WP4 – Nitrogen management in side stream

D 4.3: Operation and optimization of membrane ammonia stripping

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Deliverable 4.3	***Operation and optimization of membrane ammonia stripping***
Related Work Package:	4
Deliverable lead:	Eawag
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Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the European Commission Services)
	CO	Confidential, only for members of the consortium (including the European Commission Services)

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Preliminary notes and executive summary

The present report describes the work and outcomes of case study 6 in the second period of the project POWERSTEP (month 19 – 30). The case study – implemented in work package 4 "Nitrogen management in side stream" – is intended to demonstrate the recovery of nitrogen by membrane stripping. Outcomes and results are documented in the deliverable 4.2 "Planning and design of a full scale membrane ammonia stripping".

According to the CS6 timeline, this document should report on the operation and optimization of the stripping plant at WWTP Altenrhein. The realization of the stripping plant is late due to a delay of decision regarding the awarding of contracts to the executive company. Main reasons for the delay are missing clarifications on costs and the final decision by the administrative board of *Abwasserverband Altenrhein* for the realization.

Furthermore, the operator of WWTP Altenrhein waited for the final decision of the Federal Office for the Environment of Switzerland (Bafu) about a subsidy (CO_2 compensations). Against this background, it will not be possible to gain and to evaluate operational data from WWTP Altenrhein in the frame of the Powerstep project.

In parallel to the activities in CS6, the first membrane stripping plant was realized in the western part of Switzerland at WWTP Yverdon-les-Bains in 2016. This encouraged the CS6 leader Eawag to get in touch with the WWTP Yverdon-les-Bains and the manufacturer of the membrane plant Alpha Wassertechnik AG (the manufacturer of the Yverdon-les-Bains plant will also be the constructor of the Altenrhein plant).

This was very positively received by Alpha Wassertechnik AG and the WWTP Yverdon-les-Bains, and a contractual agreement for a trustful cooperation was concluded. Since November 2017, an employee of Eawag has been working directly with Alpha Wassertechnik AG and WWTP Yverdon-les-Bains to review and evaluate existing operational data. Therefore, these activities will make it possible to generate important key values and operating parameters from a full-scale ammonia stripping plant. First results of these works are documented in section 0.

The ammonia membrane stripping plant in Yverdon-les-Bains has undergone continuous optimization by Alpha Wassertechnik AG since 2016, and will, whenever possible, incorporate optimization suggestions from Powerstep in the future. A balanced work program and the objectives of the cooperation have been agreed and defined between the partners (see section 4.2.3).

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1. Introduction and background

In terms of costs and energy consumption, anaerobic ammonium oxidation (anammox) is currently the optimal treatment process for sludge liquids to reduce the internal N-load and to conserve some of the design capacity of WWTPs. But over the last years, experience in operating the biological anammox process showed some difficulties with process stability.

Air, steam or membrane stripping are the only physico-chemical processes for the recovery of nitrogen into a valuable liquid fertilizer (ammonia sulfate) for agriculture. But, free ammonia stripping requires heavy dosage of base. Costs and energy consumption to produce the base are a significant part of the overall operational costs and energy consumption. The investigated novel processe, therefore, uses optimized pH and temperature conditions as well as CO_2 pre-stripping, which reduces the amount of sodium hydroxide, the commonly used base, by up to 40%. Ammonia is physically removed from sludge liquids by stripping as gaseous free ammonia (NH_3), with typical efficiencies of up to 90 %. In a two-step process, NH_3 is stripped from the sludge liquid and subsequently removed from the gaseous phase by sulfuric acid. An innovative method is the use of a cross-flow membrane that separates the sludge liquid from the sulfuric acid, resulting in a compact membrane treatment unit.

The case study 6 - integrated in WP 4 “Nitrogen management in side stream” – is intended to demonstrate the full-scale recovery of nitrogen contained in liquids from sludge treatment of the WWTP Altenrhein. In parallel to these activities PowerStep is in close contact with WWTP Yverdon-les-Bains, which is operating a full-scale ammonia stripping plant since mid-2016. The ammonia stripping project in Yverdon-les-Bains was an initiative of the WWTP Yverdon-les-Bains and Alpha Wassertechnik and is independent from the Powerstep program.

2. Goals and task 4.2: "Membrane ammonia stripping of sludge process water [M1-30] (EAWAG, SUSTEC, ATEMIS) - Case study 6 (CS6)

2.1. Goals and outcomes of CS6 months 1-18 (first period of the project – "Realization of a membrane stripping plant at WWTP Altenrhein"

In the first period of CS6 the main goal was the realization of an ammonia membrane stripping plant at WWTP Altenrhein to produce a liquid fertilizer for agricultural use.

In this phase of the project the consortium provided substantial support for the evaluation and definition of design parameters for the pre-treatment, the membrane unit, caustic soda dosage equipment and for the implementation of the plant into the existing infrastructure of WWTP Altenrhein. In addition, the consortium gave substantial input for the preparation of the documents to invite tenders. At the end of the first period, the consortium evaluated the outcomes from the invitation to tender and gave a recommendation to award the contract. A detailed documentation of the activities and outcomes is given in deliverable D4.2 "Planning and design of a full-scale membrane ammonia stripping".

2.2. Goals of CS6 months 19-30 (second period of the project - "Operation and optimization of membrane ammonia stripping")

In the second period of the project, it was intended to gain long-term operational experience and to optimize the process at WWTP Altenrhein after its realization. As explained in chapter 1, the construction of this plant is delayed. Therefore, the consortium will evaluate the Yverdon-les-Bains plant instead and a cooperation was launched with WWTP Yverdon-les-Bains and Alpha Wassertechnik AG.

Goals of this cooperation in a superordinate view are:

- Energetic balance in terms of heat demand and electricity
- Mass balance in terms of the use of chemicals (NaOH, H_2SO_4, HCl, etc.) related to recycled nitrogen as a fertilizer
- Quality of the product
- Comparison with alternative technologies (costs and efficiency)
- Evaluation of the energy balance and CO_2-emissions of WWTP as well as economic feasibility
- Process performance and operational experiences (maintenance strategy)
- Description of design and operation for future adaptation of this technology including operational recommendations (process start-up and shut-down)
- Suggestions for optimizing the operation of the Yverdon-les-Bains plant
- Suggestions for an optimal realization of the Altenrhein plant on the basis of the experiences at the Yverdon-les-Bains plant.

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2.3. Additional goals in CS6 - N_2O measurement at WWTP Altenrhein

Biological nitrogen removal processes destroy the inorganic nitrogen. A fraction of the nitrogen is transformed into the very strong greenhouse gas nitrous oxide. The Swiss CO_2 law was revised in 2011 and provides the legal basis for Switzerland's climate policy from 2013 to 2020. The law came into force on January 1st 2013. The law sets the targets and means of climate policy and is intended to implement sustainable energy and climate policies. The Foundation for Climate Protection and Carbon Offset (KliK. www.klik.ch) operates as a carbon offset grouping for mineral oil companies retailing fossil motor fuels for consumption.

The compensation processes have to take place in Switzerland. Cost of up to CHF 120.- per ton of CO_2 are guaranteed as revenue for projects reducing CO_2 equivalents and meeting the goals of the law. In accordance with this background the N_2O-emmissions of the main lane at WWTP Altenrhein are of high interest. Recovery of nitrogen and therefore a reduction of the internal N-load will reduce the N_2O-emissions of the plant significantly. These activities are directly linked to CS6 and to the economic feasibility of the membrane stripping plant. If a considerable reduction in the N_2O emissions can be achieved by recovery of nitrogen, there will be a financial benefit, which compensates partly the operational costs of the stripping plant.

Full-scale studies of N_2O emissions at WWTP Altenrhein are carried out since December 2015 up to summer 2017.

2.4. Structure and partners of CS6

The project team of CS6 consists of the POWERSTEP consortium and the local partner WWTP Altenrhein and their local engineering consultant Kuster & Hager. The following partners and persons have fundamental input into CS6:

2.4.1. Partners involved in POWERSTEP and in CS

- Marc Böhler **Eawag**, case study leader, process engineering, scientific supervision, (CH)
- Julian Fleiner **Eawag**, project manager, process engineering scientific supervision, (CH)
- Wenzel Gruber **Eawag**, N_2O-studies, process engineering, PhD-student, (CH)
- Antonio Hernández **Eawag**, project manager, process engineering scientific supervision, (CH)
- Hansruedi Siegrist subcontractor, consultant and scientific supervisor, (CH)
- Luchien Luning DMT Environmental technology, process engineering, plant manufacturer, (NL)
- Alexander Seyfried **ATEMIS GmbH**, engineering consultant, (D)
- Doris Schäpers **ATEMIS GmbH**, engineering consultant, (D)
- NN **ATEMIS GmbH**, engineering consultant, draftsperson (D)
- Steffen Zuleeg **Kuster & Hager**, local engineering consultant, (CH)

- Christoph Egli — **Abwasserverband Altenrhein**, director/operator of WWTP (CH)

Since mid of 2016 a membrane stripping plant is in operation at WWTP Yverdon-les-Bains (western part of Switzerland). This plant will be evaluated in the frame of CS6 and serve as a kind of "Sub-CS." The following people and institutions collaborate with Eawag in CS6:

- Marcel Pürro — **Service des Travaux et de l'Environnement**, director/operator of WWTP (CH)
- Emmanuel Bonvin — **Alpha Wassertechnik AG**, President (CH)
- Frédéric Gindroz — **Alpha Wassertechnik AG,** engineering consultant, (CH)

2.5. Proposed procedure for the remaining project time in CS6

- Ongoing consulting by the Powerstep team in construction meetings for the realization of the Altenrhein plant **(Eawag, Atemis)**
- Co-working and finalizing task 4.3 Technico-economical comparison of options for nitrogen management in side stream (months 18 – 32, **all partners, lead TU Vienna)**
- Cooperation with Alpha Wassertechnik AG and WWTP Yverdon-les-Bains to generate important key values and operating parameters from a full-scale ammonia stripping plant (months 28 – 33)
- Updating of this report (deliverable D4.3 "Operation and optimization of membrane ammonia stripping") with outcomes of cooperation with Alpha Wassertechnik AG and WWTP Yverdon-les-Bains (month 35, **Eawag, Atemis**)
- Formulation of recommendations for an optimized operation of a membrane stripping plant

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3. Status of CS 6

3.1. Status months 1 - 18

In the first period of the project between month 1 and 18, all the work was done, which was a prerequisite to enable a fully technical realization of the plant at WWTP Altenrhein. This includes the whole design of the plant, the definition of the flow scheme as well as the tendering and the awarding of contract of the plant. This work is described in detail in D 4.2 Planning and design of a full-scale membrane stripping (Boehler et al. 2016).

Parallel to this work, N_2O off-gas measurements were carried out by Eawag at WWTP Altenrhein. With the results from the first period of the project (12/2015 – 5/2016), the first proposal of a two-step application was made to the Federal Office for the Environment to get compensations for the reduction of N_2O emissions and the CO_2 equivalents linked with it. The results of these measurements can also be found in Boehler et al. 2016. Additional measurements were conducted in 2017 (see 4.1.2).

A proposal for the award of contract was already formulated mid-2016 by the Powerstep team and the local engineering consultant KUSTER & HAGER. However, the awarding of contract was delayed and was done by the WWTP Altenrhein in the beginning of the second period of the project in early 2017.

3.2. Status months 19 - 30

Based on the work of the first period, the activities at WWTP Altenrhein were pushed, especially in the field of consulting for the realization of the plant (4.1.1) as well in the N_2O topic (see section 4.1.2).

Since the commissioning of the full-scale facility at WWTP Altenrhein will be delayed for the Powerstep project, Eawag took the initiative and contacted Alpha Wassertechnik AG and WWTP Yverdon-les-Bains, which is operating a full-scale ammonia stripping plant since mid of 2016. In the frame of the Powerstep project, this plant will be evaluated in terms of mass balances for energy (primary energy and electricity demand), chemical demand, productivity and quality of the product, et cetera (see section 4.2). Results will be found in section 0.

The following section gives a detailed overview of all activities and results between months 19 – 30.

4. Results and activities in months 19 - 36

4.1. Ongoing Activities at WWTP Altenrhein

4.1.1. Ongoing consulting by the Powerstep team

The award of contract went to the company Alpha Wassertechnik AG. Since the award of contract (at the beginning of 2017), there are ongoing planning and construction meetings at WWTP Altenrhein between WWTP Altenrhein, consultant KUSTER & HAGER and Alpha Wassertechnik AG, at which Eawag and ATEMIS GmbH (via correspondence with Eawag) are always involved. In these construction meetings, details for the realization are discussed. The flow scheme of the plant will be somewhat different to the base line of the invitation to tender. In the following paragraph an example is given:

The final lay out of the stripping plant for WWTP Altenrhein is based on a construction variant ("Unternehmer Variante") of the invitation for tender, which is very similar to the flow scheme of the Yverdon-les-Bains plant. In contrast to the layout of the invitation to tender, in this variant the CO_2-stripping is performed in a water column without heat addition (cold stripping). Against this background, there were ongoing questions on how to design the CO_2-stripping, which were solved by the input of ATEMIS GmbH and Eawag.

Nevertheless additional pilot scale trials were conducted by Eawag between November and January 2018 at WWTP Altenrhein with sludge liquids of WWTP Altenrhein to verify the design values given by Eawag and Atemis GmbH (see Figure 1).

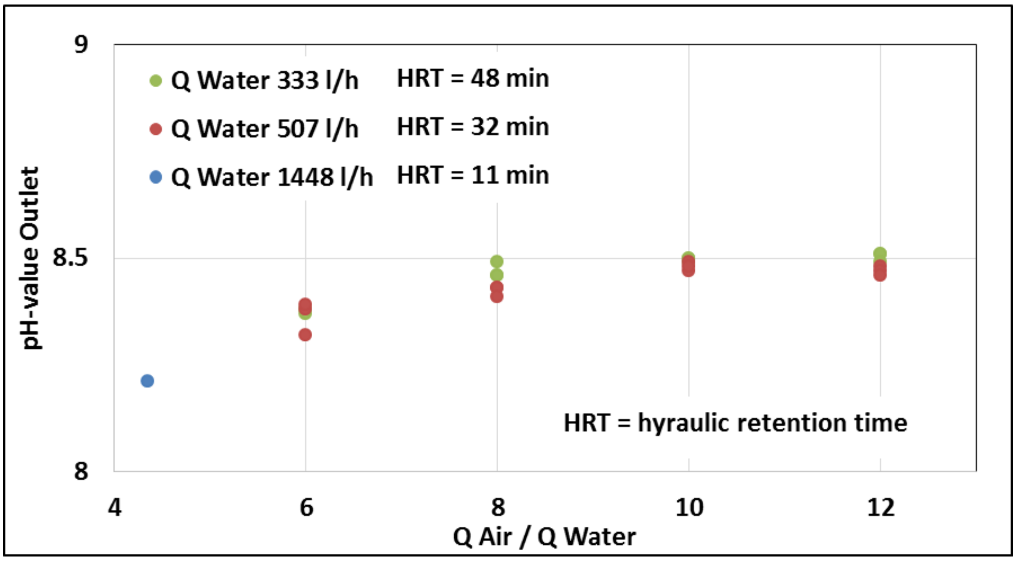

Figure 1: Increasing of pH of the sludge liquid after CO_2-stripping at different Qair/Qwater ratios. Initial pH values were in the range of 8.0 to 8.2. Stripping temperature of the sludge liquid was in the range of 25.5 to 27.5 °C. The used stripping column has a diameter of 0.2 m, a height of 2.1 m and a volume of 0.25 m^3.

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The CO_2 stripper will be designed with a contact time of the sludge liquid in the column of 30 minutes and an air to sludge water ratio of 8-10. The operation temperature will be up to 50°C.

4.1.2. N_2O-measurements at WWTP Altenrhein

N_2O-measurements were finalized in 2017. Over a period of over two years the N_2O emissions of WWTP Altenrhein were observed by Eawag. With this data set the second proposal for CO_2 compensation were successfully submitted to the Federal Office for the Environment of Switzerland (Bafu). Due to this engagement the WWTP will get a financial support of up to 100'000 Sfr. per year for the operation of the membrane stripping plant after start up until 2020. There are also good perspectives, that the specific program will be prolonged. See also webpage http://powerstep.eu; rubric "related news".

4.1.3. Evaluation of new and robust membrane stripping modules at WWTP Altenrhein

The demand of sodium hydroxide for raising the pH value and to increase the degree of protonation of ammonium in the sludge liquid is the key costs driver for the economic feasibility of the process. Beside the increase of pH by base dosage, the protonation can be also raised by increasing the temperature.

Up to now only the module "Liqui Cel" of the company Membrana GmbH / 3M is used for the technology of membrane stripping, but this module is currently limited to an operation temperature of maximum 50°C (maximal temperature resistance of the glue fixing the hollow fibers in modules). Another limitation are the quite narrow distances between single hollow fibers, which resulted in an extensive pre-treatment need of the sludge liquid, which correlates with high investment cost for the adequate infrastructure (filter, etc.) Against this background a Dutch/Swiss project was launched to develop a new membrane module. This module will be tested at WWTP Altenrhein in 2017/18. This project is totally independent of Powerstep, but these modules might be a good option, if the plant in Altenrhein is extended by additional membrane modules or if modules must be replaced in future.

The project is supported by the Dutch Department of Agriculture.

4.2. Activities at WWTP Yverdon-les-Bains

4.2.1. WWTP Yverdon-les-Bains as a "Sub CS 6"

The Yverdon-les-Bains plant will be handled as a kind of sub CS in Powerstep. To get more insight and experiencies into the stripping of ammonia by membranes in full-scale, a cooperation between WWTP Yverdon-les-Bains and Alpha Wassertechnik AG was resolved. A co-worker of Eawag is working since November 2017 at WWTP Yverdon-les-Bains to evaluate the operation and maintenance of the plant. More details about this activity is given in the next sections.

4.2.2. Agreement with WWTP Yverdon-les-Bains and Alpha Wassertechnik AG (Nidau)

For the collaboration between Eawag and Alpha Wassertechnik AG an NDA – Non Disclosure Agreement (Vertraulichkeitsvereinbarung) has been completed. Eawag or Powerstep is not interested in details of the technical implementation, but rather in higher-level operating results, from which it is possible to derive central operating parameters and optimizations. Specific knowledge, information or data, which is directly linked to the Yverdon-les-Bains plant may only be published by mutual agreement.

4.2.3. Work program WWTP Yverdon-les-Bains

WWTP Yverdon-les-Bains and Alpha Wassertechnik AG are very interested to extract detailed information on the overall operation of the stripping. In this context, a work program was elaborated concerning the following aspects:

- Clarification and assessment of existing operational data in terms of:
- Heat demand of process
- Electricity demand of process
- Chemical demand e.g. NaOH, H_2SO_4 related to the amount of produced fertilizer
- Performance of the CO_2-stripper (increase of pH, precipitations, foaming)
- Product quality (N concentration, micro pollutants)
- General cost and design considerations (ATEMIS)

4.3. Stripping system in Yverdon-les-Bains

Figure 2 shows a simple flow scheme of the membrane stripping plant of WWTP Yverdon-les-Bains. After collection and storage of the sludge liquid the water is prepared in a multi-stage pre-treatment before entering the membranes. The pre-treatment consists of a CO_2 stripping (two water filled columns). The division of the CO_2 stripping in two successive water filled columns is due to the given room height. After the CO_2 stripping, the pH is adjusted by the addition of sodium hydroxide in the coagulation tank, which is stirred. A subsequent flocculation and sedimentation in a lamella settler allows the separation of the further precipitates and of organic solids of the sludge liquid. A sand filter removes finest precipitates and solids from the sludge liquid.

After an additional fine filtering in cartridge filters to avoid a clogging of the fine hollow fiber membrane bundles in the membrane unit, the first heating of the sludge liquids takes place by means of a heat exchanger. The first heat exchanger uses the already treated sludge liquid of the membrane unit in countercurrent flow to the filtered sludge liquid. A second increase in temperature is provided by another heat exchanger, which uses hot water from the hot water cycle of the WWTP.

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After reaching the target temperature, the sludge liquid is passed over the membranes. The membrane unit is multi-laned and several membrane modules are connected in series.

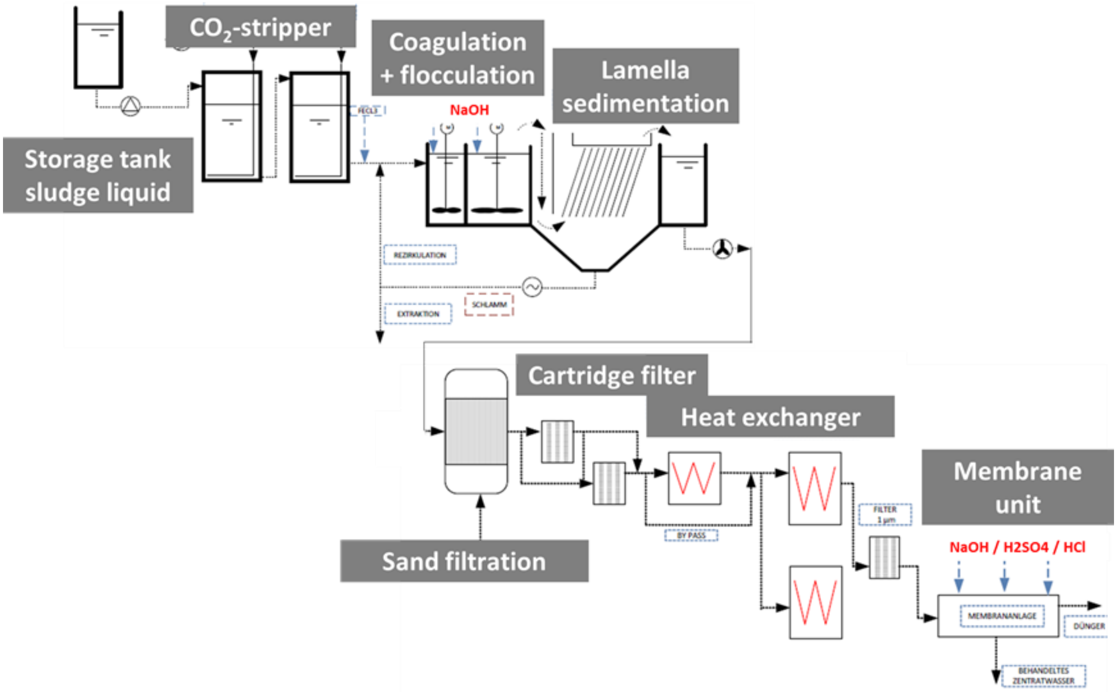

Figure 2: Principle flow scheme of the ammonia membrane stripping plant of WWTP Yverdon-les-Bains.

4.4. Results of evaluation of operational data of WWTP Yverdon-les-Bains

4.4.1. Approach and underlying data

Characteristic data of the ammonia Stripping plant in Yverdon-les-Bains was collected from the supervisory control and data acquisition system. Ammonium concentrations were measured in the laboratory and electric power consumption measurements were made on site with an ampere meter and verified by comparison with the recorded value by the data acquisition system.

Based on the stripping process characteristics which have been shared by Alpha Wassertechnik AG, calculations have been completed to fill the gaps in case of missing data.

The collected data from the data acquisition system and from laboratory measurements corresponds to a period of 18 months (August 2016 – January 2018). During this period, the stripping was operated in a "pilot full scale mode". The setpoint of control variables (as for example sludge liquid flow, pH and temperature of sludge liquid entering the membrane) were varied throughout the entire period to gain experience with the stripping unit and to improve the process performances. The configuration of the components of the recovery system were changed by Alpha Wassertechnik AG for optimization until November 2017. Besides, the sludge liquid production of the WWTP Yverdon-les-Bains was low and did not allowed to operate the stripping unit continuously with the wanted sludge liquid flow. The stripping unit was therefore operated only 27% of the period considered. Production of fertilizer in "steady state" conditions was therefore limited.

To ensure reliability of the recorded and calculated data, plausibility calculations were performed with mass balances over the entire system and on single components of the stripping plant. Additionally, chemical consumptions were verified comparing level decrease in the storage tanks with recorded data by the flow meters. An example of plausibility check calculation is presented in Figure 3, where the Ammonium mass balance over the lumen side of the membranes was compared with the mass balance over the acid side of the membranes.

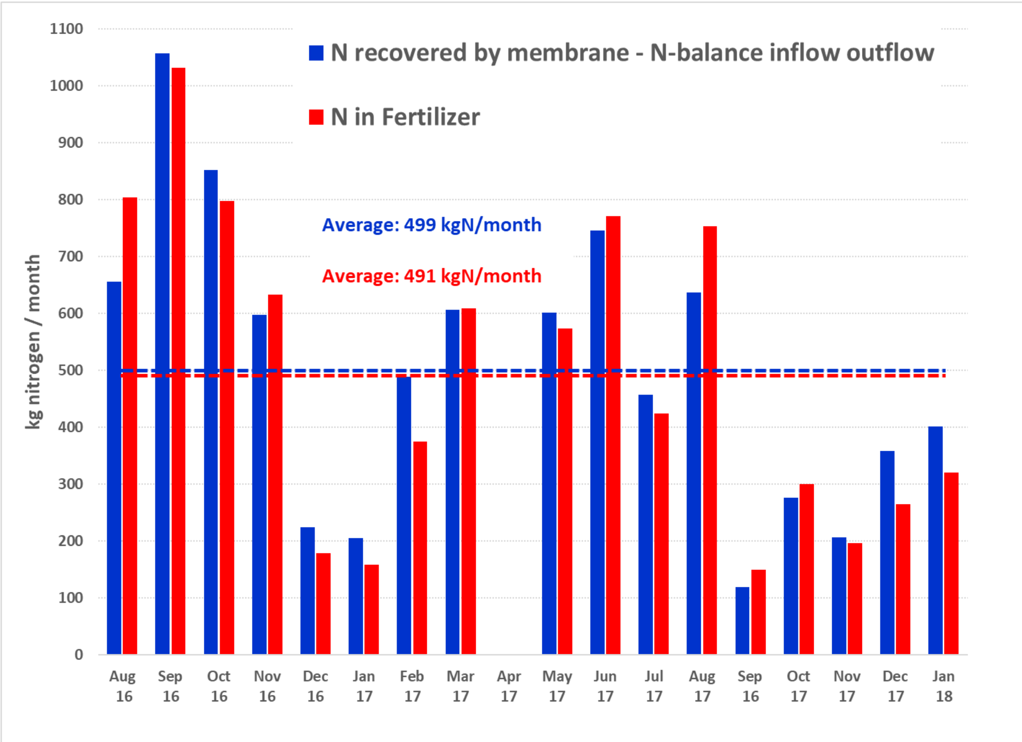

Figure 3: Independent mass balances of nitrogen, e.g. comparison of nitrogen, which is recovered by membrane stripping or found in the product ammonium sulphate per month.

The average nitrogen removed from the sludge liquid is 499 kgN/month. In comparison, the average nitrogen accumulated in the fertilizer is 491 kgN/month. Based on the 2% difference it can be reasonably confirmed that the recorded data is reliable.

4.4.2. Overall performance and general data of the stripping plant

The monthly average nitrogen concentrations in the raw, the pre-treated and the treated sludge liquid are presented in Figure 4.

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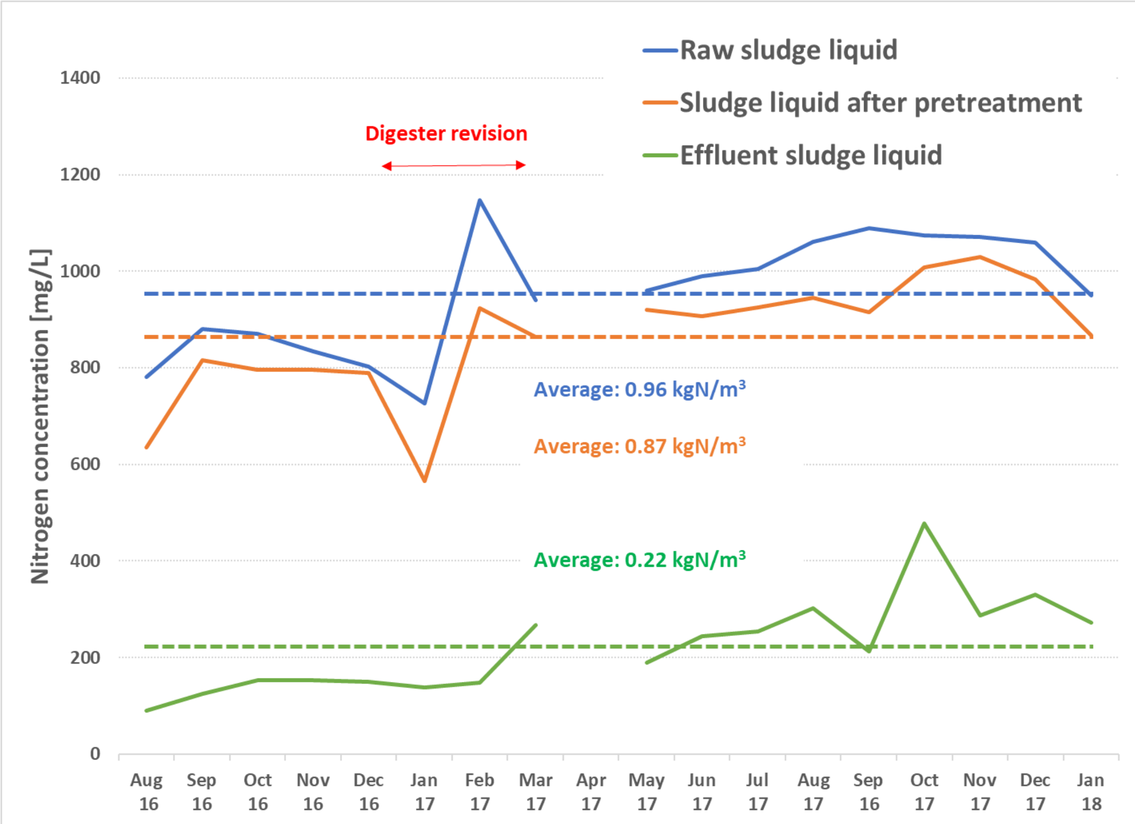

Figure 4: Monthly average Nitrogen concentrations in the raw, the pre-treated and the treated sludge liquid.

The nitrogen concentration fluctuations from December 2016 to March 2017 are attributed to the revision of the digester at the WWTP Yverdon-les-Bains.

The average ammonia inlet concentration of the sludge liquid is is 0.96 kgN/m^3. After the first caustic soda addition in the coagulation tank, the high pH of the sludge liquid leads to free ammonia losses of 10% due to the open coagulation and flocculation tank and the strong ventilation of the stripping room. The sludge liquid entering the membranes has therefore only an average ammonia concentration of 0.87 kgN/m^3 sludge liquid of which 0.65 kgN/m^3 are recovered by the membranes. The average effluent ammonia concentration is 0.22 kgN/m^3 sludge liquid. After 1.5 years of operation, the membrane modules recover more than 70% of the inflowing nitrogen with an inflow temperature of about 40°C and a pH of about 9.4, the lifetime of the membrane modules can therefore not be assessed yet. The cartridge filters are replaced monthly or less, depending on the operation of the ammonia stripping unit.

Average process data of the stripping plant in Yverdon-les-Bains are given in Table 1.

Table 1: Characteristic data of the stripping plant in Yverdon-les-Bains (average over the period from August 2016 to January 2018). To notify is that during this period the plant was undergoing continuous optimization and operational parameters were change frequently

Fraction of time stripping was in operation	27%
Sludge liquid flow	6-8 m^3/h
NH_4-N content in the sludge liquid	0.96 kg/m^3
Total NH_4-N elimination	80%
NH_4-N recovery by membranes	70% (75% of membrane inflow)
Fertilizer production	20 L fertilizer/m^3 sludge liquid (in total 362m^3) 13'000 kgN
NH_4-N content of fertilizer	36 kg/m^3 (19-60 kg/m^3) Respectively up to 5.2% in weight
Temperature-range in front of the CO_2-stripper	17-27⁰ C
pH increase by CO_2-stripping	0.4

The average sludge liquid flow was between 6 m^3/h and 8 m^3/h and a total sludge liquid volume of 18'000 m^3 has been treated during the investigated period. The overall nitrogen elimination of the stripping process was 80%. 70% of the initial nitrogen is recycled to the fertilizer and 10% was lossed by the room ventilation. With respect to the membrane nitrogen inflow, 75% are recovered as fertilizer. The fertilizer production is in average 20 L of fertilizer produced per m^3 of sludge liquid treated. A total of 362 m^3 of fertilizer were produced, corresponding to 13'000 kg of nitrogen. The nitrogen concentration in the end product was between 19 kgN/L and 60 kgN/L (corresponding to 5.2%N by weight) with an average of 36 kgN/L. No heat is supplied to the sludge liquid in front of the CO_2-stripping. Therefore, the temperature varied in front of the CO_2-stripping columns between 17°C and 27°C and the pH increased by 0.4 units during CO_2 stripping.

4.4.3. Energetic balance in terms of heat and electricity demand related to recycled nitrogen

The temperature of the sludge liquid is increased by 2 successive heat exchangers. The first one recovers the heat from the treated sludge liquid. The second one is supplied by heat from the warm-water circuit of the WWTP Yverdon-les-Bains.

The average temperature of the raw sludge liquid is 22°C and the temperature increase by the two heat exchangers is18°C. The heat supplied by the first heat exchanger allows to rise the temperature of the sludge liquid by 13°C on average. The additional required heat is covered by the second heat exchanger which increases the temperature by 5°C on average. Assuming that the calorific capacity is similar to that of water (4180 J/K/Kg), 5°C corresponds to about 5.8 kWh/m³ sludge liquid. Related to the average nitrogen recovered (75 %) this is about 2 $kWh_{primary}/kgN_{recovered}$ (primary energy factors (PEF) of heat from biogas = 0.232 $kWh_{primary}$/kWh, compare Table 3).

The total average heat supply is 36 kWh/kg nitrogen recovered, corresponding to 21 kWh/m³ treated sludge liquid. 75% are covered by the treated sludge liquid and 25% are supplied by the warm-water circuit of the WWTP.

The monthly average temperature of the sludge liquid before and after the heat exchangers and the monthly average heat supplied per m³ sludge liquid are presented in Figure 5.

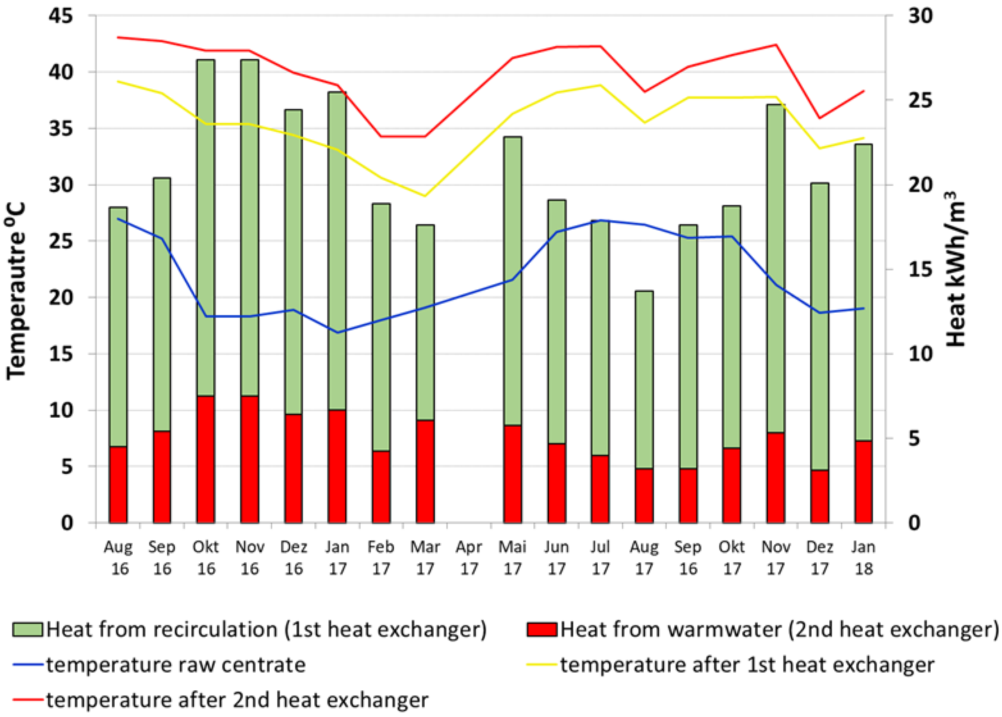

Figure 5: Heat balance of ammonia stripping plant Yverdon-les-Bains. The temperature of the sludge water is in the range of 17° to 27°C depending on season and retention time in the storage tank. The sludge water is heated up to 40°C before the membranes, which needs on average 18°C. 13°C can be recovered from the treated sludge liquid and 5°C is covered by warm water from the WWTP. In April 2017 no data is available because the plant was not working due to lack of sludge water and renovation of the flocculation step.

The warm-water circuit of the WWTP Yverdon-les-Bains is heated by a heat and power co-generation plant which is supplied by the biogas production of the WWTP Yverdon-les-Bains. Heat is available in excess (about 400'000 kWh/year) in the WWTP Yverdon-les-Bains, consequently no investment must be made to provide it.

The average electrical power consumption of the stripping plant in Yverdon-les-Bains during production periods is 2.55 $kWh/kgN_{recovered}$. The corresponding energy fractions consumed by the different stripping units are presented in Table 2. Compressors, pumps and motors contributing to the consumption of the stripping units are listed in Table 2.

Table 2: Average electric power consumption of the stripping plant in Yverdon-les-Bains and fraction consumed by the different treatment steps. Compressors, pumps and motors contributing to the electrical power consumption are listed below the considered treatment step.

Total consumption	**2.55 kWh/kgNH_4-N$_{recovered}$**
Pre-treatment before coagulation and flocculation *CO_2-compressor*	26%
Coagulation, flocculation and sedimentation tank *Agitators (2x), recirculation pump, polymer station*	18%
Membrane unit *Circulation and sulphuric acid pump*	2%
Pumps to move sludge liquid through the stripping system *2 pumps*	26%
Room ventilation *1 ventilator*	18%
Others	10%

The CO2-compressor and the pumps (2x) to transport the sludge liquid through the stripping system are the main electric power consumers, contributing equally to 52% of the total energy consumption. The agitators (2x), the recirculation pump and the polymer station of the coagulation, flocculation and sedimentation tanks consume 18% of the electricity, the same proportion as the room ventilation. The compressor operating the valves, the heat exchanger pump of the warm-water circuit (2nd heat exchanger), flow variators, sensors and other low consumers account for 10% of the total electric power consumption. Most electric power consumption can be attributed to the pre-treatement, the fraction consumed by the membrane unit is 2%.

During production stops some devices (as for example the room ventilation or the coagulation and flocculation agitators) run continuously. As a result, the electric power consumption per recycled N including the production stops would be higher.

4.4.4. Consumption of chemicals related to recycled nitrogen

The total caustic soda required for ammonia stripping in Yverdon-les-Bains was 1.7 mole NaOH/mole N recovered of which 80% were used during pre-treatment in the coagulation tank, 12% were consumed in between the 2 membrane modules and 8%

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were used to increase the pH of the product to be at an adequate pH for agricultural use. The monthly average pH evolution of the sludge liquid before and after the different treatment steps are depicted inFigure 6.

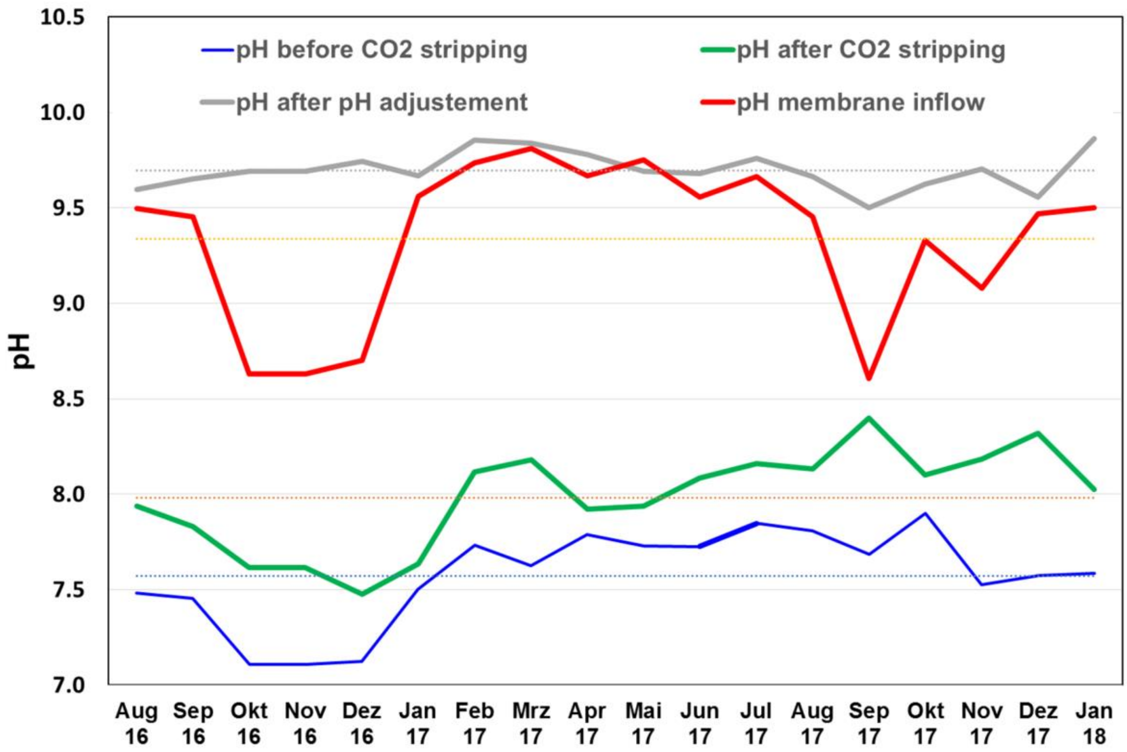

Figure 6: pH of the liquid sludge before pre-treatment, after CO_2-stripping, after coagulation (where caustic soda is added) and before the membrane module inflow. The average pH increase by the CO_2-stripping is 0.4 pH-units. The caustic soda addition in the coagulation tank increases the pH by 1.7 pH-units to 9.4. The pH decreases by 0.3 units between the coagulation tank and the membrane entrance.

The cold (17°C – 27°C) CO_2-stripping increases the pH by 0.4 units on average from 7.6 to 8. The pH after caustic soda addition in the coagulation tank is 9.7 on average. The heat addition after coagulation and the 10% loss of ammonium are decreasing the pH of the sludge liquid by 0.3 units before entering the membrane modules where the sludge liquid has an average pH of 9.4.

The average sulphuric acid consumption is 0.6 mole H_2SO_4/mole N recovered. This is slightly higher than the 0.5 mole H_2SO_4/mole N recovered which is due to over dosage. Sulphuric acid remains in the product which is accompanied by a low product pH. As aforementioned, the product pH is increased by a final caustic soda addition. With an additional polishing membrane, sulfuric acid consumption could be reduced by 20% and would also significantly reduce NaOH consumption.

The average citric acid consumption is 0.004 mole $C_6H_8O_7$ / mole N recovered. Citric acid is only used for cleaning of the different devices and is therefore low in comparison with the caustic soda and sulphuric acid consumptions.

4.4.5. Overall primary energy demand of membrane ammonia stripping at WWTP Yverdon-les-Bains

The primary energy demand of the membrane stripping plant in Yverdon-les-Bains was estimated with the primary energy factors (PEF) presented in Figure 7 The heat is recovered from the excess heat produced by the WWTP Yverdon-les-Bains and is therefore not considered for the primary energy consumption.

Table 3: Primary energy factors (PEF) used for the conversion of consumables into primary energy.

Consumables	Primary energy factor	References
Caustic soda (100%)	4.24 $kWh_{primary}/kgNaOH$	Ecoinvent v3.4. (2017)
Sulfuric acid (100%)	1.82 $kWh_{primary}/kgH_2SO_4$	Ecoinvent v3.4. (2017)
Citric acid (100%)	11.4 $kWh_{primary}/kgC_6H_8O_7$	Ecoinvent v3.4. (2017)
Heat from biogas	0.232 $kWh_{primary}/kWh$	Ecoinvent v2.2.(2016)
Electric power	1.44 $kWh_{primary}/kWh$	Ecoinvent v3.4. (2017) Market group for electricity [RER] (2017)

The total primary energy required by the ammonia stripping plant is 32 $kWh_{primary\ energy}/kgN_{recovered}$. The primary energy required by the added chemicals and the plant operation are presented in Figure 7.

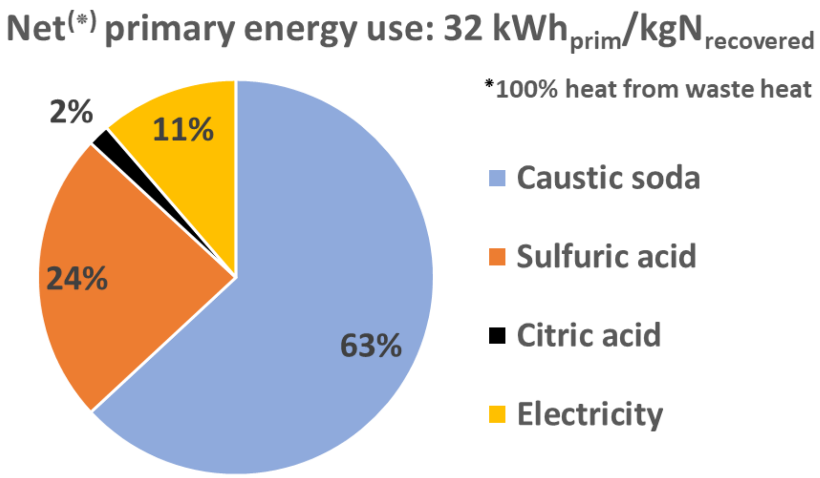

Figure 7: Primary energy consumption by the consumed chemicals and the electric power consumption.

The main contributor (63%) to the primary energy need is the caustic soda consumption followed by the sulfuric acid (24%) and the electric power consumption (11%). The high PEF of the citric acid is counter balanced by the low consumption and accounts only for 2% of the total primary energy need.

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4.4.6. Quality of the product

The nitrogen concentration in the product is largely influenced by the nitrogen concentration initially present in the sludge liquid.

The average nitrogen concentrations in the fertilizer (after the final caustic soda addition to increase the end product pH) is 36 kgN/m^3 on average and varies between 19 kg/m^3 fertilizer (660 mgN/m^3 initially present in the sludge liquid) and 60 kg/m^3 fertilizer (1050 mgN/m^3 initially present in the sludge liquid).

4.4.7. Overall experience

The efforts undertaken by Alpha Wassertechnik to continuously optimize the stripping plant during the past 1.5 years improved the process performances and allows a better understanding of the process. The stripping unit was operated in a pilot mode and became progressively an industrial plant. Especially the flow scheme and the plant control have been improved. The experiences gained during the operation of the stripping plant in Yverdon-les-Bains will be used by Alpha Wassertechnik to further improve the recovery system in Yverdon-les-Bains and will also improve the stripping plant in Altenrhein.

4.4.8. Optimization potential membrane ammonia stripping plant Yverdon-les-Bains

Sludge liquid

Dewatering of the excess sludge before digestion is a measure that allows to improve the ammonia concentration in the digester tank, which would also increase the fertilizer quality. The addition of co-substrates (eg. food and meat waste, blood) to the digester input is an additional measure which would increase the digestion efficiency and increase the nitrogen concentration in the digested sludge liquid.

CO_2-stripping

A higher sludge liquid temperature in front of CO_2-stripping by addition of excess heat from the WWTP Yverdon-les-Bains would allow a higher CO_2 removal, which would reduces the caustic soda consumption in front of the membranes. Treating the sludge liquid right after digestion without cooling during storage would reduce excess heat addition.

Coagulation, flocculation and sedimentation

Covering the coagulation, flocculation and sedimentation tanks allows to limit the nitrogen loss during pre-treatment and increases the nitrogen recovery. Furthermore, the ventilation of the stripping room could be reduced which in turn would reduce the electric power consumption.

Ammonia stripping membranes

A higher temperature of the liquid on the acid side than on the lumen side in the membranes limits the diffusion of water vapour to the product, which dilutes the fertilizer. This measure should first be tested to assess its efficiency. It has to be taken into account that the hollow fibre functioned as an ideal heat exchanger. Against this background the success will be limited.

Membranes allowing to work with higher temperatures would allow to set the process pH lower and reduce the caustic soda need.

A final polishing step

A final polishing step where the end product passes a final membrane module on the acid side and pre-treated sludge liquid passes the membrane on the lumen side. Remaining acid on the acid side would be consumed by free ammonia passing the membrane. This would increase the end product quality, decrease the sulfuric acid consumption and increase the final product pH and therefore reduce the caustic soda consumption. Also for this measure a higher temperature of the liquid on the acid side of the membranes than on the lumen side would limit the dilution of the product by water vapour diffusion. This final polishing step should also first be tested to assess the improvement potential of this measure.

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5. Outlook CS6 WWTP Altenrhein and "sub-case study" Yverdon-les-Bains

During the remaining time in the POWERSTEP project and beyond, the CS6 consortium will continue to provide WWTP Altenrhein with technical support for the successful implementation and commissioning of the ammonia stripping plant.

Final work is currently done at the WWTP Yverdon-les-Bains. In detail the following task are in progress and will be finished 5/2018. The results of these activities will be documented in an upgraded deliverable 4.3.

- Single trials for optimal operational parameters (pH, temperature, flow, ……..): Additional tests will be performed on the stripping plant for optimal operational parameters (fine tuning)
- Life time of different filters: Particle size distribution analysis of suspended matter in the sludge liquid passing the different pre-treatment devices will be made. This will allow to rethink the filter pore sizes and module configurations to enhance the life time of the cartridge filters.
- Measurements to evaluate product quality (N concentration, micro pollutants): The product quality will be monitored continuously measuring its nitrogen content and additionally, micropollutant concentrations in the end-product will be measured too.
- Further electric power consumption measurements with a power logger will be made by Eawag to have more precise data about the electric power consumption of the different devices.

The results and experiences of the plant in Yverdon-les-Bains confirms the feasibility of this treatment process in full scale. The operation costs should drop drastically (30-40%) through the optimization possibility which will be implemented on the WWTP Altenrhein. In this context a key aspect is the reduction of base demand of the process. This can be reached by an optimal operation of the CO2-stripper and by using optimized membrane modules, operating at higher temperatures, which are in development.