields the greatest biogas increase when 5 600 m^3 fatty sludge and 20 000 m^3 food waste slurry are added, 39 %.
- Prior to continuing these studies, it is recommended that precipitation tests as well as anaerobic digestion tests (serial operation) are carried out to verify the assessments of the biogas increase and the potential effects on the processes at the Henriksdal WWTP, and to give further guidance in the final selection of suitable measures.
- Addition of enzymes, electroporation and ozone treatment are three interesting methods with great potential that are under development, and the results can be expected to improve during the coming years. The development should therefore be monitored closely, possibly also through trials together with the different suppliers. Trials regarding ozone treatment of sludge will shortly be initiated by IVL Svenska miljöinstitutet AB, and Stockholm Vatten will also be involved in this study.
- Thermal hydrolysis yields the greatest gross biogas increase, and the method becomes more cost-effective if greater amounts of EOM are received. However, the method is still the least cost-effective method of the alternatives that include the addition of 25 600 m^3 EOM/yr. Thermal hydrolysis is the only one of the proposed alternatives that leads to a hygienisation of the sludge. It is, however, undoubtedly the most complex and space–demanding method of the alternatives that have been compared here. It is also associated with the highest risk for operational problems. Thermal hydrolysis, however, might result in fewer problems with foaming in the anaerobic digester. The reason for this is that both filamentous and hydrophobic structures are degraded at high temperatures. Assessment of the suitability of thermal hydrolysis when large amounts of EOM are received requires a more complete analysis of the costs.

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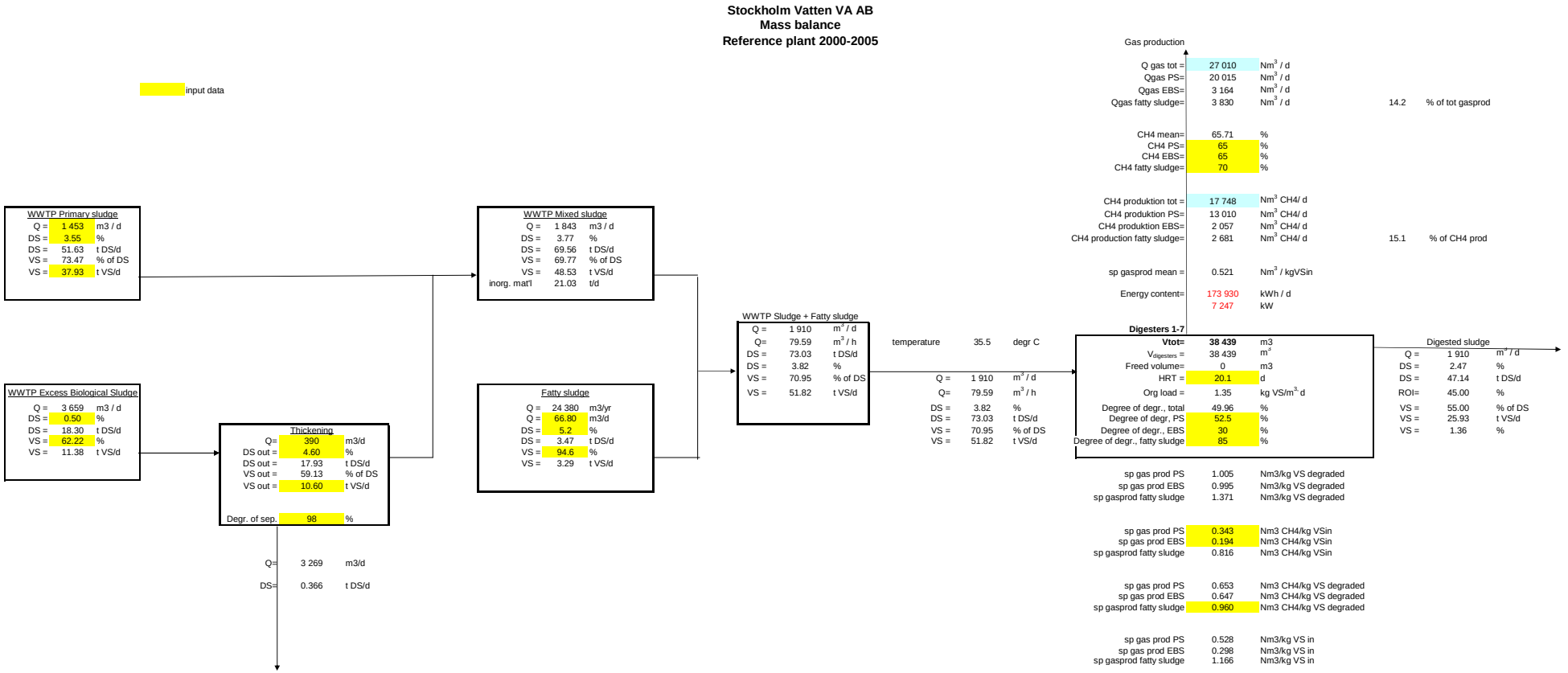
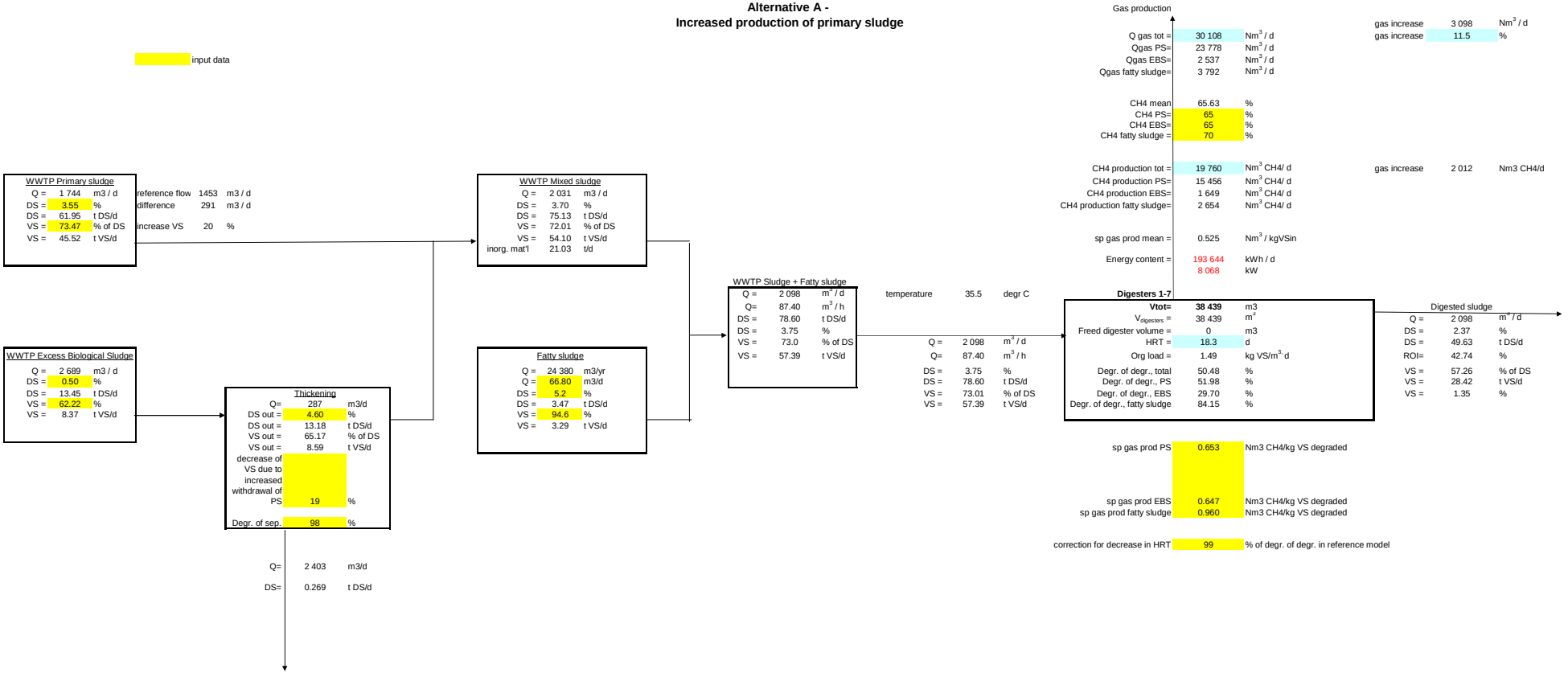
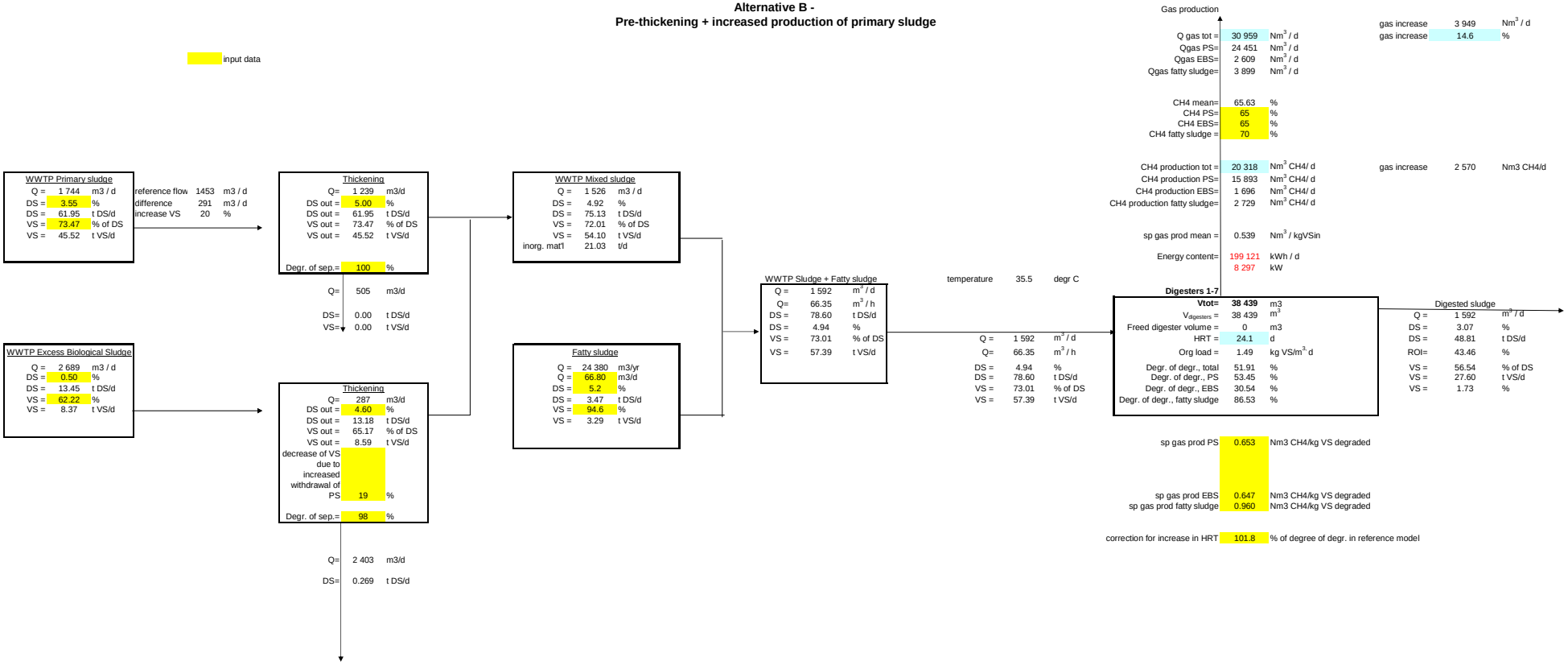
Appendix I - Mass balances and compilation of data



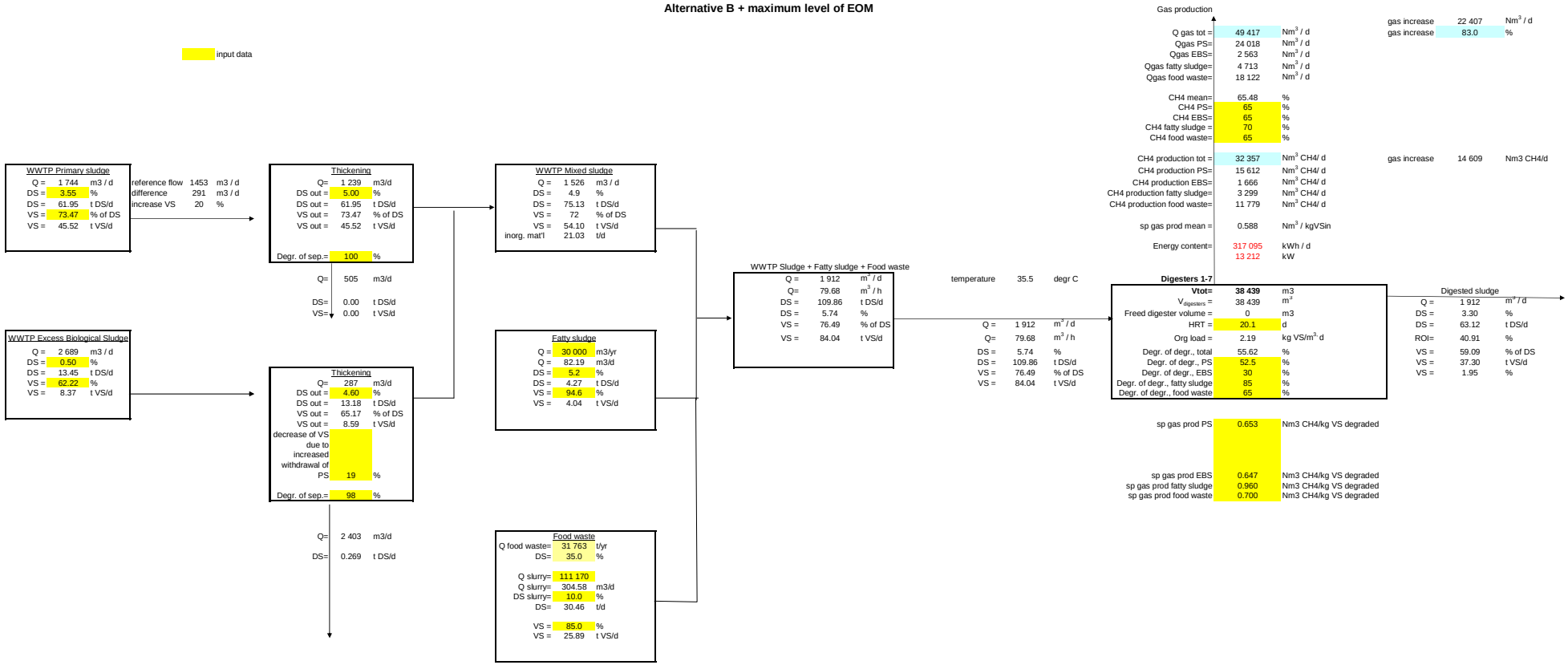
Stockholm Vatten VA AB
Mass balance
Alternative A -
Increased production of primary sludge



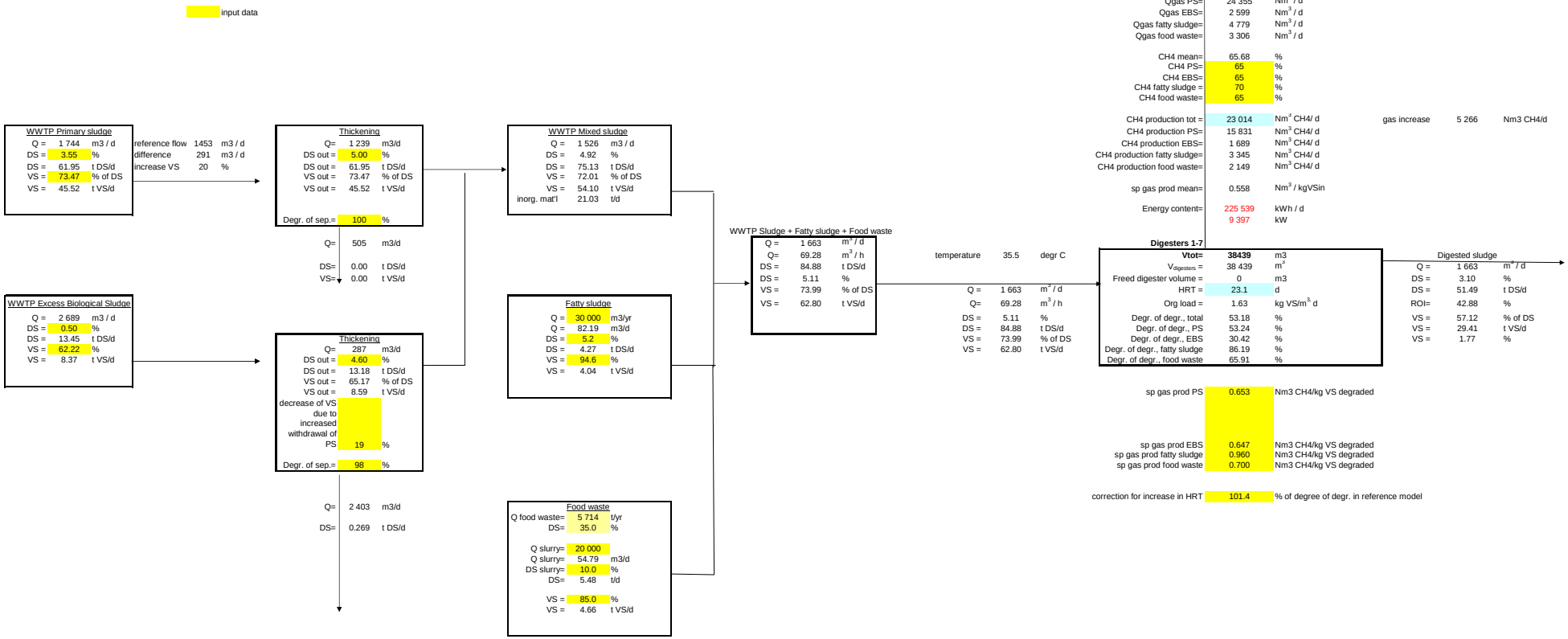
Stockholm Vatten VA AB
Mass balance
Alternative B -
Pre-thickening + increased production of primary sludge



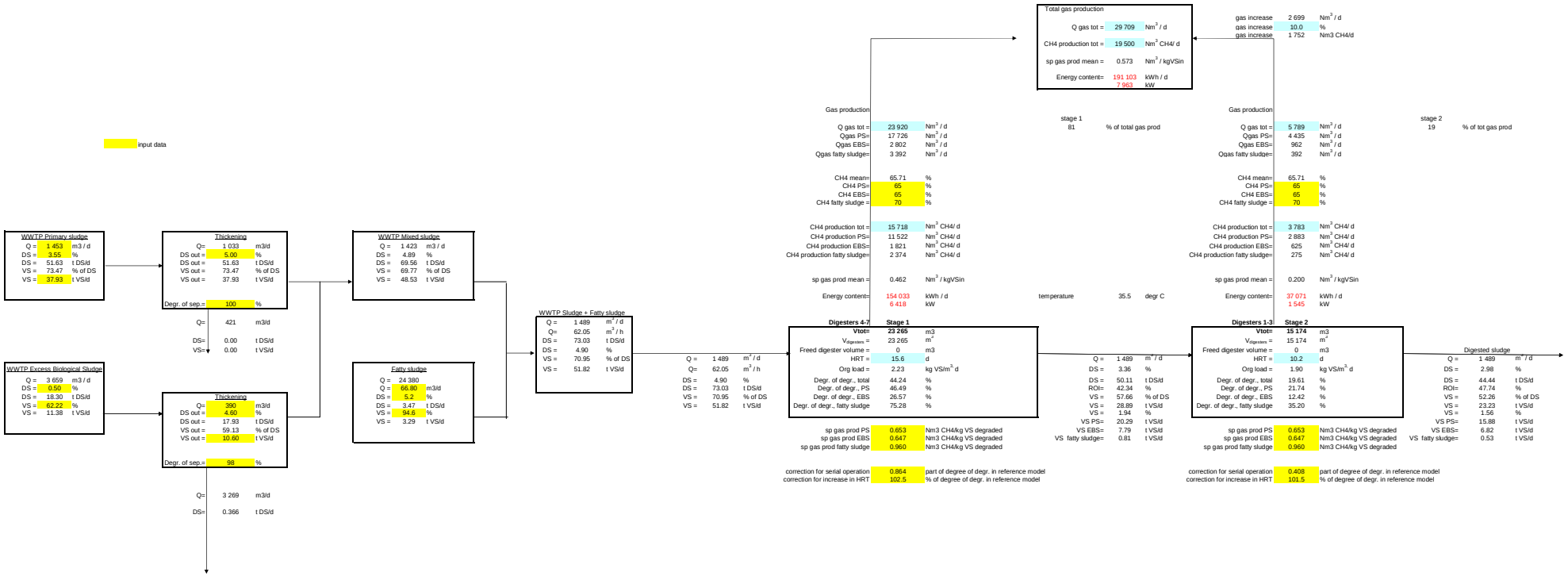
Stockholm Vatten VA AB
Mass balance
Alternative B + maximum level of EOM



Stockholm Vatten VA AB
Mass balance
Alternative B + 25 600 m3 EOM/yr



Stockholm Vatten VA AB
Mass balance
Alternative C -
Pre-thickening + serial operation



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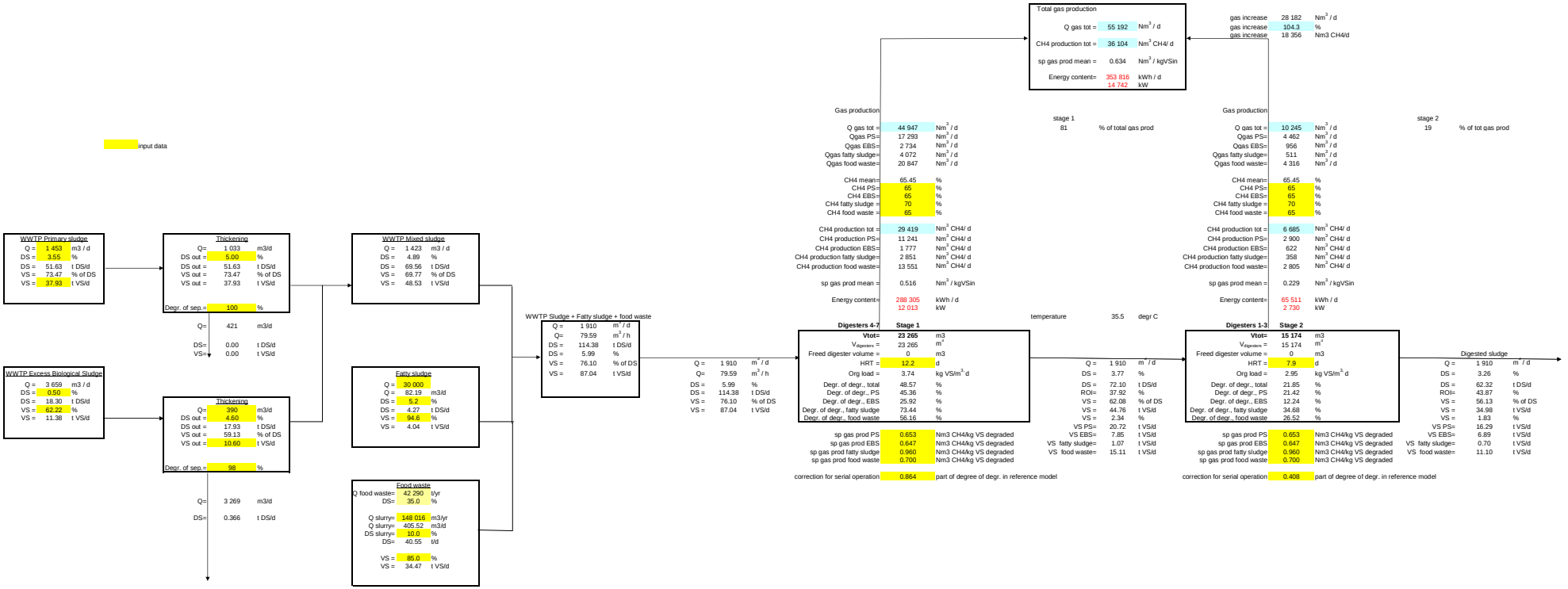
Mass balance
Alternative C + maximum level of EOM



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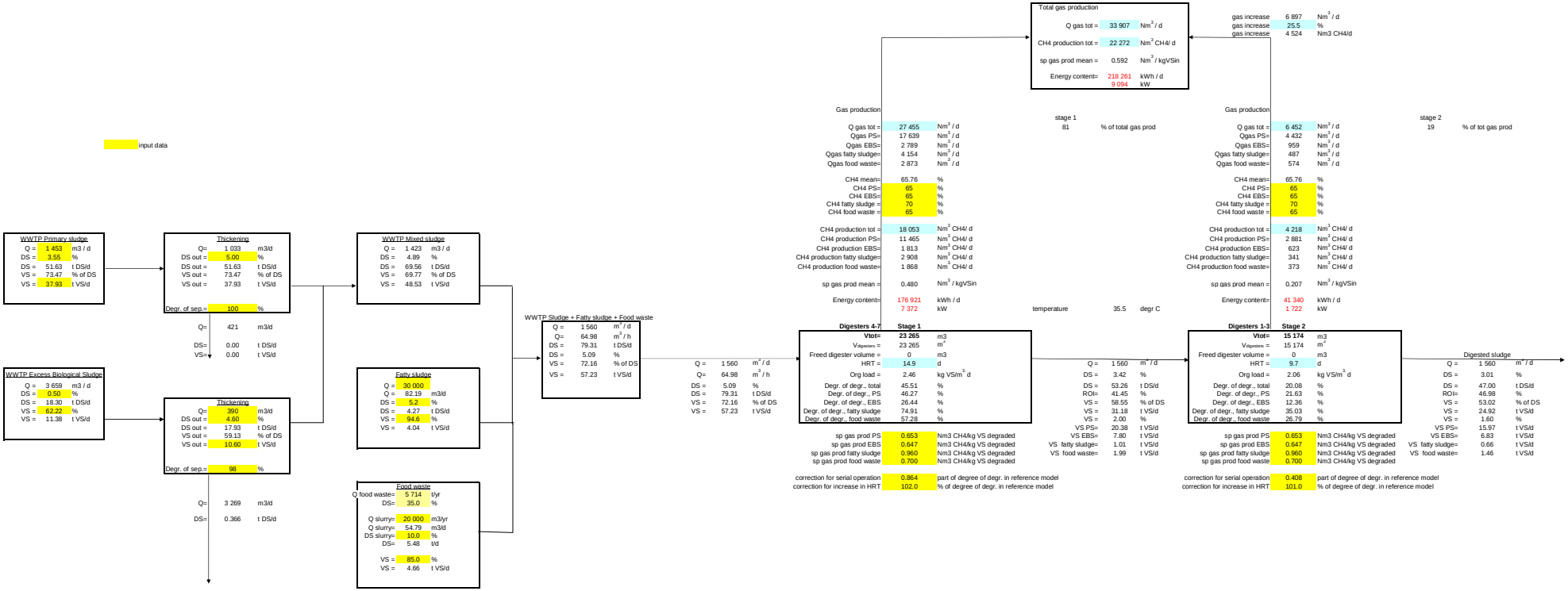
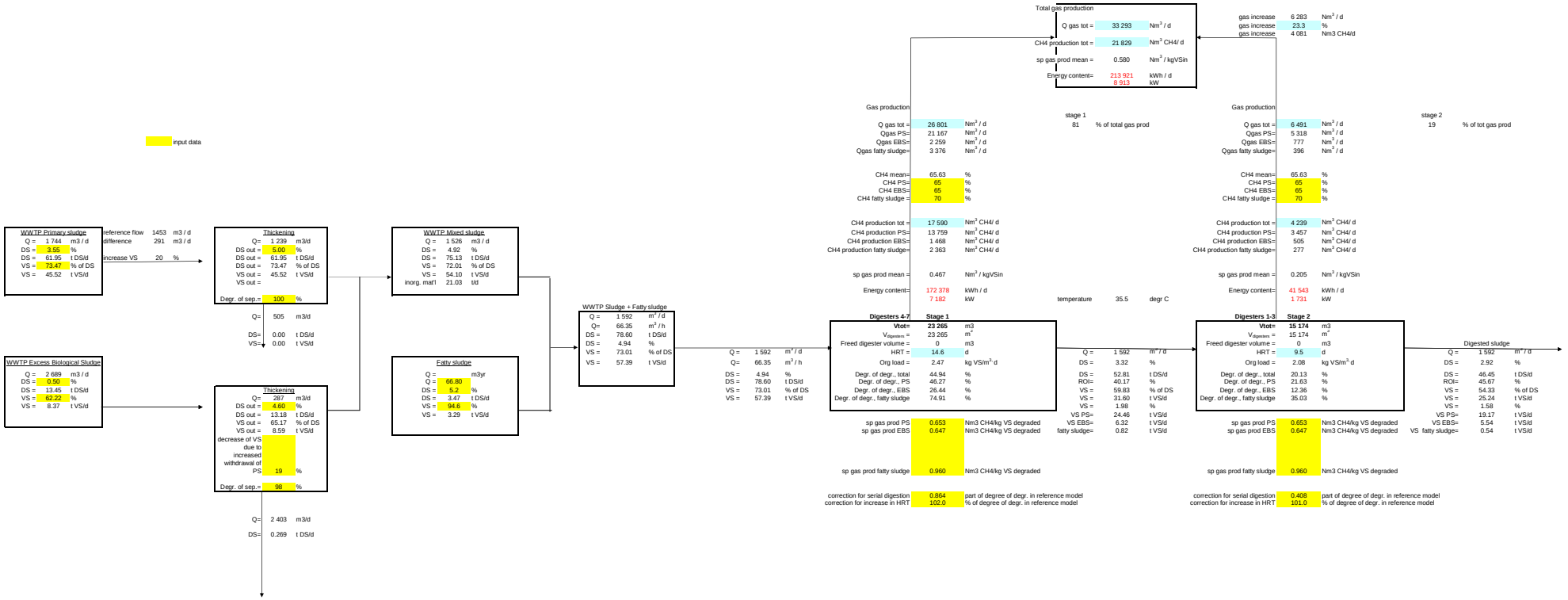
Mass balance
Alternative C + 25 600 m3 EOM/yr



Stockholm Vatten VA AB
Mass balance
Alternative D -
Pre-thickening + increased production of primary sludge + serial operation



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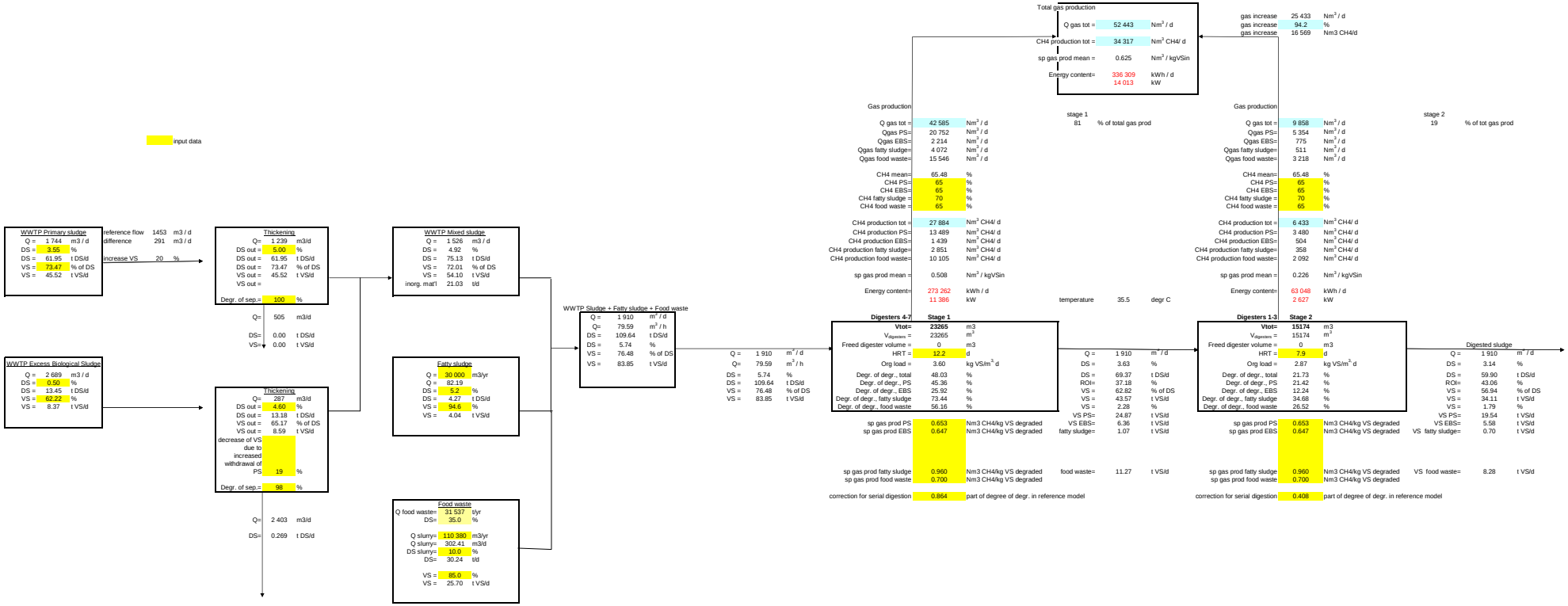
Mass balance
Alternative D + maximum level of EOM



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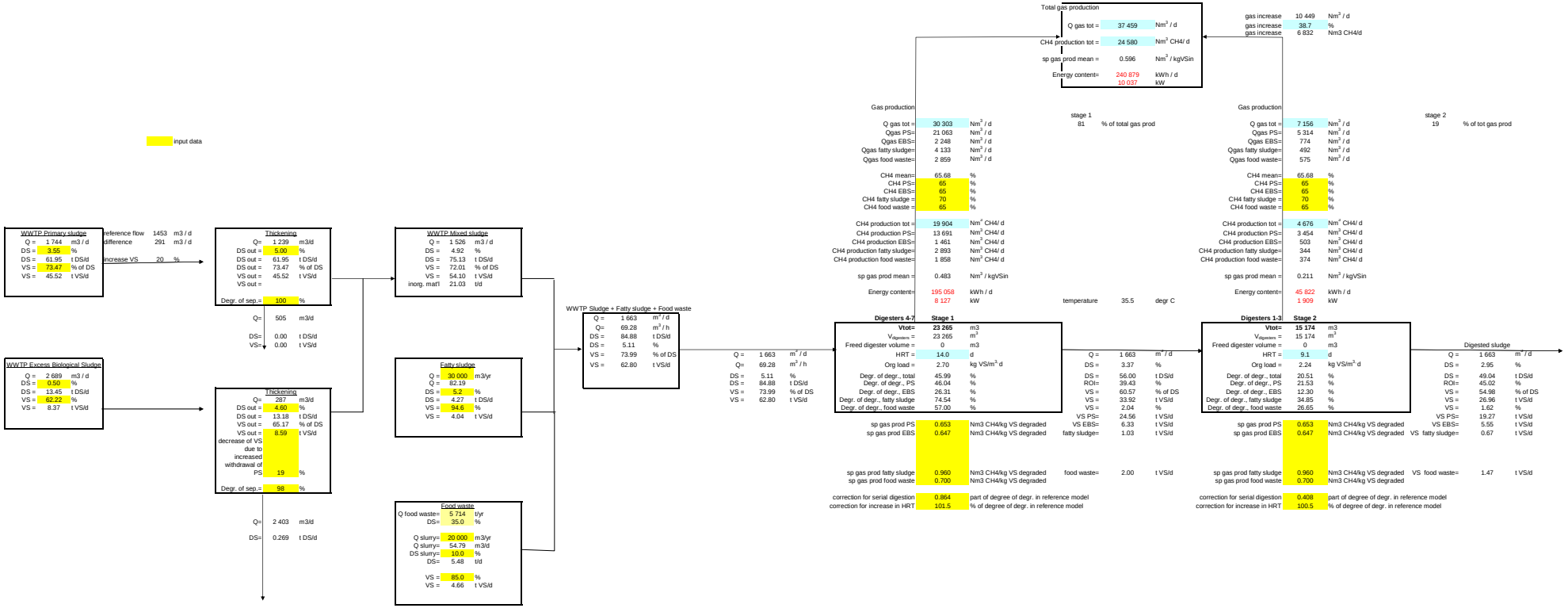
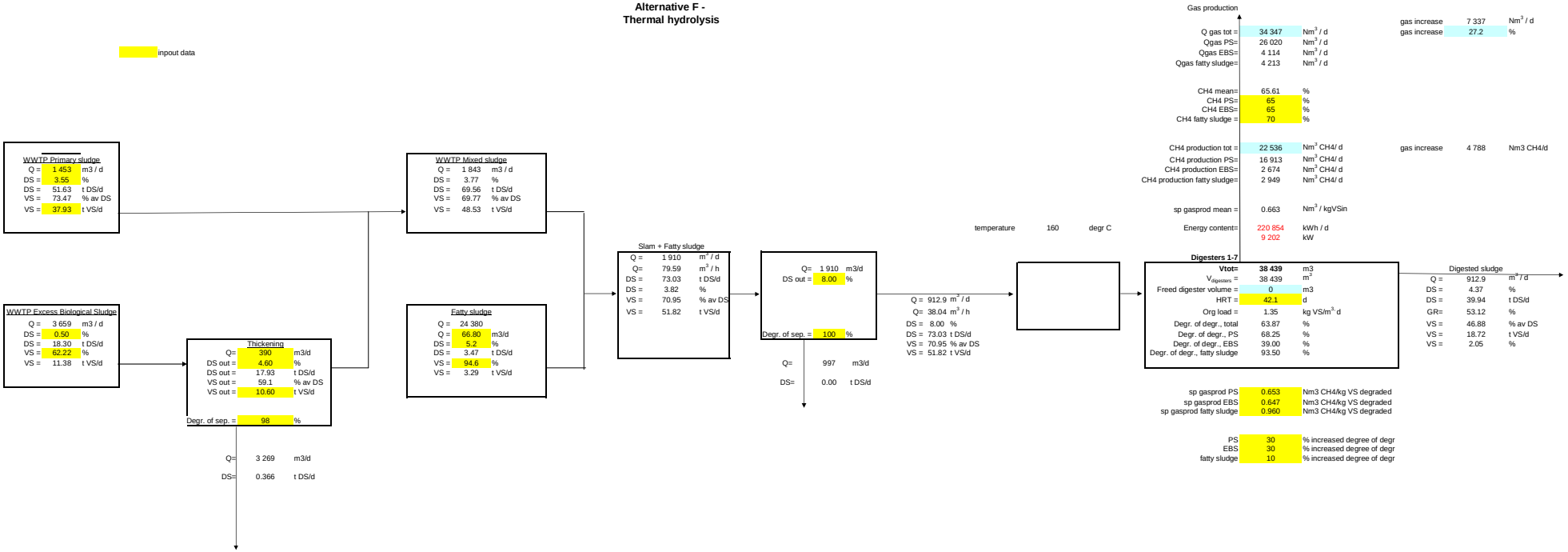
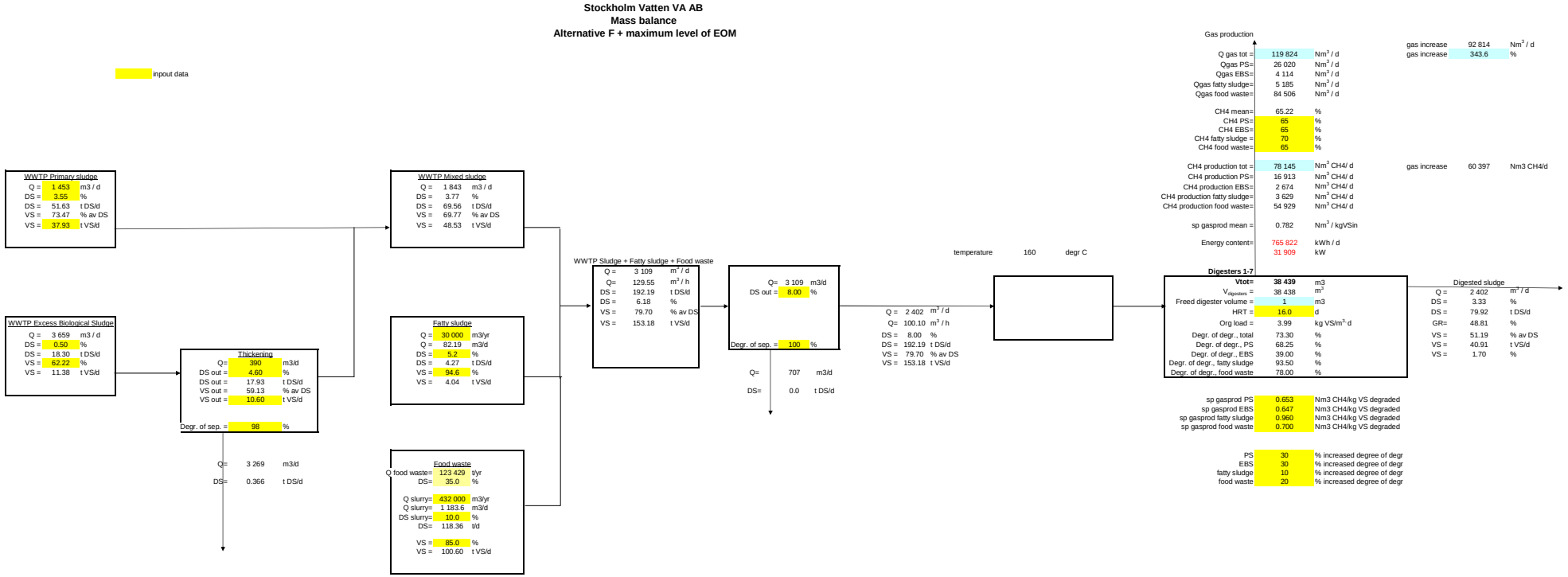
Mass balance
Alternative D + 25 600 m3 EOM/yr



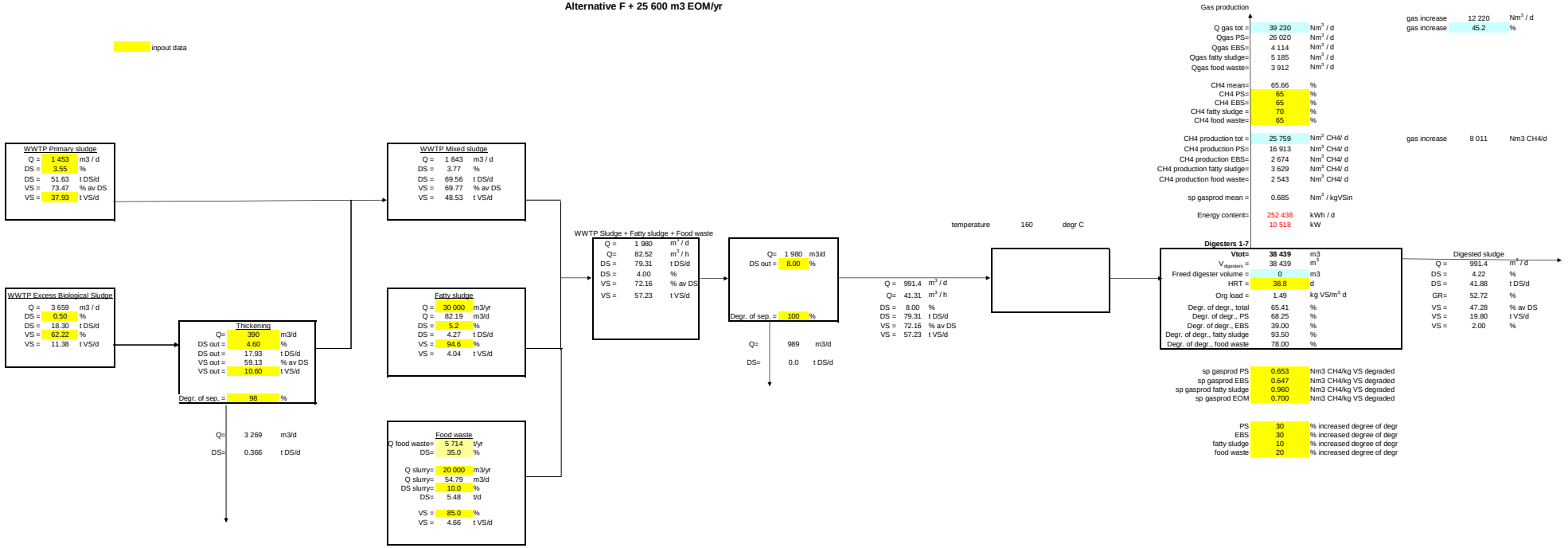
Stockholm Vatten VA AB
Mass balance
Alternative F -
Thermal hydrolysis

inpout data



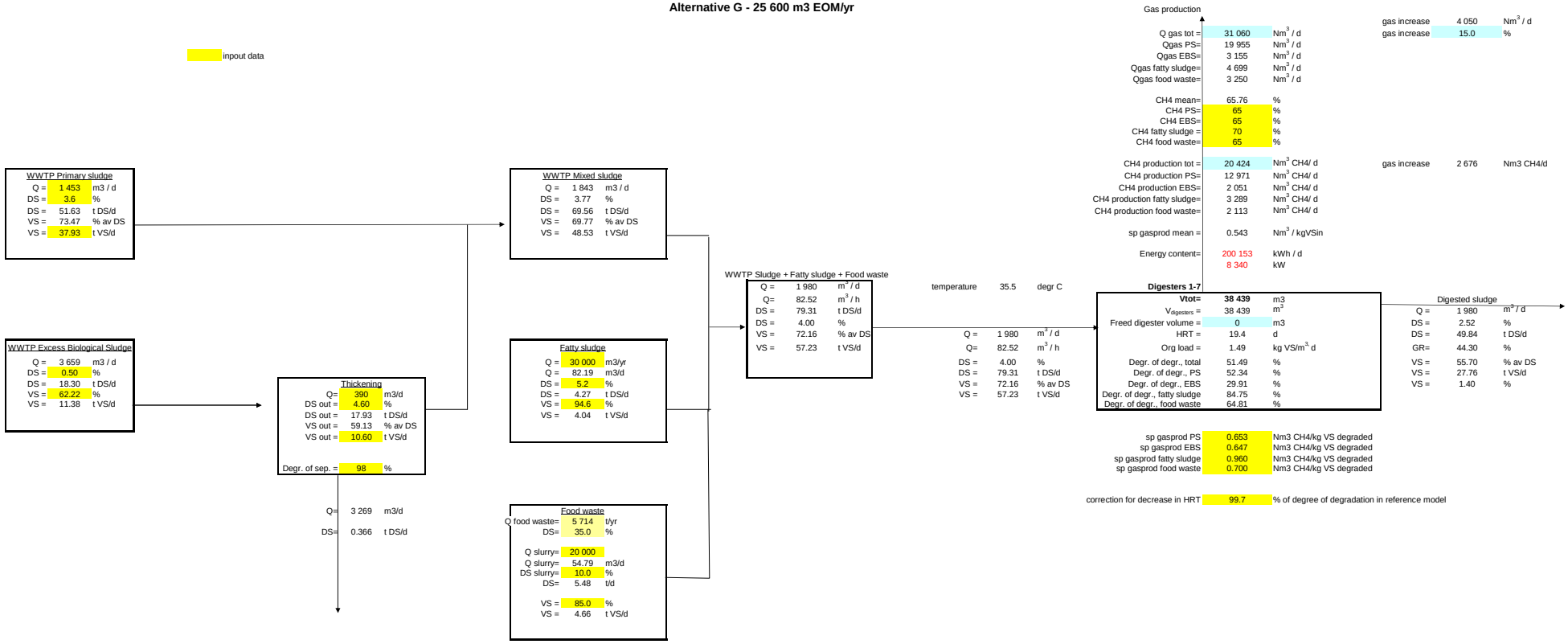

Stockholm Vatten VA AB
Mass balance
Alternative F + maximum level of EOM
inpout data
WWTP Primary sludge
Q = 1 453 m3 / d
DS = 3.55 %
DS = 51.63 t DS/d
VS = 73.47 % av DS
VS = 37.93 t VS/d
WWTP Excess Biological Sludge
Q = 3 659 m3 / d
DS = 0.50 %
DS = 18.30 t DS/d
VS = 62.22 %
VS = 11.38 t VS/d
Thickening
Q= 390 m3/d
DS out = 4.60 %
DS out = 17.93 t DS/d
VS out = 59.13 % av DS
VS out = 10.60 t VS/d
Degr. of sep. = 98 %
Q= 3 269 m3/d
DS= 0.366 t DS/d
WWTP Mixed sludge
Q = 1 843 m3 / d
DS = 3.77 %
DS = 69.56 t DS/d
VS = 69.77 % av DS
VS = 48.53 t VS/d
Fatty sludge
Q = 30 000 m3/yr
Q = 82.19 m3/d
DS = 5.2 %
DS = 4.27 t DS/d
VS = 94.6 %
VS = 4.04 t VS/d
Food waste
Q food waste= 123 429 t/yr
DS= 35.0 %
Q slurry= 432 000 m3/yr
Q slurry= 1 183.6 m3/d
DS slurry= 10.0 %
DS= 118.36 t/d
VS = 85.0 %
VS = 100.60 t VS/d
WWTP Sludge + Fatty sludge + Food waste
Q = 3 109 m3 / d
Q= 129.55 m3 / h
DS = 192.19 t DS/d
DS = 6.18 %
VS = 79.70 % av DS
VS = 153.18 t VS/d
Q= 3 109 m3/d
DS out = 8.00 %
Degr. of sep. = 100 %
Q= 707 m3/d
DS= 0.0 t DS/d
Q = 2 402 m3 / d
Q= 100.10 m3 / h
DS = 8.00 %
DS = 192.19 t DS/d
VS = 79.70 % av DS
VS = 153.18 t VS/d
temperature 160 degr C
Gas production
Q gas tot = 119 824 Nm3 / d
Qgas PS= 26 020 Nm3 / d
Qgas EBS= 4 114 Nm3 / d
Qgas fatty sludge= 5 185 Nm3 / d
Qgas food waste= 84 506 Nm3 / d
CH4 mean= 65.22 %
CH4 PS= 65 %
CH4 EBS= 65 %
CH4 fatty sludge = 70 %
CH4 food waste= 65 %
CH4 production tot = 78 145 Nm3 CH4/ d
CH4 production PS= 16 913 Nm3 CH4/ d
CH4 production EBS= 2 674 Nm3 CH4/ d
CH4 production fatty sludge= 3 629 Nm3 CH4/ d
CH4 production food waste= 54 929 Nm3 CH4/ d
sp gasprod mean = 0.782 Nm3 / kgVSin
Energy content= 765 822 kWh / d
31 909 kW
gas increase 92 814 Nm3 / d
gas increase 343.6 %
gas increase 60 397 Nm3 CH4/d
Digesters 1-7
Vtot= 38 439 m3
Vdigesters = 38 438 m3
Freed digester volume = 1 m3
HRT = 16.0 d
Org load = 3.99 kg VS/m3 d
Degr. of degr., total 73.30 %
Degr. of degr., PS 68.25 %
Degr. of degr., EBS 39.00 %
Degr. of degr., fatty sludge 93.50 %
Degr. of degr., food waste 78.00 %
Digested sludge
Q = 2 402 m3 / d
DS = 3.33 %
DS = 79.92 t DS/d
GR= 48.81 %
VS = 51.19 % av DS
VS = 40.91 t VS/d
VS = 1.70 %
sp gasprod PS 0.653 Nm3 CH4/kg VS degraded
sp gasprod EBS 0.647 Nm3 CH4/kg VS degraded
sp gasprod fatty sludge 0.960 Nm3 CH4/kg VS degraded
sp gasprod food waste 0.700 Nm3 CH4/kg VS degraded
PS 30 % increased degree of degr
EBS 30 % increased degree of degr
fatty sludge 10 % increased degree of degr
food waste 20 % increased degree of degr

Stockholm Vatten VA AB
Mass balance
Alternative F + 25 600 m3 EOM/yr



Stockholm Vatten VA AB
Mass balance
Alternative G - 25 600 m3 EOM/yr

inpout data



Stockholm Vatten VA AB
Compilation of data in mass balances

Methods from Stage 1

	Flow to digesters m3/d	Change in flow comp. with reference plant, m3/d	Available digester volume, m3	Organic load on digesters, kg VS/(m3*d)	HRT, d	Gas increase, %		Freed volume at HRT 20.1 d, m3
Reference	1 910	0	38 439	1.35	20.1	0.0		
1. Pre-thickening	1 489	-421	38 439	1.35	25.8	2.5		8 504
2. Increased PS production	2 098	187	38 439	1.49	18.3	11.5		
3. Serial operation, step 1	1 910	0	23 265	2.23	12.2	8.0		
3. Serial operation, step 2	1 910	0	15 174	1.94	7.9			
4. Enzyme treatment	1 910	0	38 439	1.35	20.1	15.0		
5. Thermal hydrolysis	912.9	-997	38 439	1.35	42.1	27.2		23 833*
6. EOM	1 980	70	38 439	1.49	19.4	15.0		

Alternatives from Stage 2

	Flow to digesters m3/d	Change in flow compared with reference plant, m3/d	Available digester volume, m3	Organic load on digesters, kg VS/(m3*d)	Received amount of fatty sludge (in addition to ref. plant), tonnes/yr	Received amount of food waste (in addition to ref. plant), tonnes/yr	HRT, d	Gas increase, %	Gas increase, Nm3 CH4/d	Freed volume at HRT 20.1 d, m3
A. Increased PS production	2 098	187	38 439	1.49			18.3	11.5	2 012	
B. Pre-thickening + increased PS	1 592	-318	38 439	1.49			24.1	14.6	2 570	6 431
B. Maximum EOM	1 912	2	38 439	2.19	5 620	111 170	20.1	83.0	14 609	
B. 25 620 tonnes EOM	1 663	-248	38 439	1.63	5 620	20 000	23.1	29.7	5 266	5 020
C.Pre-thickening + serial op, step 1	1 489	-421	23 265	2.23			15.6	10.0	1 752	5 126
C. Step 2	1 489	-421	15 174	1.90			10.2			3 344
C. Maximum EOM, step 1	1 910	0	23 265	3.74	5 620	148 016	12.2	104.3	18 356	
C. Maximum EOM, step 2	1 910	0	15 174	2.95			7.9			
C. 25 620 tonnes EOM, step 1	1 560	-351	23 265	2.46	5 620	20 000	14.9	25.5	4 524	4 272
C. 25 620 ton EOM, step 2	1 560	-351	15 174	2.06			9.7			2 786
D. Pre-thickening + increased PS + serial operation, step 1	1 592	-318	23 265	2.47			14.6	23.3	4 081	3 871
D. Step 2	1 592	-318	15 174	2.08			9.5			2 524
D. Maximum EOM, stage 1	1 910	0	23 265	3.60	5 620	110 380	12.2	94.2	16 569	
D. Maximum EOM, stage 2	1 910	0	15 174	2.87			7.9			
D. 25 620 tonnes EOM, stage 1	1 663	-248	23 265	2.70	5 620	20 000	14.0	38.7	6 832	3 016
D. 25 620 tonnes EOM, stage 2	1 663	-248	15 174	2.24			9.1			1 967
E. Enzyme treatment	1 910	0	38 439	1.35			20.1	15.0	2 662	
F. Thermal hydrolysis	912.9	-997	38 439	1.35			42.1	27.2	4 788	23 833*
F. Maximum EOM	2 402	492	38 439	3.99	5 620	432 000	16.0	343.6	60 397	
F. 25 620 tonnes EOM	991.4	-919	38 439	1.49	5 620	20 000	38.8	45.2	8 011	18 512*
G. EOM	1 980	70	38 439	1.49	5 620	20 000	19.4	15.0	2 676	

*Freed volume at HRT 16 d

Constants used in the reference model

sp gas prod PS	0.343	Nm3 CH4/ kgVS$_{in}$
sp gas prod EBS	0.194	Nm3 CH4/ kgVS$_{in}$
sp gas prod fatty sludge	0.816	Nm3 CH4/ kgVS$_{in}$
sp gasprod food waste	0.455	Nm3 CH4/ kgVS$_{in}$
CH4 content, mean	65.71	% of Nm3 gas
CH4 PS	65.00	% of Nm3 gas
CH4 EBS	65.00	% of Nm3 gas
CH4 fatty sludge	70.00	% of Nm3 gas
CH4 food waste	65.00	% of Nm3 gas
Energy content	9.80	kWh/Nm3 CH4
Degree of degradation total	49.96	% of VSin
Degree of degradation PS	52.50	% of VSin
Degree of degradation EBS	30.00	% of VSin
Degree of degradation fatty sludge	85.00	% of VSin
Degree of degradation food waste	65.00	% of VSin

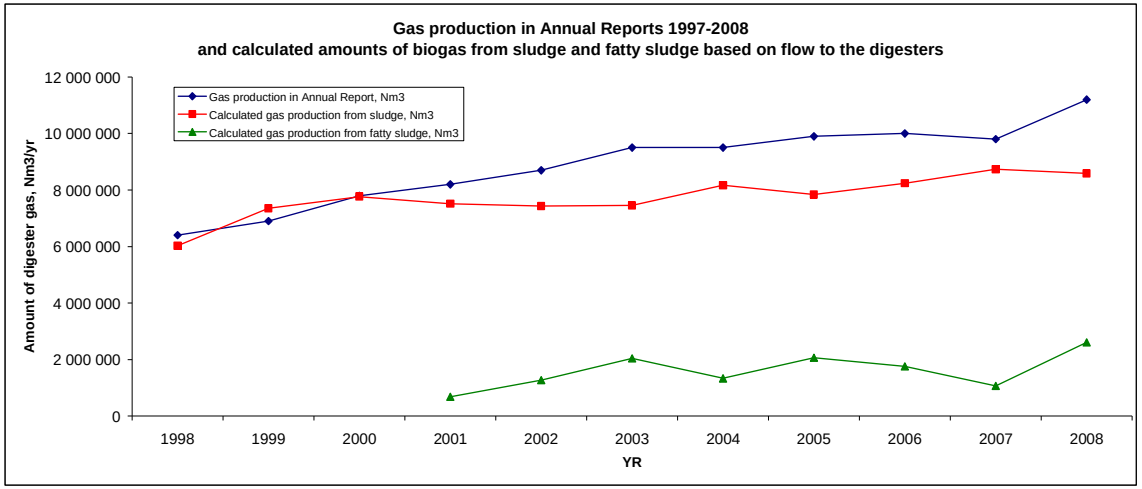
Gas increase due to changed HRT, from Biogasmax report D2.15_SVAB_v1.

SRT	% of maximum gas production	change relative to 20. 1 d
0		
10	79.98%	-9.41%
12	82.46%	-6.60%
15	85.20%	-3.50%
16	85.93%	-2.67%
17	86.59%	-1.92%
18	87.19%	-1.24%
19	87.74%	-0.62%
20	88.24%	-0.05%
20.1	88.29%	0.00%
21	88.70%	0.47%
22	89.13%	0.95%
23	89.53%	1.40%
24	89.89%	1.82%

Appendix II - Calculations of the biogas production from fatty sludge during the reference period

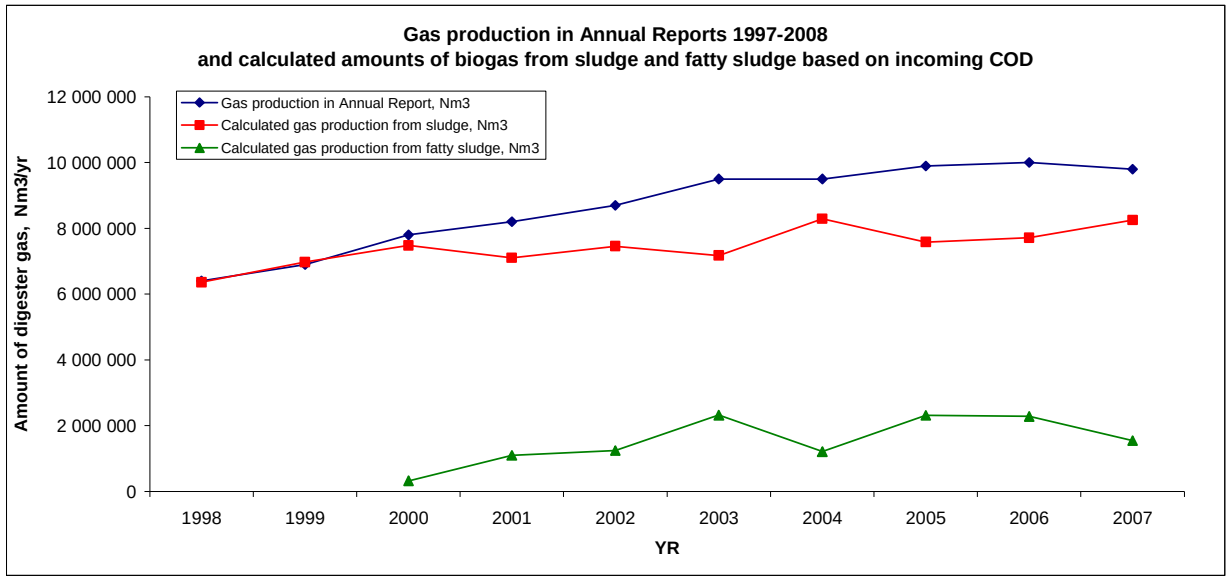
Stockholm Vatten VA AB
Calculation of biogas production from fatty sludge
based on incoming amount of PS and EBS to the digesters

Yr	Nm3 digester gas/yr	Fatty sludge m3/yr	PS m3/yr	EBS m3/yr	EBS/PS	PS+EBS m3/yr	Nm3 gas/m3 sludge	Mean value Nm3 gas/m3 sludge 1998-1999	Calculated amount of gas from sludge mean value 1998-1999 based on incoming sludge flow, Nm3/yr	Gas from fatty sludge Nm3/yr	Nm3 gas/m3 fatty sludge	Ratio of gas from fatty sludge to total gas prod., %
1998	6 400 000	0	411 713	115 486		527 199	12.14	11.43	6 026 433			
1999	6 900 000	0	502 545	140 965		643 510	10.72		7 355 983			
2000	7 800 000	14 330	536 512	143 182	0.2669	679 693			7 769 594			
2001	8 200 000	23 865	526 645	130 808	0.2484	657 453			7 515 367	684 633	29	8
2002	8 700 000	25 592	529 898	120 455	0.2273	650 354			7 434 213	1 265 787	49	15
2003	9 500 000	25 169	506 539	145 876	0.2880	652 415			7 457 780	2 042 220	81	21
2004	9 500 000	28 490	570 918	143 687	0.2517	714 605			8 168 674	1 331 326	47	14
2005	9 900 000	28 875	514 845	170 815	0.3318	685 660			7 837 797	2 062 203	71	21
2006	10 000 000	28 809	554 866	166 265	0.2996	721 131			8 243 270	1 756 730	61	18
2007	9 800 000	30 247	582 235	181 819	0.3123	764 054			8 733 925	1 066 075	35	11
2008	11 200 000	33 586	578 647	172 772	0.2986	751 419			8 589 494	2 610 506	78	23
				mean EBS/PS	0.2805	factor for missing EBS values				mean 2000-2005	15.8	%
										mean 2000-2008	16.3	%



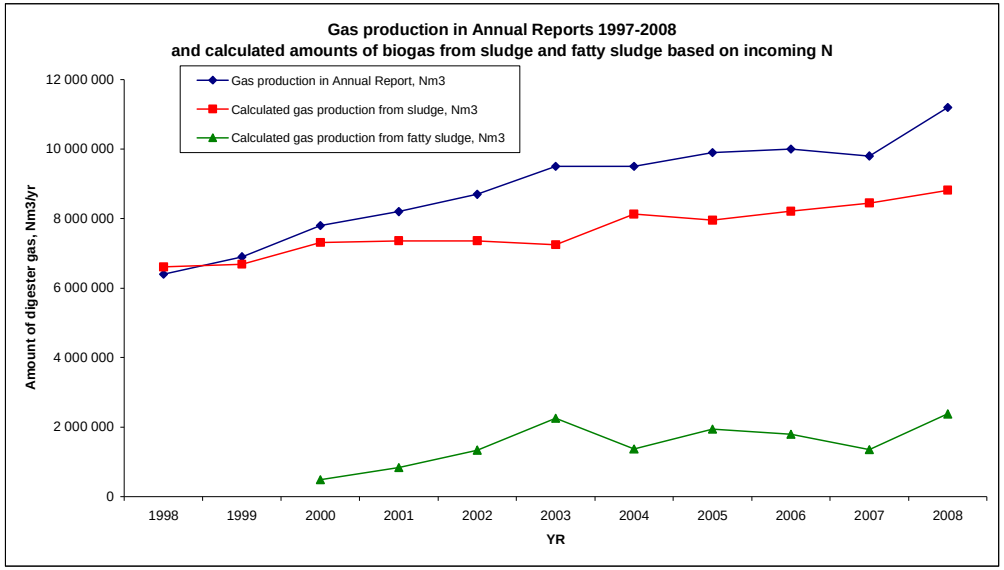
Stockholm Vatten VA AB
Calculation of biogas production from fatty sludge based on incoming amount of COD to the WWTP

Yr	Nm3 digester gas/yr	Fatty sludge, m3/yr	COD tonne/yr	Nm3 digester gas/tonne COD	Mean, Nm3 gas /tonne COD (1998-1999)	Calculated amount of gas from sludge mean values 1998-1999 based on incoming COD , Nm3/yr	gas from fatty sludge Nm3 /yr	Ratio, gas from fatty sludge to total gas production, %	
1998	6 400 000	0	34300	187	185.5	6 362 650			
1999	6 900 000	0	37600	184		6 974 800			
2000	7 800 000	14 330	40300	194		7 475 650	324 350	4.2	
2001	8 200 000	23 865	38300	214		7 104 650	1 095 350	13.4	
2002	8 700 000	25 592	40200	217		7 457 100	1 242 900	14.3	
2003	9 500 000	25 169	38700	246		7 178 850	2 321 150	24.4	
2004	9 500 000	28 490	44700	213		8 291 850	1 208 150	12.7	
2005	9 900 000	28 875	40900	242		7 586 950	2 313 050	23.4	
2006	10 000 000	28 809	41600	240		7 716 800	2 283 200	22.8	
2007	9 800 000	30 247	44500	220		8 254 750	1 545 250	15.8	
							mean 2000-2005	17.6	%
							mean 2000-2007	18.0	%



Stockholm Vatten VA AB
Calculation of biogas production from fatty sludge based on incoming amount of nitrogen to the WWTP

Yr	Nm3 digester gas/yr	Fatty sludge, m3/yr	N tonnes/ yr	Nm3 digester gas/tonnes N	Mean Nm3 gas /tonne N (1998-1999)	Calculated amount of gas from sludge mean values 1998-1999 based on incoming N, Nm3/yr	Gas from fatty sludge Nm3 /yr	Ratio, gas from fatty sludge to total gas production, %	
1998	6 400 000	0	3 014	2 123	2 193	6 609 279			
1999	6 900 000	0	3 050	2 262		6 688 222			
2000	7 800 000	14 330	3 336	2 338		7 315 379	484 621	6.2	
2001	8 200 000	23 865	3 358	2 442		7 363 622	836 378	10.2	
2002	8 700 000	25 592	3 358	2 591		7 363 622	1 336 378	15.4	
2003	9 500 000	25 169	3 306	2 874		7 249 594	2 250 406	23.7	
2004	9 500 000	28 490	3 707	2 563		8 128 930	1 371 070	14.4	
2005	9 900 000	28 875	3 629	2 728		7 957 887	1 942 113	19.6	
2006	10 000 000	28 809	3 744	2 671		8 210 066	1 789 934	17.9	
2007	9 800 000	30 247	3 853	2 543		8 449 088	1 350 912	13.8	
2008	11 200 000	33 586	4 021	2 785		8 817 488	2 382 512	21.3	
							mean 2000-2005	14.9	%
							mean 2000-2008	15.8	%



Appendix III - Nitrogen balance at increased production of primary sludge

Reduction SS today	0.59
Reduction SS in future	0.71

	Ratio (in)	IN (mg/l)	AP* - today (mg/l)	AP* - future (mg/l)
COD total	100%	480	249	202
COD biosol	14%	69	69	69
COD insol	4%	20	20	20
COD biopart	54%	260	107	75
COD inpart	27%	131	54	38
COD bio	69%	329	176	144
NH4-N		28	28	28
Ntot		43	36	*34*
Ntot - NH4-N		15	8	*6*

	Present	"Future"	Change
COD, AP* (% of inc)	52%	42%	-19%
COD, PS (% of inc)	48%	58%	20%
COD bio, AP* (% of inc)	53%	44%	-18%
COD bio, PS (% av in)	47%	56%	20%
COD bio/NH4-N	6.3	5.2	
COD bio/tot-N	4.9	4.2	

Nitrogen balance 2005	Tonnes/yr	Ratio, % of incoming	Converted to concentration in incoming water (mg/l)
In	3600	100%	43
Out	640	18%	7.6
Sludge	640	18%	7.6
Difference = Denitrified?	2320	64%	28

AP = After Primary sedimentation
PS = Primary Sludge

Estimate of COD/N ratio at increased separation in primary sedimentation.

Appendix IV - Cost calculations

STOCKHOLM VATTEN AB
Increased biogas production

Stockholm Vatten VA AB
Increased biogas production at the Henriksdal WWTP
Cost estimates

INPUT DATA

Transport, digested and dewatered sludge	EUR/tonne	27.9
Write-off times		
Mechanical equipment, yrs		15
Construction, yrs		30
Other costs, yrs		15
Interest rate, %		5.00
ENERGY		
Electricity	EUR/kWh	0.10
District heating	EUR/kWh	0.06

PROCESS ALTERNATIVES		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
SLUDGE (+EOM)													
Primary sludge	m3/d	1 453	1 744	1 744	1 744	1 033	1 033	1 239	1 239	1453	1 453	1 453	1 453
Primary sludge	tonne DS/d	51.63	61.95	61.95	61.95	51.63	51.63	61.95	61.95	51.63	51.63	51.63	51.63
Change primary sludge	tonne DS/d		10.33	10.33	10.33	0.00	0.00	10.33	10.33	0.00	0.00	0.00	0.00
EBS + PS to the digesters	m3/d	1 843	2 031	1 526	1 526	1 423	1 423	1 526	1 526	1 843	1 843	1 843	1 843
EBS + PS to the digesters	tonne DS/d	69.56	75.13	75.13	75.13	69.56	69.56	75.13	75.13	69.56	69.56	69.56	69.56
Change of sludge (DS) to digesters	tonne DS/d		5.57	5.57	5.57	0.00	0.00	5.57	5.57	0.00	0.00	0.00	0.00
Total flow to digesters	m3/d	1 910	2 098	1 592	1 663	1 489	1 560	1 592	1 663	1 910	912.9	991.4	1 980
Total flow to digesters	m3/h	79.59	87.4	66.4	69.3	62.1	65.0	66.4	69.3	79.6	38.0	41.3	82.5
Change total flow to digesters	m3/h		7.8	-13.2	-10.3	-17.5	-14.6	-13.2	-10.3	0.0	-41.6	-38.3	2.9
Total DS to digesters	tonne DS/d	73.0	78.6	78.6	84.9	73.0	79.3	78.6	84.9	73.0	73.0	79.3	79.3
Change total DS to digesters	tonne DS/d		5.57	5.57	11.85	0.00	6.28	5.57	11.85	0.00	0.00	6.28	6.28
DS out from digesters	tonne DS/d	47.1	49.6	48.8	51.5	44.4	47.0	46.5	49.0	44	40	42	50
DS out from digesters	tonne DS/yr	17 208	18 115	17 816	18 792	16 221	17 155	16 955	17 900	16 060	14 577	15 285	18 192
Change DS out from digesters	tonne DS/d		2.5	1.7	4.3	-2.7	-0.1	-0.7	1.9	-3.1	-7.2	-5.3	2.7
Digested sludge, dewatered	tonne/d	168.4	177.3	174.3	183.9	158.7	167.9	165.9	175.1	146.7	114.1	119.6	178.0
Digested dewatered sludge, change	tonne/d		9	6	16	-10	-1	-2	7	-22	-54	-49	10
DS concentration digested dew. sludge	%	28	28	28	28	28	28	28	28	30	35	35	28
BIOGAS PRODUCTION													
Biogas	Nm3/d	27 010	30 108	30 959	35 039	29 709	33 907	33 293	37 459	31 061	34 347	39 230	31 060
Biogas	Nm3/h	1 125	1 254	1 290	1 460	1 238	1 413	1 387	1 561	1 294	1 431	1 635	1 294
Change biogas	Nm3/h		129	165	335	112	287	262	435	169	306	509	169
Methane	Nm3/d	17 748	19 760	20 318	23 014	19 500	22 272	21 829	24 580	20 410	22 536	25 759	20 424
Methane	Nm3/h	739	823	847	959	813	928	910	1 024	850	939	1 073	851
Change methane	Nm3/d		2 012	2 570	5 266	1 752	4 524	4 081	6 832	2 662	4 788	8 011	2 676
Use of methane	Nm3/d		0	0	0	0	0	0	0	0	4 263	4 630	0
Net change methane	Nm3/d		2 012	2 570	5 266	1 752	4 524	4 081	6 832	2 662	525	3 381	2 676
Substrate													
EOM													
Total amount slurry 10 % DS, m3/yr			0	0	20 000	0	20 000	0	20 000	0	0	20 000	20 000

Stockholm Vatten VA AB
Increased biogas production at the Henriksdal WWTP
Cost estimates

		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
1. Sludge disposal													
Dewatered digested sludge	tonne/d		9	6	16	-10	-1	-2	7	-22	-54	-49	10
Transport dewatered digested sludge	EUR/tonne		27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9
Transport dewatered digested sludge	EUR/yr		90 546	60 700	158 116	-98 492	-5 231	-25 248	69 080	-221 387	-553 450	-496 949	98 255
Sum, total annual fees	EUR/yr	0	90 546	60 700	158 116	-98 492	-5 231	-25 248	69 080	-221 387	-553 450	-496 949	98 255

2. Operational costs: energy		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
ELECTRICITY													
Price, electricity	EUR/kWh		0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Power usage, mean power 24-h	kW		2	22	22	65	65	67	67	0	175	175	0
Electricity consumption	kWh/yr		17 520	192 720	192 720	569 400	569 400	586 920	586 920	0	1 533 000	1 533 000	0
Operational time	h/yr		8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760
Annual cost of electricity	EUR/yr		1 718	18 894	18 894	55 824	55 824	57 541	57 541	0	150 294	150 294	0
Sum, annual cost of electricity	EUR/yr		1 718	18 894	18 894	55 824	55 824	57 541	57 541	0	150 294	150 294	0
HEAT													
Heat requirement, district heating	MWh/yr	16 732	19 395	14 638	15 251	12 868	13 482	14 638	15 251	16 732	5 700	6 200	17 345
Increased heat requirement, district heating	MWh/yr		2 663	-2 094	-1 481	-3 864	-3 250	-2 094	-1 481	0	-11 032	-10 532	613
Price, district heating	EUR/kWh	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Annual cost of district heating	EUR/yr	984 212	156 671	-123 153	-87 094	-227 271	-191 153	-123 153	-87 094	0	-648 918	-619 506	36 082
Heat requirement, gas	MWh/yr	0	0	0	0	0	0	0	0	0	15249	16560	0
Increase, heat requirement gas	MWh/yr		0	0	0	0	0	0	0	0	15249	16560	0
Price, gas	EUR/kWh	0	0	0	0	0	0	0	0	0	0	0	0
Annual cost of gas	EUR/yr		0	0	0	0	0	0	0	0	0	0	0
Sum, annual cost of heat	EUR/yr		156 671	-123 153	-87 094	-227 271	-191 153	-123 153	-87 094	0	-648 918	-619 506	36 082
Total annual cost of energy	EUR/yr		159 000	-104 259	-68 200	-171 447	-135 329	-65 612	-29 553	0	-498 624	-469 212	40 000

3. Operational costs: maintenance		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
2.5 % % of investment for mechanical eq.			9 804	17 157	17 157	14 706	14 706	24 510	24 510	4 902	229 902	229 902	0
Total cost of maintenance	EUR/yr		9 804	17 157	17 157	14 706	14 706	24 510	24 510	4 902	229 902	229 902	0

Stockholm Vatten VA AB
Increased biogas production at the Henriksdal WWTP
Cost estimates

4. Operational costs: chemicals		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
Enzymes	EUR/yr									715 686			
Precipitation chemicals													
Ferrous sulphate	EUR/d	1176											
Triple precip., ferric chloride + 2 polymers	EUR/d		1716	1716	1716			1716	1716				
Triple precip., increase compared with reference	EUR/d		539	539	539			539	539				
Triple precip., increased cost per yr	EUR/yr		196 814	196 814	196 814	0	0	196 814	196 814	0	0	0	0
Annual cost, precipitation chemicals	EUR/yr		196 814	196 814	196 814	0	0	196 814	196 814	715 686	0	0	0
Polymers, final dewatering													
Amount	kg/tonne DS		6	6	6	6	6	6	6	6	6	6	6
Price	EUR/kg		3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43
Operational time	h/yr		8760	8760	8760	8760	8760	8760	8760	8760	8760	8760	8760
Increase of DS	tonne DS/d		2.5	1.7	4.3	-2.7	-0.1	-0.7	1.9	-3.1	-7.2	-5.3	2.7
Annual cost, polymers for dewatering	EUR/yr		18 681	12 523	32 622	-20 320	-1 079	-5 209	14 252	-23 633	-54 162	-39 591	20 271
Annual cost, chemicals	EUR/yr		215 495	209 337	229 436	-20 320	-1 079	191 605	211 066	692 054	-54 162	-39 591	20 271

5. Operational costs: personnel		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
5-day week													
Daytime, h/d											3	3	
Nighttime, h/d													
Weekends:													
Daytime, h/d													
Nighttime, h/d													
Sum, h/v			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0	15.0	0.0
Sum h/yr			0	0	0	0	0	0	0	0	780	780	0
Cost per hour, daytime, EUR			31	31	31	31	31	31	31	31	31	31	31
Annual cost, personnel	EUR/yr		0	0	0	0	0	0	0	0	24 000	24 000	0

6. Revenues		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
GAS													
Operational time	h/yr		8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760	8 760
Methane production	Nm3/d												
Gross power content, produced biogas	kW												
Gas for heating	Nm3/d		0	0									
Methane for sales	Nm3/d		2 012	2 570	5 266	1 752	4 524	4 081	6 832	2 662	588	3 471	2 676
Revenue upgraded gas	EUR/Nm3												
Annual revenue from sales of upgraded gas	EUR/yr		0	0	0	0	0	0	0	0	0	0	0
EOM													
Amount of waste	m3/d		0	0	25 620		25 620		25 620			25 620	25 620
Receiving fee	EUR/m3		0	0	0	0	0	0	0	0	0	0	0
Annual revenue from reception of waste	EUR/yr		0	0	0	0	0	0	0	0	0	0	0
Total annual revenue	EUR/yr		0	0	0	0	0	0	0	0	0	0	0

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7. Investement costs, EUR		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
Mechanical/electrical/automation works	EUR		392 157	294 118	294 118	294 118	294 118	294 118	294 118	196 078	8 529 412	8 529 412	0
Mechanical/electrical/automation works	EUR			392 157	392 157	294 118	294 118	392 157	392 157		666 667	666 667	0
								294 118	294 118				
Sum, mechanical/electrical/automation	EUR		392 157	686 275	686 275	588 235	588 235	980 392	980 392	196 078	9 196 078	9 196 078	0
Civil works				490 196	490 196	490 196	490 196	490 196	490 196		1 274 510	1 274 510	0
Sum, civil works	EUR		0	490 196	490 196	490 196	490 196	490 196	490 196	0	1 274 510	1 274 510	0
Unforeseen, 10 % (in applicable cases)			39 216							19 608	294 118	294 118	0
Detailed design			39 216			29 412	29 412	58 824	58 824	39 216	784 314	784 314	0
Sum, other costs	EUR		78 431	0	0	29 412	29 412	58 824	58 824	58 824	1 078 431	1 078 431	0
Total cost of construction	EUR		480 000	1 180 000	1 180 000	1 110 000	1 110 000	1 530 000	1 530 000	260 000	11 550 000	11 550 000	0

8. Capital cost		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
Interes rate, %													
Mechanical/electrical/automation works			5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Civil works			5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Other costs			5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Write-off, yrs													
Mechanical/electrical/automation works			15	15	15	15	15	15	15	15	15	15	15
Civil works			30	30	30	30	30	30	30	30	30	30	30
Other costs			15	15	15	15	15	15	15	15	15	15	15
Remaining value:													
Mechanical/electrical/automation works			0	0	0	0	0	0	0	0	0	0	0
Civil works			0	0	0	0	0	0	0	0	0	0	0
Other costs			0	0	0	0	0	0	0	0	0	0	0
Capital costs:													
Mechanical/electrical/automation works			37 781	66 117	66 117	56 672	56 672	94 453	94 453	18 891	885 971	885 971	0
Civil works			0	47 227	47 227	47 227	47 227	47 227	47 227	0	122 789	122 789	0
Other costs			7 556	0	0	2 834	2 834	5 667	5 667	5 667	103 899	103 899	0
Annual capital costs	EUR/yr		46 000	114 000	114 000	107 000	107 000	148 000	148 000	25 000	1 113 000	1 113 000	0

Summary of operational costs		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
Maintenance	EUR/yr		9 804	17 157	17 157	14 706	14 706	24 510	24 510	4 902	229 902	229 902	0
Energy	EUR/yr		159 000	-104 259	-68 200	-171 447	-135 329	-65 612	-29 553	0	-498 624	-469 212	40 000
Chemicals	EUR/yr		215 495	209 337	229 436	-20 320	-1 079	191 605	211 066	692 054	-54 162	-39 591	20 271
Personnel	EUR/yr		0	0	0	0	0	0	0	0	24 000	24 000	0
Sum, total operational costs	EUR/yr		384 299	122 235	178 392	-177 062	-121 703	150 503	206 023	696 956	-298 883	-254 900	60 271

Total annual costs		Reference plant	A Increased PS production	B Pre-thickening + increased PS production	B' Pre-thickening + increased PS production + 25 600 m3 EOM	C Pre-thickening + serial operation	C ' Pre-thickening + serial operation + 25 600 m3 EOM	D Pre-thickening + serial operation + increased PS production	D' Pre-thickening + serial op. + increased PS prod.+ 25 600 m3 EOM	E Enzymes	F Thermal hydrolysis	F' Thermal hydrolysis + 25 600 m3 EOM	G reference + 25 600 m3 EOM
OPERATIONAL COSTS	EUR/yr		384 299	122 235	178 392	-177 062	-121 703	150 503	206 023	696 956	-298 883	-254 900	60 271
CAPITAL COSTS	EUR/yr		46 000	114 000	114 000	107 000	107 000	148 000	148 000	25 000	1 113 000	1 113 000	0
REVENUE	EUR/yr		0	0	0	0	0	0	0	0	0	0	0
SLUDGE DISPOSAL	EUR/yr		90 546	60 700	158 116	-98 492	-5 231	-25 248	69 080	-221 387	-553 450	-496 949	98 255
Total annual costs	EUR/yr		520 845	296 935	450 509	-168 553	-19 933	273 255	423 103	500 569	260 667	361 151	158 526
EUR/increase Nm3 CH4			0.71	0.32	0.23	-0.26	-0.01	0.18	0.17	0.52	1.36	0.29	Cost effectiveness is not calculated