REPORT

Increased total efficiency in sewage treatment- ITEST
Evaluation report

Part of the LIFE+ Project ITEST

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B2149
December 2013

The report approved:
2013-12-17

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Report Summary

Project title

ITEST Increased total efficiency in sewage treatment

Project sponsor

Oskarshamn Municipality (and EU), SIVL

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Title and subtitle of the report

Increased total efficiency in sewage treatment-ITEST

Evaluation report, Part of LIFE+ project ITEST

Summary

In the LIFE+ project ITEST, Increased Total Efficiency in Sewage Treatment, a technical solution for efficient and improved nitrogen removal from municipal wastewater was demonstrated. This technical solution, which is based on operating the sewage treatment plant (STP) at a temperature of about 20°C even during periods with a cold inflow using waste heat, has been tested in pilot scale at Hammarby Sjöstadsverk i Stockholm.

In this report, the results and evaluation of the demonstration period of the technology, performed at Hammarby Sjöstadsverk, Stockholm is presented. The results show that the nitrogen removal increased in a treatment line operated at 20°C in comparison to the removal efficiency in a parallel line with fluctuating temperature, thus achieving lower output concentrations. The need for aeration was reduced, but on the other hand increased use of electrical power was needed to overcome the pressure drop in the heat exchanger. Among other parameters, choice of heat exchanger influences the life cycle assessment of the process.

Keyword

Increased nitrogen removal, pre-heating, sewage treatment, treatment efficiency, waste heat

Bibliographic data

IVL Report B2149

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Homepage: www.ivl.se, e-mail: publicationservice@ivl.se, fax+46 (0)8-598 563 90, or via IVL, P.O. Box 21060, SE-100 31 Stockholm Sweden

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Background

The Baltic States and other nations experiencing cold periods have severe problems to meet the demands on nitrogen emission reduction from sewage treatment plants (STP) as stated in The Directive 98/15/EEC. The Directive 98/15/EEC stipulates that the concentration of total nitrogen (N) from municipal sewage treatment plants must be limited to 10 mg/l for plants of 100 000 person equivalents (p.e.) or more as an annual average. In the Scandinavian countries and in the Baltic Region in general, low temperatures of the sewage (10°C or less) during cold weather and snowmelt are an obstacle to fulfil this requirement since the removal efficiency of nitrogen is reduced at lower temperatures.

The temperature of the inlet water mainly changes with the seasons, but also over shorter periods at rainstorms and snow melt. It is well known that problems in STP are common in spring and autumn with fast changes in temperature. The biomass has to adjust to the transient conditions, which can give problems e.g. in sludge properties. This in turn can lead to loss of sludge and low efficiency in the STP. Occasional spills occurring at low temperature and high flow events can be a substantial part of the total emission load from the STP.

A common technology to remove nitrogen from sewage water is by oxidation of organic nitrogen compounds and NH_4 to nitrate which by denitrification are converted to nitrogen gas. To some extent the denitrification process also leads to the formation of N_2O. Both the nitrification and denitrification processes are strongly temperature dependent and are the efficiency is generally assumed to be almost zero below 5°C. This makes it almost impossible to reduce nitrogen emissions to the limit of 10 mg N/l as an annual average in colder climate areas such as The Baltic Region.

The main reason to the observed difficulty is that the temperature of the sewage water during the winter season may, as an average be below 10° C. which hampers the biological conversion of nitrogen species to elemental nitrogen, N_2. Increasing the temperature of the incoming sewage water will facilitate nitrogen reduction and thus provide a possible means for many EU countries to comply with legislation and reduce the impact on the European lakes and seas. To increase the temperature of the sewage water has so far been considered as cost prohibitive.

In the LIFE+ project ITEST, Increased Total Efficiency in Sewage Treatment, a technical solution to the mentioned problem where the sewage treatment plant (STP) is operated at a temperature of about 20°C during periods with a cold inflow has been tested in pilot scale. The project has been partly funded by the European Commission within LIFE+ Environment.

In this report the results and evaluation of the demonstration period of the technology, performed at Hammarby Sjöstadsverk, Stockholm are presented.

The support of Mr. Gunnar Hovsenius, especially for his knowledge on heat exchange and wastewater simulations, and the personnel at Okarshamns municipaltiy and at Ernemar wastewater treatment plant, namely Conny Johansson and his colleagues, , is gratefully acknowledged.

The project is part of the ITEST project, which has been partly funded by the European Commission within LIFE+ Environment. This report corresponds to deliverable D3.1., 3.2, and 3.3 in this project.

Objectives

A main objective of the ITEST project was to demonstrate in pilot scale that by pre-heating wastewater before biological treatment the following can be achieved:

- The nitrogen objective in the Directive 98/15/EEC can be met during all seasons.
- The net heat input to raise the temperature of the sewage water to 20°C can be limited to a maximum of 10 % of the total heat flux to achieve the desired temperature.
- The increased efficiency in the nitrification and denitrification processes at 20°C cuts the retention time so much that the reduced capital cost overcompensate for the cost of the heat supply.
- The supply of electric power for blowers and mixers for the sewage treatment can be reduced by 25 – 30 % compared to a traditionally designed sewage treatment plant.
- The extra supply of electric power for pumping of sewage water through the heat exchangers is limited to 50 % of the energy saved for blowers and mixers.

The heat source can either be the back flow of a combined heat and power plant or warm flue gases from any utilization of biogas from the sewage sludge digesters.

If the heat source is the back flow of a combined heat and power plant, the heat transfer to the sewage system should improve the yield of electricity at the power plant by about 3 % according to own estimations.

Important advantages with the proposed procedure are that the results can easily and simply be implemented to upgrade existing sewage treatment plants and that modifications of a conventional sewage treatment plant can be done by technical methods often applied in other applications.

The test equipment and methods

Composition and flow of municipal sewage vary over time. In order to be able to assess the effect of achieving a constant treatment temperature, it had been decided to make use of two parallel test units. The demonstration plant was installed at Hammarby Sjöstadsverk, a pilot test facility in Stockholm (www.sjostadsverket.se). The facility is located on top of Stockholms main sewage treatment plant. The ITEST equipment got the same municipal waste water as the full scale plant. It shared the grid and sand trap with the full scale sewage treatment plant. Both lines had a common phosphorous precipitation and pre-sedimentation. After pre-precipitation of phosphorous the two test lines worked separate from each other, but both comprise anoxic and aerobic biological treatment, sedimentation and sludge recirculation.

One of the test lines started with heat exchangers to hold the temperature in the activated sludge zone to the desired level of 20°C. In a first step, the outgoing water after treatment was used for a first pre-heating step. In a second heat exchanger the temperature was raised in order to maintain 20°C. This temperature has been chosen based on simulations with different temperatures. The parallel lines made it possible to have the same hydraulic load variations of the two test lines as the full scale STP, changing with time of the day. Figure 1 shows the setup of the temperature controlled line, in Annex 1 a drawing of both lines can be found as well as a photo of the equipment. The biological treatment consisted of five steps, with the last three steps aerated.

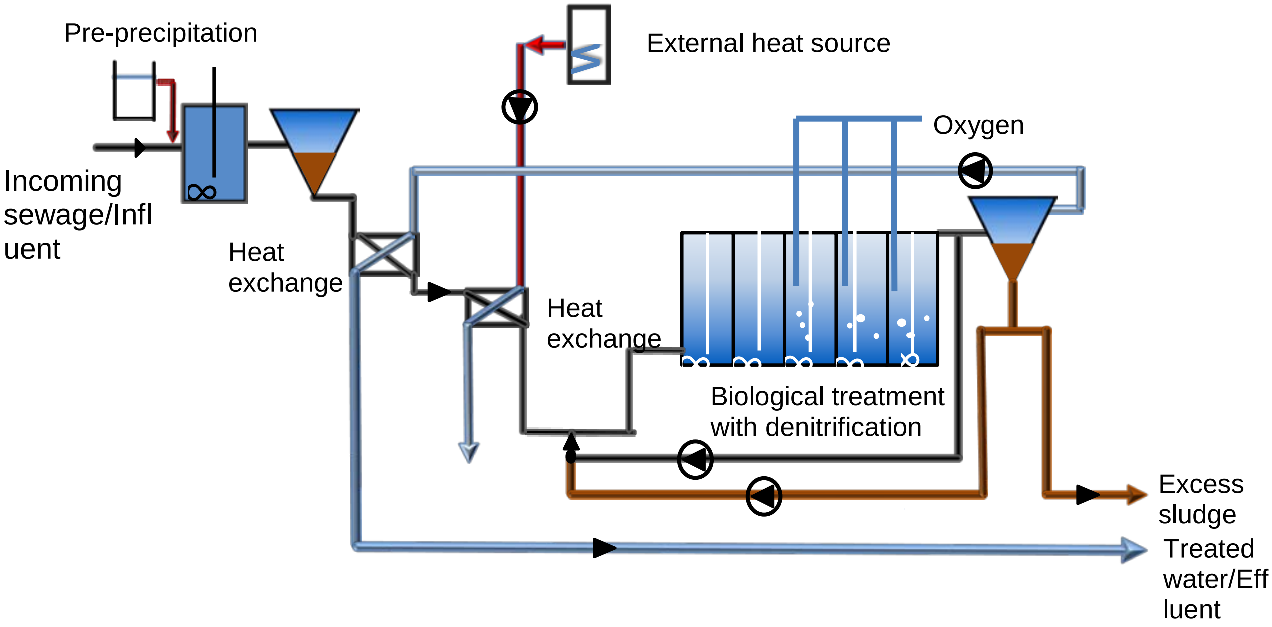


Figure 1. Treatment line with heat exchange to maintain 20°C in the activated sludge zone

The source of heat for the second heat exchanger was a hot water tank at a temperature of about 50°C to simulate the temperature of the back flow in a district heat system. This allowed some control of the energy demand.

During operation, one of the two test units was run at temperatures, sludge concentration and sludge age similar to that in the full scale STP. The other unit was run with a "constant" temperature of 20°C but heated only during cold periods, i.e. when incoming water temperature was low during winter time of about October to April.

Heat exchangers

During experiments, two different types of heat exchangers have been tested. The first heat exchanger was of plate type. At the size of the equipment it was not possible to apply a wide-gap plate heat exchanger. After discussion with different suppliers, a combination of Sondex S4A-1G for the first step and Sondex S8A-1G for the 2nd step was chosen. As an alternative spiral-wound heat exchangers from Alfa Laval, ALSHE LTL 8S and ALSHE LTL 2L were tested.

Parameters

Table 1: The main parameters for control and logging of the function are summarized in the following table:

Flow	**Physical parameters**	**Chemical parameters**
Inflow of sewage	Flow (m^3/h) Temperature °C	COD (mg/l) N_{tot} and P_{tot} (mg/l)
Inflow of sewage to biological treatment	Temperature °C Conductivity	pH
Outflow of treated sewage	Temperature °C	COD (mg/l) N_{tot} and P_{tot} (mg/l)
Return sludge	Flow (m^3/h)	
Excess sludge	Flow (m^3/h)	
Supply of air	Flow Nm^3/h or (kg/h)	

To follow the treatment results, the following parameters were measured weekly in the treated sewage water from the two experimental lines:

- Organic: BOD, COD, TOC,
- Suspended solids TSS
- Nitrogen: Tot-N, NH_4-N and NO_3-N
- Phosphorous: Tot-P and PO_4-P

The untreated sewage water was analyzed for TOC, Tot-N and Tot-P.

In addition to continuous on line instruments, like temperature, pH, conductivity and possibly nitrate, ammonium and sludge content, laboratory analyses were performed for complement and control. The weekly samples were taken by automatic sampling over one day, Tuesday to Wednesday, to get representative samples from the two pilot plant lines and for the untreated sewage water. Sludge properties have been checked when larger operational changes were established. Tests include sludge volume and TSS.

Operational data of the equipment was logged to a database.

Originally, it was planned to measure pharmaceuticals and N_2O, but this was not done due to technical problems, which made it necessary to reduce the size of investigations.

Test results

The demonstration equipment was operated during two cold seasons: winter 2011-2012 and winter 2012-1013. At some dates, the automatic sampling did not work properly, often due to sludge in the sample. At these dates, data from chemical analysis of parameters are not representative and have been removed.

Technical issues during the test period

The set-up of the equipment as well as the operation was accompanied by a number of technical issues, which reduced the possible time for demonstration. For the first winter period, tests could only start from January. The 2nd winter period was intermittent.

Some of the issues during the test periods include:

- At the beginning, there was a lack of some vital instruments due to a delayed delivery, especially of the dissolved oxygen sensors.
- Pre-precipitation did not work properly in the beginning and had to be adjusted
- The supply of water failed a number of times. In addition, control of the inflow had to be completed with flow meters and online control to avoid accidental pilot shutdowns.
- The biology build-up was delayed by galvanic corrosion caused by using wrong sealing materials.
- The control system was especially programmed for the ITEST project, which facilitates a tailor-made application but which also caused a number of failures due to undesired blockage of pumps etc. These problems were difficult to identify in the beginning.
- DO-meters were not working properly for a long time. (They had to be replaced with different fabricate).
- The aeration system had to be adjusted to varying loads that required faster changes in the oxygen supply than considered when dimensioning the system.
- The external heating of the influent encountered some electrical failures that caused temperature drops during some periods.

- The post-sedimentation had to be adjusted in order to facilitate a better settlement of the sludge and higher recirculation rates than considered in the design.
- Difficulties in the data logging system.

Temperature

The temperature was measured at different process steps of the equipment:

- Incoming water (T-In)
- After first heat exchanger (1^{st} HX)
- After 2^{nd} heat exchanger (2ndHX)
- In the beginning and end of the temperature controlled line (temp-line)
- In the beginning and end of the reference line (ref-line)

Figure 2 and 3 show the measured temperatures during the test periods in winter 2012 (some data not available for 2012) and winter 2013.

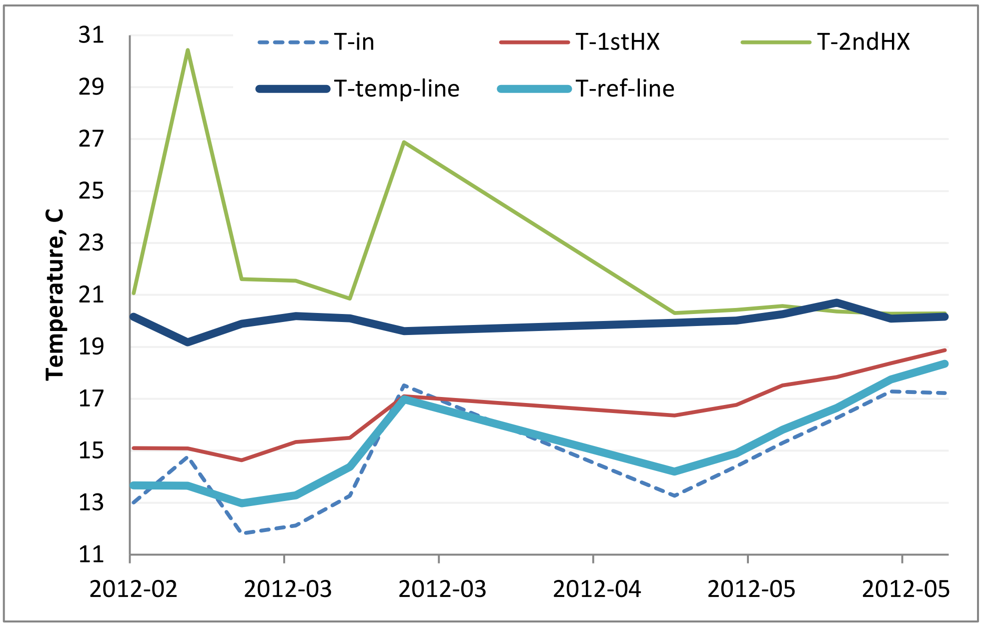


Figure 2. Temperature at different treatment steps 2012 (Feb-May)

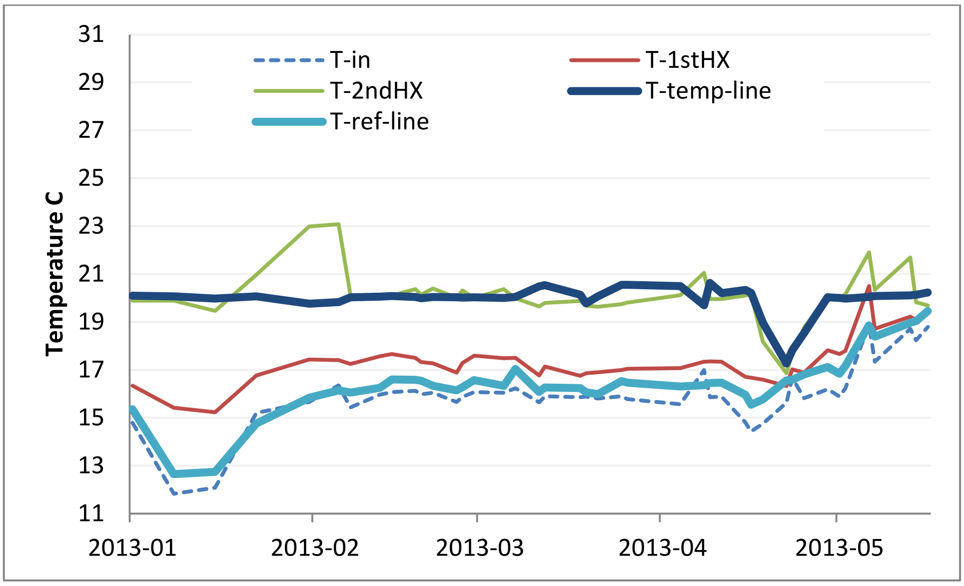


Figure 3. Temperature at different treatment steps 2013 (Jan-May)

Nitrogen removal

The nitrogen concentration was analysed before and after treatment. The results are shown for winter 2011-2012 and winter 2012-2013, respectively. During the first winter period, there are two values, one for the reference line, and one for the temperature line that are much higher and most likely wrong due to sampling or analysis errors.

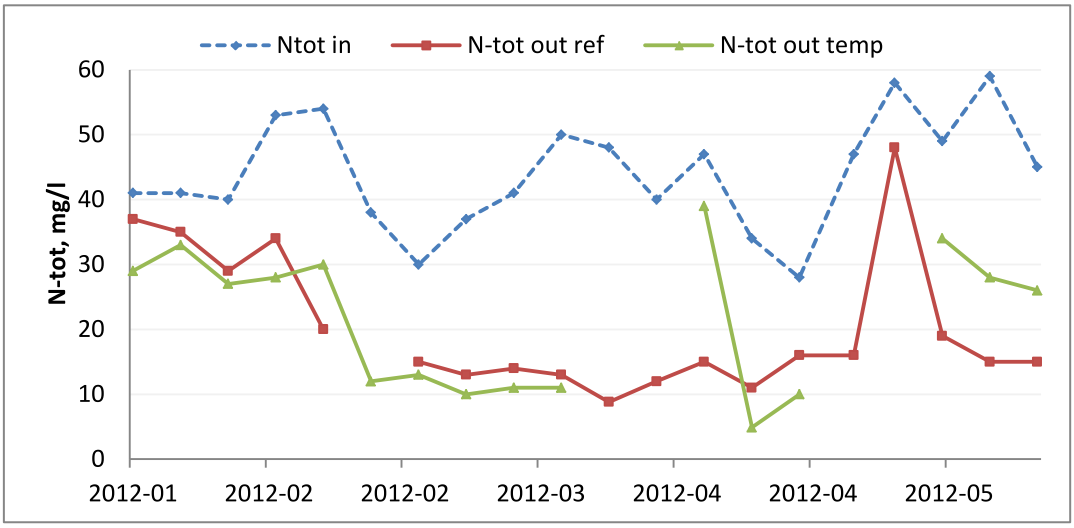


Figure 4. Nitrogen removal winter 2011-2012

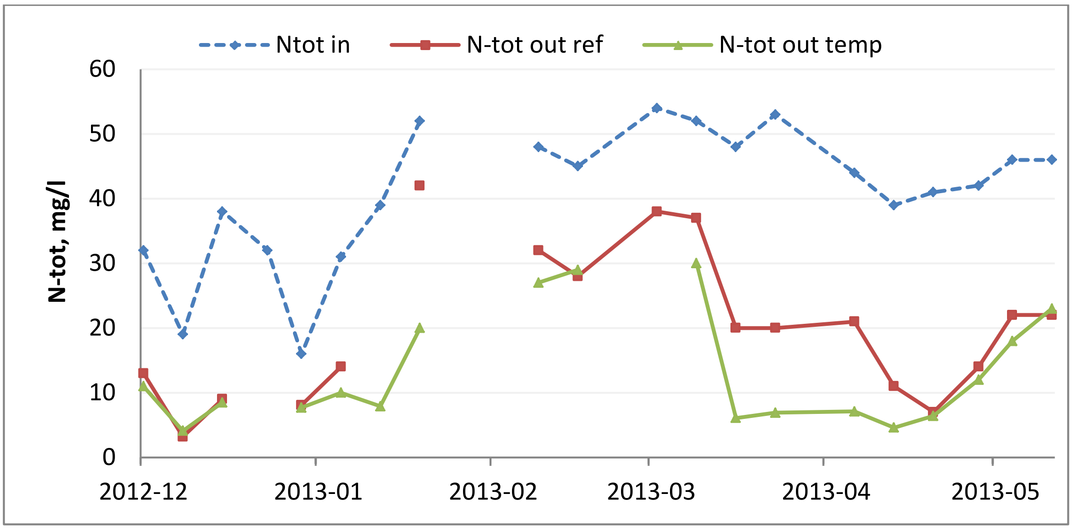


Figure 5. Nitrogen removal winter 2012-2013

Other effluent parameters

The Chemical Oxygen Demand (COD) was analysed before and after treatment. The results are shown for winter 2011-2012 and winter 2012-2013, respectively. There are no inlet values available in the beginning of the test period. During the first winter period, there are three values higher than 200 mg/l that are much higher and most likely wrong due to sampling or analysis errors.

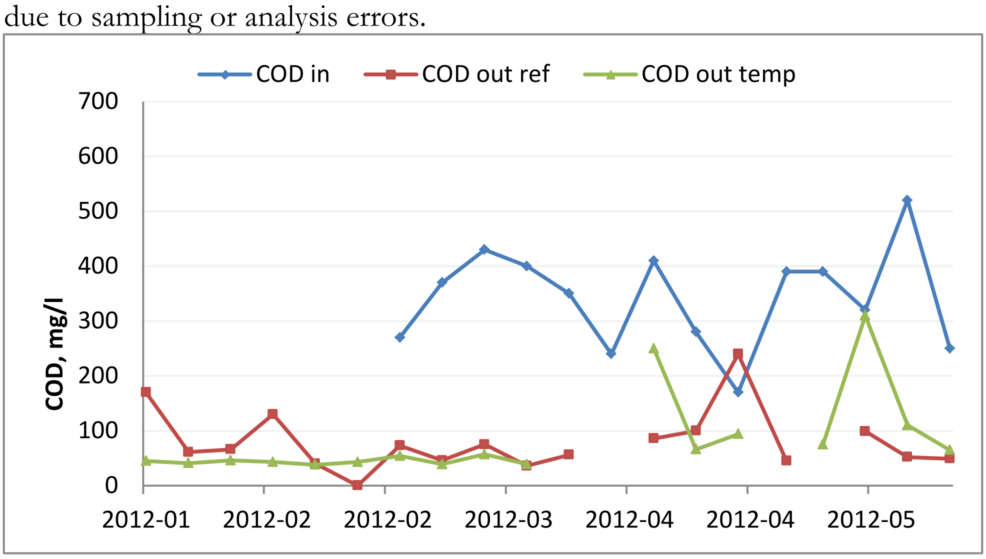


Figure 6. COD content 2012

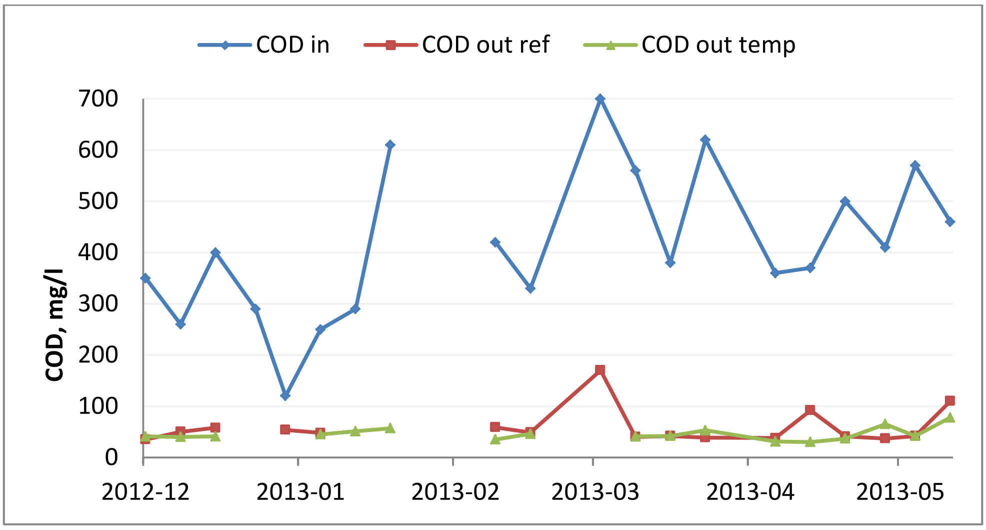


Figure 7. COD content 2013

Phosphorous is another parameter with threshold values. Data from analysis are shown for winter 2011-2012 and winter 2012-2013. Some of the analysis values where obviously wrong,e.g. values higher after treatment than the inlet, these were removed.

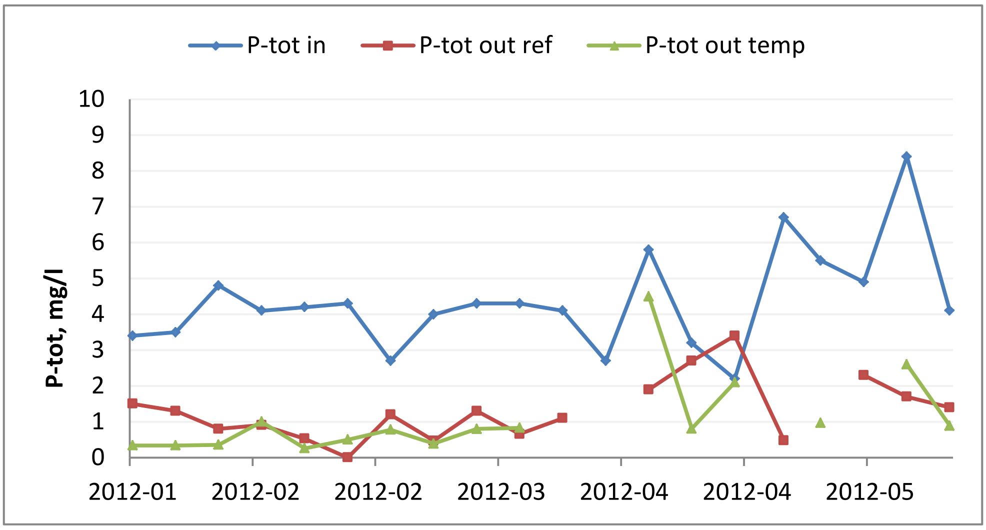


Figure 8. Phosphorous removal winter 2011-2012

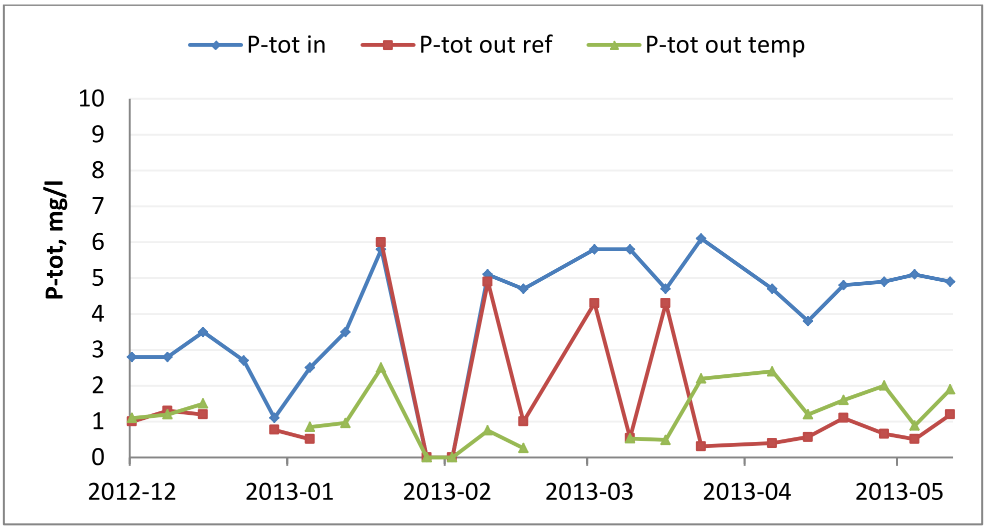


Figure 9. Phosphorous removal winter 2012-2013

Sludge

During some weeks of the demonstration period, problems with floating sludge in sedimentation emerged. As real STPs have to deal with similar problems during warm weather conditions, i.e. summer, these problems were partly expected. Filamentous bacteria that are favoured in warm process water are responsible for this and they are difficult to avoid. The problems were however manageable and did not significantly affect the evaluation period despite some problems during sampling from the bioreactors. Generally, the altered sludge characteristics led to bad settling of the sludge in the post-sedimentation basins. During the project period, no clear difference in the sludge settling in the post-sedimentation basins could be observed between the two lines. To evaluate this, manual sludge level meters were applied.

Heat exchanger

Two types of heat exchangers have been tested during the project. The plate heat exchangers unfortunately clogged very fast, thus it was not able to operate them over a longer time. They were replaced by spiral-wound heat exchangers

Energy demand

The heat demand is dependent on the temperature and flow of the incoming water. As shown, the incoming temperature varied during the winter season. Figure 10 illustrates the heat demand for warming the water to 20 °C. Internal heat is the heat used by the outlet from the treated water, thus it is provided by the process itself. External heat is the heat needed by an external source.

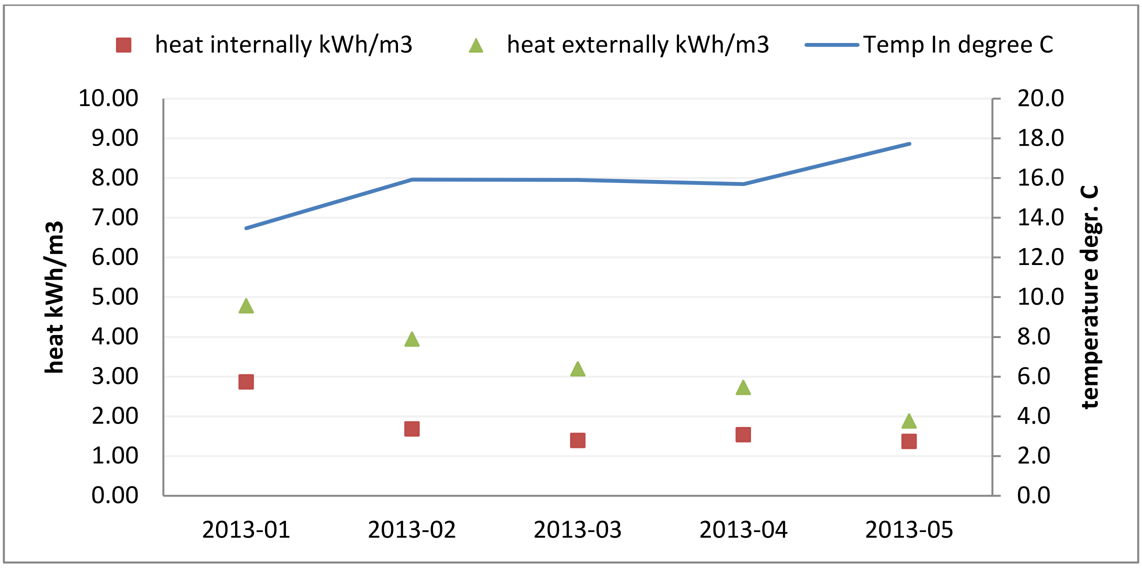


Figure 10. Heat demand for warming wastewater

Other important energy parameters are the energy demand for aeration and the energy demand for mixing and pumping. These are described in the following chapter.

The method for environmental evaluation

Energy and cost estimations

Electricity for blowers

The aeration in the pre-heated treatment train is lowered in the activated sludge as a consequence of the higher temperature of the water entering this treatment step. Although the oxygen solubility is lower at higher temperature, chemical reactions, and biological processes are faster at the higher temperature used in ITEST. Simulations show that the net effect should be a reduced need for aeration.
The value of this saving have been calculated as a percentage difference between the two treatment trains, i.e. the data are mean values from the period of 27/2 – 25/3 2012 (evaluation period for the LCA assessment). The mean percentage saving during this period of time was approximately 7 %. This saving was then used as a basis for the calculations of the blowers at Ernemar STP, Oskarshamn, where two kinds of blowers are used to aerate the wastewater. The effect and percentage of usage of these blowers was given by personnel from Ernemar STP.

Electricity for pumps

The power consumed by the extra pump, used for the heat exchange between influent and effluent wastewater, was calculated from data given in the annual environmental report of

Ernemar STP environmental report of 2011. In these calculations an average flow of 400 m^3/h was assumed and that the pump shall lift the water 3 meters.
The extra energy input necessary to overcome the pressure drop in the heat exchangers have been calculated using data given by Alfa Laval together with information about the operating conditions given in the annual environmental report of Ernemar STP (see Annex 1 of this report).

Cost for main equipment

The purchase cost for the extra treatment was given by the providers. In the calculations of the operational costs a service life of 25 years for the heat exchangers and a service life of 10 years for the pump are assumed.

Life cycle assessment

Objectives of the LCA assessment

The overall objective is to assess the environmental effects induced by preheating influent wastewater to 20° C prior to the activated sludge treatment step at a wastewater treatment plant. Will the total environmental impact be higher for the case without warming than for the case with warming?

General Methodology

For the purpose of modelling the wastewater treatment systems (with and without pre-heating of the wastewater) in order to carry out LCA calculations, the unit processes of the systems are divided into two categories:

- Core processes, defined as processes which are part of the treatment system as such. Their performance may be affected by changes of the properties of the treated wastewater.

- Peripheral processes, i.e. processes which deliver commodities such as energy or chemicals to the wastewater treatment system (upstream processes), or processes which treat wastes or other outputs from the treatment system (downstream processes). The performances of the peripheral processes are not affected by changes of the properties of the treated wastewater. They only react to changes by supplying more or less of their commodity or treating larger or smaller quantities of outputs.

For the inventories of the different treatment trains, the LCA software GaBi was used. GaBi is specialized LCA software convenient for compilation of inventories and for characterization and impact assessment calculations.

Functional Unit

The Functional Unit is **1 m^3 of wastewater to be treated, that is 1 m^3 of wastewater entering the treatment system under study**.

System Boundaries

The upstream boundary is the wastewater coming from the pre-sedimentation step, which means that precipitation is not included in the system. System parts that are not affected by any changes between the present and future situations and will thus be retained unchanged are considered to be outside the system boundaries.

The downstream boundary is the treated wastewater, when it has been discharged to a receiving watercourse. The potential impact of the treated wastewater is thus part of the system.

The side stream boundaries, i.e. the boundaries of the commodity supply chains, are the natural resources required to generate energy and to manufacture construction materials. Sludge treatment is not included in the system since no data have been gathered to explore if and how the temperature difference of the wastewater entering the active sludge treatment step might affect the sludge.

Geographical Boundaries

The wastewater treatment plant is assumed to be located in Sweden and to be supplied by Swedish suppliers. The added material used in the equipment needed to pre-heat the wastewater is assumed to be delivered by Swedish companies. Effluent water is assumed to be discharged to the Baltic Sea.

Impact Assessment Boundaries

In this report impact assessment is limited to the following categories:

- Global warming potential
- Acidification potential
- Eutrophication potential
- Use of primary energy resources
- Use of primary material resources

The emissions from the wastewater treatment process are assumed to be emissions to sea water.

Temporal Boundaries

All data regarding inputs and outputs to and from the treatment trains have been collected from the pilot trials conducted at Hammarby Sjöstadsverket. All data assessed in the LCA are mean values from the period of 27/2 – 25/3 2012. Flow and electricity consumption data was collected from the environmental report of the year of 2011 from Ernemar municipal wastewater treatment plant, situated in Oskarshamn, Sweden. Data for the side stream processes is collected from Xylem and Alfa Laval during the year of 2012. The composition of the electricity mix is collected from the statistics of Svenska Kraftnät for the year 2011 (www.svk.se). In the calculations of the environmental effects caused by the pre-heating equipment it was assumed that the pump has a service life of 10 years and the heat exchangers a service life of 25 years. Maintenance and cleaning of the equipment is not included.

Specific Methodological Choices

Allocation

No specific allocations are applied in the balance calculations to the treatment systems in this report although some of the generic data may contain allocations.

Characterisation (Impact Assessment Calculations)

For the characterizations the weighting factors of CML2001 – Nov 2010 as they are available in GaBi 6.0, are used throughout.

Assessments of Impacts Avoided by the Wastewater Treatment

The impacts caused by the wastewater treatment shall be compared to the impacts avoided by the treatment. The avoided impacts are calculated by comparing the effluent wastewater that is discharged to a receiving water course coming from the treatment with and without pre-heating. The impacts that would be caused by such a discharge are calculated from the composition of the wastewater using the CML2001 methodology. The avoided impacts are then calculated as the difference between the impacts from the discharge of the water treated without pre-heating and from the discharge of the pre-heated water.

Avoided impacts are nutrient enrichment potential. The discharge of untreated wastewater has no effect on any of the other impact categories which are assessed. Global warming potential, photochemical oxidant potential and resource consumption are not environmental burdens on the base wastewater treatment process.

Reporting of Results

The results are reported as potential impact of each category and as dominance analysis showing the percentage contribution in the assessed impact categories.

Inventory of the Peripheral Processes

Electricity

The composition of the electricity mix is collected from the statistics of Svenska Kraftnät for the year 2011 (www.svk.se). It is the supply mix, which are the production mix + the gross import. The electricity from thermal sources is split on separate energy wares according to IEA statistics from 2009.

Figure 11. GaBi flowchart of the electricity inventory.

Results of the environmental evaluation

Energy and cost estimations

Electricity for blowers

The calculation of electricity need for blowers is based on the fans used currently at Ernemar treatment plant:

Kaeser EB 420C, rated power 44 kW, 35% utilisation (average)

HST S2500-1-H-4, rated power 83 kW, 90% utilisation (average)

In the experiments, the reference line, corresponding to the current treatment, needed 1.47 l/min more air in average during a stable operation period (week 9-12, 2012), thus treatment at elevated temperature leads to reduced need for electricity for fans. This means a saving of 7 % in the heated line.

Today, Ernemar use, according to calculations, is 0.23 kWh/m^3 for aeration, thus 0.016 kWh/m^3 could be saved.

Electricity for pumps

The incoming water is heated by means of heat exchangers. As the heat exchangers have a pressure drop, pump energy is needed to overcome this pressure drop. Depending on the use of heat exchanger, pressure drop can vary. In addition, the pressure drop depends on flow velocity. Simplified, a higher flow velocity reduces risk for fouling of biological material, but increases pressure drop. For the evaluation we have calculated with heat exchangers, from Alfa Laval, type WideGap350S-FM for outgoing and TS20M for external heat.

Two cases have been investigated, based on the same heat exchanger, but different designs. In the first case the pressure drop would be about 100 kPa, corresponding to an additional need for energy of 0.034 kWh/m^3 (see Annex 1, Table A1).

In the second case the pressure drop would be about 30 kPa, corresponding to an additional need for energy of 0.01 kWh/m^3.

In both cases there will be additional pump energy of 0.010 kWh/m^3 to pump the treated wastewater for heat exchange.

Cost for main equipment

The proposed solution for pre-heating can be installed at existing treatment plants. Thus, the main costs for installation are:

- Costs for heat exchangers
- Costs for pumps
- Costs for additional piping
- Installation costs, including adaption of the control system.
- Installation costs and costs for additional piping would be site specific and have not been determined.

Costs for pumps and heat exchangers are estimated for the Ernemar case, but would of course have to be negotiated:

- Pump: about 75000 SEK
- Heat exchangers:
    - Heat exchanger alternative 1 (2 items): 740 000 SEK
    - Heat exchanger alternative 2 (2 items) 740 000*1.3 = 962 000 SEK (30% higher cost according to supplier)

Life Cycle assessment

Results – Inventories and Characterization of the Treatment Trains

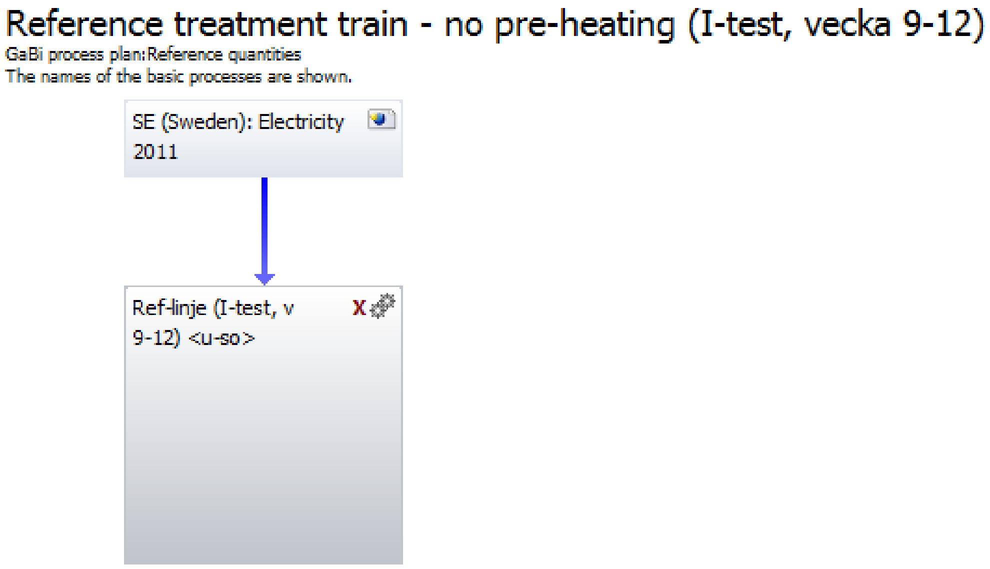
In this chapter the compiled inventories of the treatment trains are presented as flowcharts from the GaBi software. Following each flowchart is a table giving the environmental impact of the treatment trains in a characterized form, i.e. as impact potentials calculated with the weighting factors of the CML2001 methodology.

The tables report the avoided, the remaining and the induced impacts. Avoided impacts have been defined in a previous section to this report. Remaining impacts are consequences when the treated water is discharged to a receiving watercourse without any further treatment. The induced impacts are the effects caused by the treatment process.

Furthermore comparison tables showing each impact potential for the different treatment trains are also presented.

Results Treatment Train # 1 – Without Pre-heating the Influent Wastewater

The inventory flowchart is shown in Figure 12. Tables 2, 3 and 4 report the characterized results.



Reference treatment train - no pre-heating (I-test, vecka 9-12)

GaBi process plan:Reference quantities
The names of the basic processes are shown.

Figure 12. GaBi flowchart of the inventory model of treatment train # 1 – no pre-heating.

Figure 12 shows the very simple model of the reference case without any pre-heating of the influent wastewater.

Table 2. Impacts of treating wastewater through treatment train # 1, per 1 m^3 of water to be treated.

No pre-heating of the influent wastewater	**Avoided impacts**	**Remaining impacts**	**Induced impacts**
	Wastewater	**Wastewater**	**Total**
			Surveyable time
Eutrophication potential, kg PO_4^{3-} equiv.	2.1E-02	4.7E-03	5.99E-05
Global warming potential, 100 years, kg CO_2 equiv.	0	0	3.4E-02
Acidifying potential, kg SO_2 equiv.	0	0	1.38E-04
Photochemical ozone creation potential, kg Ethene equiv.	0	0	1.32E-05

Table 2 shows the impact results of the treatment without any pre-heating. In this case the avoided impacts are calculated as the difference between discharging untreated waste water and discharging the treated waste water to a receiving watercourse.

Results Treatment Train # 2 – With Pre-heating the Influent Wastewater

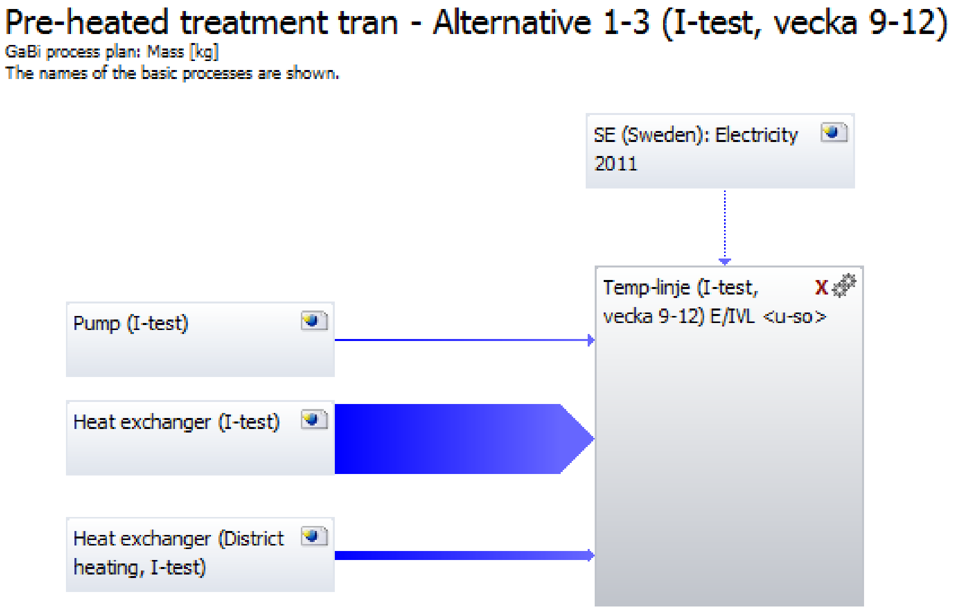


Figure 13. GaBi flowchart of the inventory model of treatment train # 2 – including pre-heating.

Two alternative cases have been assessed in treatment train # 2. In practice there were only two parallel pilot treatment trains, one with and one without pre-heating of the influent wastewater. In theory two different kinds of heat exchangers have been assessed and evaluated. In each of the theoretical cases two heat exchangers and one pump is added to enable pre-heating of the influent waste water (Figure 13). The pump, which is added to enable heat exchange between the effluent and influent water, is assumed to be the same for both cases. It is furthermore assumed in the calculations that the pump should lift the water three meters.

- In alternative 1 plate heat exchangers with quite few plates and quite large pressure drop (99.3 kPa) is assessed.

- In alternative 2 plate heat exchangers is also assessed but in this case the number of plates is increased leading to a smaller pressure drop (29.6 kPa).

In the assessment of the alternatives, only the main materials in terms of the weight (stainless steel and low-alloyed steel) were included (See Annex 1).

Table 3. Impacts of treating wastewater through treatment train # 2 including pre-heating (**alternative 1**), per 1 m^3 of water to be treated (avoided impacts are compared to treatment train #1).

Pre-heating - Alternative 1 **Plate heat exchangers**	**Avoided impacts**	**Remaining impacts**	**Induced impacts**
	Wastewater	**Wastewater**	**Total**
			Surveyable time
Eutrophication potential, kg PO_4^{3-} equiv.	8.09E-04	0.00389104	6.28E-05
Global warming potential, 100 years, kg CO_2 equiv.	0	0	3.60E-02
Acidifying potential, kg SO_2 equiv.	0	0	1.45E-04
Photochemical ozone creation potential, kg Ethene equiv.	0	0	1.39E-05

Table 3 shows the impact results caused by the treatment using plate heat exchangers, alternative # 1. In this case the heat exchanger is designed with quite a few numbers of plates causing a large pressure drop. The quality of the treated water is affected in a positive way through the introduction of the heat exchangers which can be seen in the remaining impacts category. On the other hand the induced impacts, caused by the extra equipment used for pre-heating the wastewater, are increased for all of the assessed impact categories compared to the induced impacts introduced through treatment train # 1. Actually almost all of the induced impacts come from increased electricity consumption.

Table 4. Impacts of treating wastewater through treatment train # 2 including pre-heating (**alternative 2**), per 1 m^3 of water to be treated (avoided impacts are compared to treatment train #1).

Pre-heating - Alternative 2 **Plate heat exchangers**	**Avoided impacts**	**Remaining impacts**	**Induced impacts**
	Wastewater	**Wastewater**	**Total**
			Surveyable time
Eutrophication potential, kg PO_4^{3-} equiv.	8.09E-04	0.00389104	6.08E-05
Global warming potential, 100 years, kg CO_2 equiv.	0	0	3.49E-02
Acidifying potential, kg SO_2 equiv.	0	0	1.41E-04
Photochemical ozone creation potential, kg Ethene equiv.	0	0	1.35E-05

As the introduction of different heat exchangers in all three alternatives is only done theoretically there are no differences in the avoided and remaining impact categories when comparing these alternatives. The induced impacts on the other hand are affected with the introduction of various heat exchangers (Table 4). In alternative 2, larger heat exchangers with more plates and a lower pressure drop are assessed.

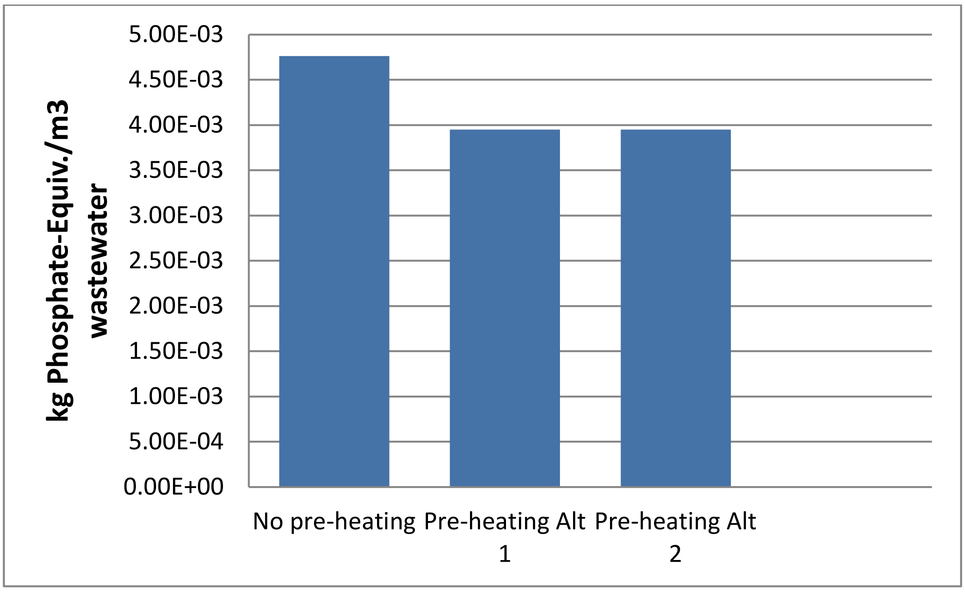


Figure 14. Eutrophication potential calculated

The eutrophication potential decreases when the water is pre-heated through the introduction of the heat exchangers. As the heat exchanger alternatives were assessed and evaluated only in theory, the effluent data (bases for eutrophication potential) in both cases are the same and the eutrophication potential not affected.

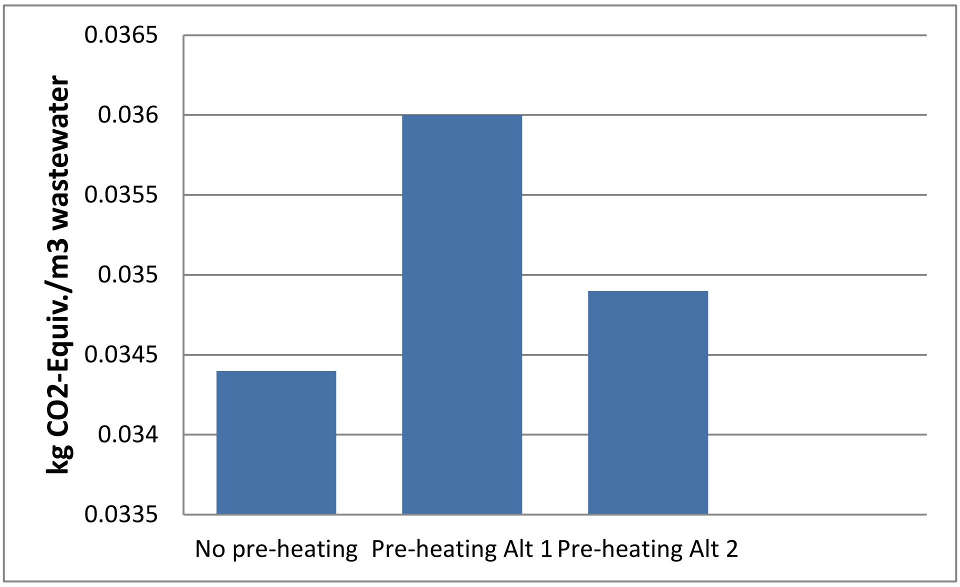


Figure 15. Global Warming potential, calculated (100 years, no biotic carbon dioxide)

Introduction of extra equipment to enable pre-heating of the wastewater increases the global warming potential. The material used in the extra equipment is not contributing significantly. The increase is instead caused by the pressure drop that comes with the different heat exchangers, which in turn means that more electricity has to be put in to the system. Pre-hating alternative #1 has the largest pressure drop. Pre-heating alternative #2 uses more material due to the introduction of more plates to enable a smaller pressure drop.

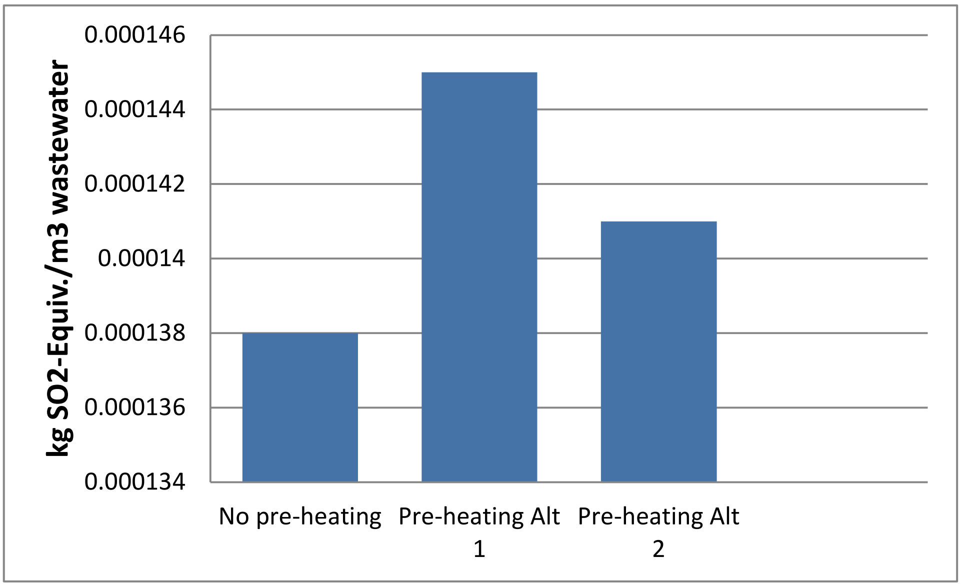


Figure 16. Acidification Potential, calculated

The acidification potential is affected in a similar way to the global warming potential and the same conclusions as for the GWP can be drawn.

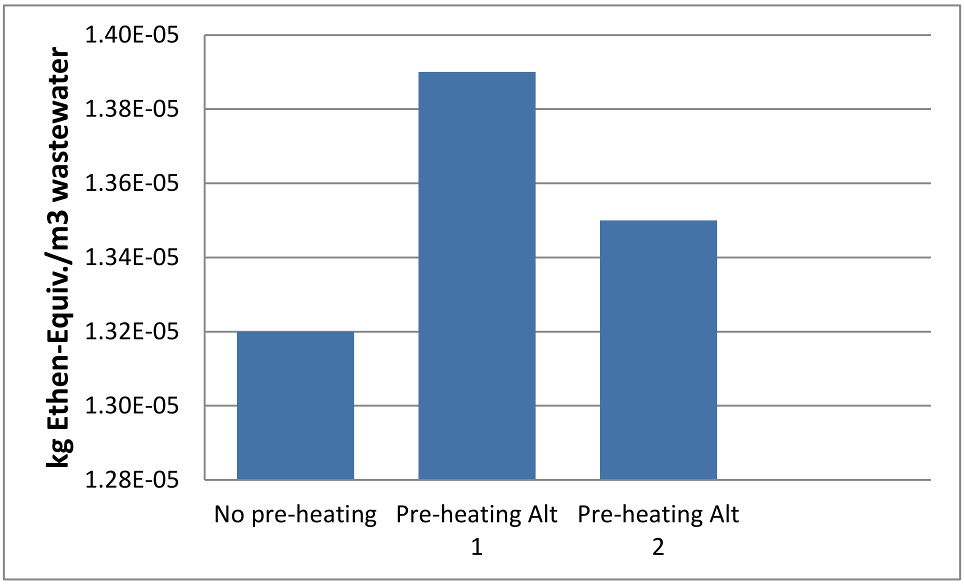


Figure 17. Photochemical Ozone Creation Potential, calculated

The photochemical ozone creation potential also is affected in a similar way to the global warming potential and the acidification potential.

Discussion and conclusions

Discussion of the results

Operational issues and measured values

The ITEST project demonstrated pre-heating of wastewater by heat exchange with external heat source by means of a pilot demonstration plant with two parallel lines, one with pre-heating and one without in order to exclude effects from the incoming water. As it has been mentioned, the pilot equipment was designed and built for the project. Although based on many years of experience, some operational issues occurred during start-up and operation. It has to be pointed out, that these difficulties and interruptions were not related to the pre-heating as such, but to malfunction of some parts of the equipment, as explained before. The heating worked well and allowed to achieve the desired temperature, except for one break done in the heating device, thus not related the heat exchange and temperature control, which was working fine.

As the treatment is based on a biological system, some changes have consequences, although the process as such is robust and well working all over the world. For example difficulties with oxygen meters influenced the treatment results and caused instable operation. At some point the external supply of sewage was stopped due to technical problems at the supplier.

There are still some periods with stable operation during cold periods. During these periods the treatment with temperature control showed a more stable and efficient operation. One of the main goals, the increased removal of nitrogen compounds from wastewater, was achieved well during these periods, especially during the 2nd winter with fewer interruptions. Also the organic compounds and phosphorous were treated well, in both treatment lines, i.e. no significant different between the treatment lines. There is an indication that phosphorous treatment was more stable in the temperature controlled line during the second winter, but this could probably be explained by analytical problems.

The results indicate that it would be possible to reduce the volume, i.e. retention time, in the aerated zone. In full scale this would most probably lead to further reduction of need for mixing and aeration energy.

During some periods, treatment values have been difficult to explain, i.e. treatment has been less efficient than expected. Especially at the end of the second period, the nitrogen removal in both lines was reduced, without any obvious reason.

Nitrous oxide

The advantages of pre-heating the influent wastewater or not can be discussed according to the tests and assessments conducted in this report. However, it should be pointed out that the production and release of nitrous oxide gas (N_2O) to the atmosphere was not part of these assessments. Nitrous oxide emissions that have a 298 times stronger greenhouse effect than carbon dioxide occur primarily during the nitrogen removal when the biological process is not performing optimally due to various reasons, i.e. inhibition by toxics, lack of oxygen or other parameters hindering an optimal biology. It has been concluded in some studies that between 2-3 % of the nitrogen reduced in the STP are released to the atmosphere as nitrous oxide (,Foley *et al.,* 2011; Westling 2011). Under unfavorable conditions, these emissions increase even more (Wicht and Beier, 1995; Foley *et al.,* 2010; Stenström *et al.,* 2013). Comparing the two treatment trains in this study, it becomes clear that the nitrogen removal is more efficient in the pre-heated train. This is of great importance in the discussion regarding the formation of nitrous oxides. Recent long-term studies indicate that a lower sewage temperature leads to an increase of nitrous oxides emissions (Kosonen 2013).

In the present evaluation, these emissions have not been measured or analyzed but since N_2O is a much more potent greenhouse gas than CO_2 its contribution to the overall environmental impact is important to keep in mind when comparing the treatment trains assessed in this study. Especially the Global warming potential of the two compared lines will be affected. Assuming a decrease of N_2O emissions by preheating the incoming sewage compared to emissions from cold sewage operated treatment may balance the additional need of energy and associated negative impacts on global warming.

Heat exchange and energy demand

Typical type of heat exchanger for an application with water containing particles and biological material would be plate heat exchangers of wide-gap type. As these were not available in appropriate dimensions, a normal plate heat exchanger was tested, but clogged almost directly. Spiral wound heat exchangers are an option and have been tested as well. They worked without problems and without maintenance during the test periods.

First discussion with the supplier indicated that spiral wound heat exchangers, although having a higher price, could be an option due to lower pressure drop and less need for maintenance. In further discussions it turned out that the pressure drop in this application probably will be as high as for plate heat exchangers. Thus only plate heat exchangers have been part of the environmental evaluation. Two options were investigated, one with standard pressure drop for wide-gap plate heat exchangers, and one with lower pressure drop. When designing heat exchangers for low pressure drop, the needed area increases as does the cost. Flow rate is reduced, which increases risk for fouling. For a full scale application, the design would probably be in between the two investigated cases, i.e. with a pressure drop that is lower than standard, but still high enough to prevent clogging risks.

For heat exchange not only external heat was used, but also the outlet after treatment, keeping about 20°C. This first step allowed to raise the temperature to about 15-17°C, raising the incoming temperature with 2-3 degrees. This reduces the need for external heat significantly. In cases with sufficient external heat, there is the alternative only to use external heat, which might be achieved in only one heat exchanger.

Enviromental and economic evaluation

For the environmental evaluation, availability of data, data quality, and system boundaries can influence the results. In general, as many parameters were measured, the availability of data was sufficient. Due to the technical issues the demonstration phase was revised and not all parameters were investigated, e.g. nitrous oxide. Furthermore, it was not possible to optimize the operation as much as possible, e.g. investigating shorter retention times and further reduced aeration.

Thus, further process optimization will probably lead to further improvements in the environmental performance.

The evaluation has been focused on the wastewater treatment process. Depending on the source of external heat, the use of external heat also causes an impact. When using the return flow from district heating, the return flow to the combined heat and power plant will hold a slightly lower temperature. This in turn allows to increase electricity production in the power plant.

Conclusions from the technical operation

The demonstration phase of the ITEST project leads, based on the time periods when equipment worked as expected, to the following conclusions:

- One of the tasks during ITEST was to demonstrate if the heat exchange can establish a constant temperature. Under the tested conditions, it was possible to do so by heat exchange from the outlet after treatment as well as with supply of external heat, it was possible to achieve an almost constant temperature of 20°C.
- Spiral wound heat exchangers worked flawlessly during the whole test period without back-flushing or any other maintenance work.
- Plate heat exchangers had clogging problems, which made them in practice not operational. Wide gap plate heat exchangers were not available at the size of the demonstration plant and could therefore not be tested.
- Treatment of pre-heated sewage allows for an improved nitrogen removal during cold periods. However, the demonstration indicates that several other factors are affecting the nitrogen removal and have to be considered.

- Treatment of other compounds like COD and P is maintained at a high level independent of the sewage temperature.

- The enhanced biological treatment process using pre-heating of cold sewage should generally allow for a reduced STP footprint, i.e. a reduced retention time.

- When using shorter retention time, it should be possible to reduce aeration and mixing even further compared to the slightly reduced need shown during demonstration.

- Treatment at 20°C may imply more frequent risk of floating sludge in sedimentation, which has to be dealt with.

Conclusions from the environmental evaluation

The main purpose of pre-heating the influent wastewater was to improve the nitrogen reduction and to reduce the potential eutrophication impact in the receiving water course (Baltic Sea), which also was proven to be the case. The introduction of heat exchangers and extra pump is necessary, which in turn increased the need for energy input (electricity) into the system. The following conclusions can be drawn:

- Under the tested circumstances, the eutrophication potential is lowered but at the same time several other impact categories (global warming potential, acidification and photochemical ozone creation potential) are increased. Thus, from an environmental point of view, the decision is between different impact categories.

- Electricity is by far the most dominating factor for all of the assessed impact categories, except for the eutrophication potential. The environmental impact caused by electricity will also be depending on the source of electricity, e.g. if it is coal power, nuclear power or renewable energy.

- The most promising pre-heating alternative according to the LCA results in this study was the one with low pressure drop heat exchangers (alternative 2), as the impact from less electricity use for overcoming the pressure drop exceeds the influence from additional material used.

- If it is possible by further optimization to reduce the need for electricity, e.g. for aeration and mixing, there might be a net effect of reduced need for electricity although electricity is needed for the pumping for heat exchange.

Recommendations for scale-up including lessons learned

Although there have been some technical difficulties during the demonstration period, there are a number of findings for a possible scale up and implementation at full scale:

- The technology as such is working, i.e. pre-heating of cold sewage is possible to achieve an almost constant elevated temperature. The results indicate as well an increased nitrogen removal efficiency that allows reaching low remaining nitrogen concentrations.

- The technical issues at the demonstration plant should not pose any limitations in full scale.

- The sludge properties might need more attention, as floating sludge could occur. At the same time, many STPs have experiences with and solutions to similar problems already today. Normally sludge problems occur at changes in temperature, not at constant temperature.

- Further optimization of the operation would be desirable. There should be a potential to reduce the energy needed for aeration and mixing when using temperature controlled biological steps.

- The demonstration does not allow to calculate the final volume needed for treatment, but results indicate that temperature controlled biological treatment will allow to use less active sludge volume or increased treatment efficiency, leading to reduced need for aeration and mixing per treated cubic meter of sewage.

- The choice of heat exchanger depends on different parameters. Spiral-wound heat exchangers proved to work well and would at full scale probably result in less maintenance, but at a higher investment cost and probably without lower pressure drop. Thus wide gap plate heat exchangers are the recommended choice. They can be dimensioned to have a lower pressure drop in order to save energy.

- Recommendations for further work and investigations:

    - Operational optimization: as treatment is more efficient, treatment volumes, i.e. retention time, might be reduced, leading to reduced need for aeration and mixing. This has to be investigated further to get quantification.

    - Partially pre-heating of cold sewage should also be considered. This implies preheating to increase the sewage temperature with only a few Kelvin during the lowest influent temperatures. This would facilitate an improved nitrogen removal during the most critical periods of the operation of STP.

- Partially pre-heating of cold sewage as explained above may also be considered as an alternative to meet more stringed nitrogen effluent requirement averages with shorter reference interval of e.g. a quarter of a year or a month.
- Optimization of the heat exchanger, to find the best combination of pressure drop and low clogging risk.

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Annexes

Annex 1: Data Used in the LCA Calculations

Table A1. Energy data that was used as a basis in the calculations leading to the LCA results.

Pre-heating alternative	Extra need for energy input to overcome pressure drop through heat exchangers (kWh/m^3)	Extra need for energy to run pump for recirculation of effluent (kWh/m^3)	Reduced energy input due to saving of energy in blow machines in active sludge treatment step (kWh/m^3)	Total extra energy need (kWh/m^3)
1	0.034	0.010	0.016	0.029
2	0.010	0.010	0.016	0.005

Table A2. Input of extra equipment used as a basis in the calculations leading to the LCA results.

Equipment	Weight (kg)	Service life (years)	Flow (m^3/year)	Extra equipment used (kg/m^3)
Small heat exchanger alternative 1	1190	25	341 600	1.39E-05
Large heat exchanger alternative 1	8074	25	341 600	9.45E-05
Small heat exchanger alternative 2	1512	25	341 600	1.77E-05
Large heat exchanger alternative 2	12601	25	341 600	1.48E-04
Pump	216	10	341 600	6.32E-06

Annex 2: Pilot plant scheme

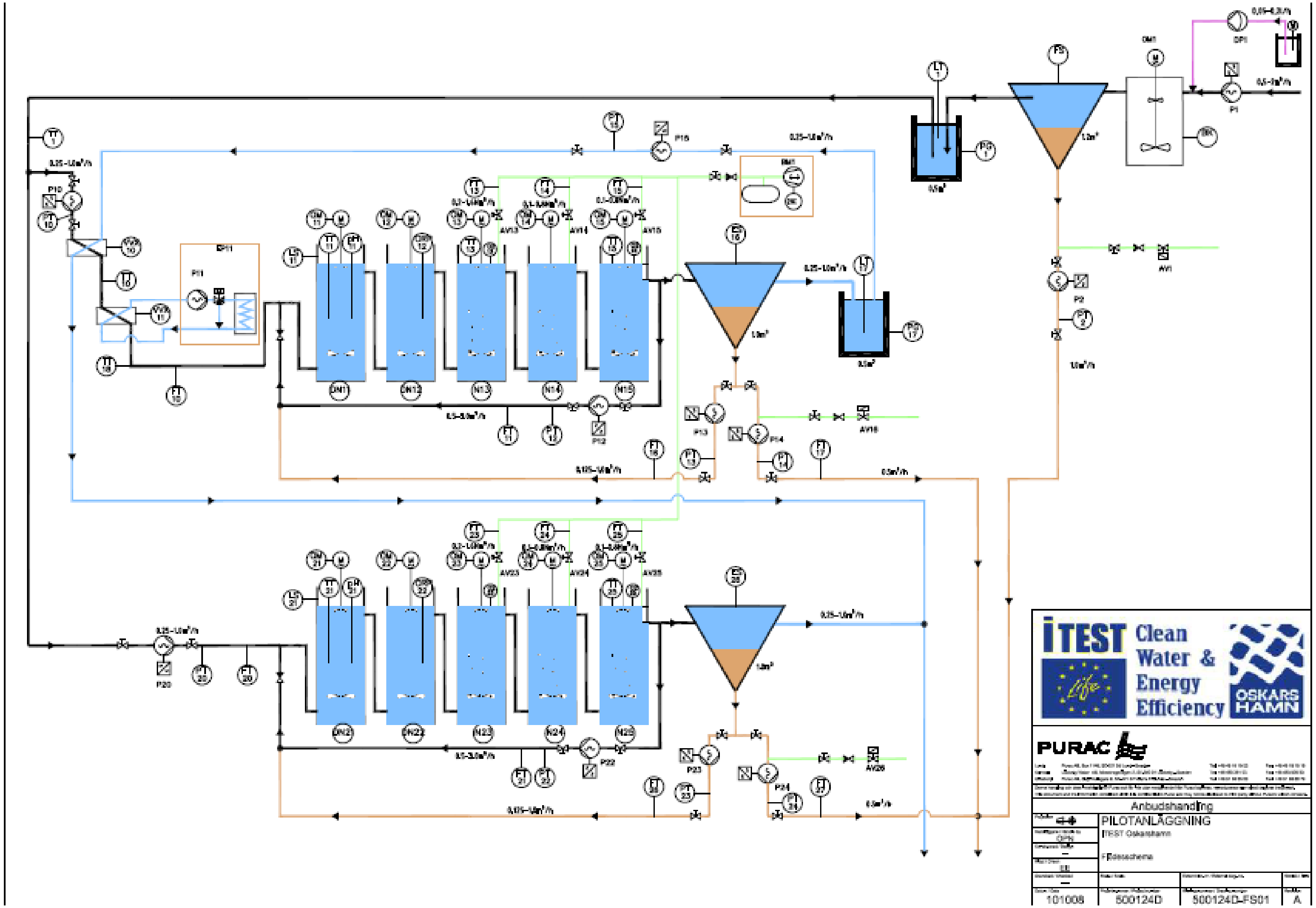

Foto of ITEST demonstration equipment