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Towards energy neutrality of wastewater treatment plants via deammonification process

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Abstract. Energy neutrality of wastewater treatment plants is possible with constant and consistent optimization and implementation of new technologies. In recent years new process called deammonification has been discovered and implemented in treatment of side streams rich in nitrogen. With its implementation on wastewater treatment plants it is possible to remove nearly all nitrogen from side stream (even 30% of overall nitrogen load) in less energy consuming way. Additionally, thanks to lower nitrogen load to main stream reactors it is possible to optimize them to further lower energy consumption. This article presents simulation studies of deammonification implementation and main stream reactor optimization in case of medium Polish WWTP (115 000 p.e.). With removal of 20% of nitrogen in side stream via deammonification and subsequent main line optimization it is possible to save 5000 euro/year by lowering sludge retention time, oxygen concentration in main stream reactors. When additional COD is precipitated in primary clarifiers with iron coagulants, 55 000 euro/year can be saved in case of energy costs which states for most of the energy costs. However, when coagulant and disposal costs are included savings are on the level of 25 000 euro/year.

1 Introduction

Wastewater sector use 1%–3% [1–3] of total energy used by industry. Energy consumption states for 11–17% of overall costs of wastewater treatment [4]. The exact percentage depends on the size of the plant: lower energy participation is typical for large WWTPs (> 100 000 p.e.), therefore energy neutrality is goal worth achieving. In municipal wastewater treatment, average energy consumption needed to meet strict requirements is at the level of 0.5–0.8 kWh/m^3 [5, 6] while chemical energy stored in wastewater is 5–6 times higher [7]. Additionally, large amounts of energy are also stored in potential, kinetic forms [8]. This implies that wastewater treatment plants can be energy self-sufficient.

To achieve energy neutrality:

a) WWTP must be equipped with sludge anaerobic digestion and efficient method for carbon removal from wastewater to prevent its oxidation in biological part, such as chemically assisted primary sedimentation (CAPS). This is necessary for efficient

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energy production and low energy use by aeration.

b) Important energy consuming processes must be well optimized for minimal energy use [9].

c) Wastewater must be rich in biodegradable carbon to enable high carbon load to anaerobic digestion without carbon deficiency for nutrient removal.

Latter condition is the biggest obstacle as typical wastewater doesn't contain excess carbon and many WWTPs experience carbon limitations even without elevated carbon removal in primary sedimentation [10]. Removal of nitrogen from digester liquor via deammonification process opens new field for WWTP energy consumption optimization in main line. Firstly, lower N concentration in wastewater directed to activated sludge process allows for lower oxygen concentration and lower sludge age, hence lower energy consumption. Secondly, as higher COD/N ratio is achieved, larger COD load can be removed in primary clarifiers without negative consequences for denitrification but with positive consequences for energy balance.

1.1 Aim and structure of paper

Aim of this paper is to present potential for energy balance improvement in main line thanks to implementation of deammonification process in side-stream. Presented studies are based on simulations of Polish WWTP. In order to quantify effects of deammonification implementation and further optimization of main line, three states of WWTP were simulated:

a. current state – WWTP without side-stream deammonification – this is real state of existing WWTP. For this state mathematical model was calibrated.

b. WWTP with side stream deammonification – this is fictional state and is represented in scenario 1.

c. WWTP with side stream deammonification, CAPS and main line optimization – this is fictional state and is represented in scenarios 2–5.

2 Materials and methods

2.1 WWTP and wastewater characteristics

Information about plant current state and wastewater characteristics were collected during model calibration and verification and are based on real experimental data. N-removal efficiency and effluent composition for partial nitritation-Anammox (PN-Anammox) process were gained during operation of this processes in a pilot-scale installation treating real reject water from sludge dewatering. Effluent composition, oxygen demand and operational costs for mainstream processes were calculated based on simulation results or literature reports if mentioned.

2.1.1 Plant description: current state and assumed Scenarios.

Existing, medium-size municipal Polish WWTP (115 000 p.e.) with calibrated ASM1 model was chosen for this study. Plant is composed of two A2O reactors with two primary clarifiers and two secondary clarifiers as well as anaerobic digestion reactors producing methane which is further used for energy production in CHP (combined heat and power) units. Digested sludge is being dewatered and transported to utilization facility. Mentioned model represents only biological part of the plant, which contains two parallel anoxic-oxic reactors and secondary clarifiers, excluding primary sedimentation and all sludge handling processes as well as deammonification process. Real operational parameters used as background for performed analysis are presented in table 1. Detailed model description is presented in section 2.2. Characteristics of wastewater after mechanical treatment and reject water are presented in table 2.

Total nitrogen (TN) for considered WWTP is set by Polish legislation at 10 g N/m^3 without ammonium nitrogen limitation [11]. SRT (sludge retention time) is adjusted according to temperature, at 10°C or 15°C required SRT is 30 d and in 20°C SRT is 15d. Currently, plant has major problems to meet TN criterion as its average concentration in the effluent is very close to the limit. Dissolved oxygen (DO) level in the aeration zone is kept at 1.5 mg O_2/L which is considered optimal in these conditions.

Nitrogen load in reject water stream from sludge dewatering was assumed 22.7% of daily N-load for whole plant, which was close to real value.

Table 1. Selected WWTP parameters.

Parameter	Unit	Value
SRT	d	15–30
Aeration zone volume	m^3	13 811 (HRT* ≈ 1 d)
Anoxic zone volume	m^3	7944 (HRT ≈ 0,57 d)
Internal recirculation	m^3/d	≈150 000 (≈ 1090% Q_i)
DO concentration	mg O_2/L	1.5
CHP electric efficiency	%	36

* - hydraulic retention time

Five fictional scenarios of possible plant development towards energy neutrality were investigated assuming side-stream deammonification process implementation (20% of N-load removal) and improved COD removal by CAPS resulting in higher gas production. As a background for each Scenario implementation, plant's state after technological optimisation was used. Following scenarios were analysed:

- Scenario 1 – side-stream deammonification implementation, no CAPS
- Scenario 2 – side-stream deammonification implementation, CAPS enhancing COD removal in primary clarifiers by 20%
- Scenario 3 – side-stream deammonification implementation, CAPS enhancing COD removal in primary clarifiers by 30%
- Scenario 4 – side-stream deammonification implementation, CAPS enhancing COD removal in primary clarifiers by 35%
- Scenario 5 – side-stream deammonification implementation, CAPS enhancing COD removal in primary clarifiers by 40%

In scenarios that assumes implementation of side-stream treatment of reject water, two-stage PN-Anammox technology was chosen. Process characteristics and efficiency were collected by authors during over 6-month stable operation of a pilot-scale installation treating real reject water. In this period, average TN removal reached 88%. These data were used in simulation studies (see Table 2).

Scenarios 2–5 assumed addition of inorganic coagulant ($FeCl_3 \cdot 6H_2O$) and anionic polyelectrolyte to enhance primary sedimentation. Such action increases amount of COD directed to anaerobic digestion with primary sludge stream and improve gas production, therefore WWTP energy balance. Coagulant dosage and COD removal efficiency was assumed at the same level as presented by De Feo et al. [12]. For 20%, 30%, 35%, 40% improvement in COD removal, ferric chloride doses were assumed 16.3, 32.5, 51.3 and 98.9 mg/L respectively. Anionic polyelectrolyte dose was the same in all Scenarios and assumed 0.1 mg/L. Coagulant and polyelectrolyte prices in Poland were 71.7 €/ton and 2 500.0 €/ton respectively.

2.1.2 Wastewater characteristics

Characteristics of wastewater after mechanical treatment were real data collected during normal plant operation. Raw and treated reject water were average data collected during operation of mentioned pilot-scale deammonification installation. In scenarios considering deammonification and/or CAPS implementation, influent composition to biological reactor was calculated based on mentioned real data and assumed level of deammonification and/or precipitation efficiency. Selected medium characteristics are summarized in table 2.

Table 2. Characteristics of wastewater after mechanical treatment (Wastewater – real data, Scenario 1 and Scenario 4 - calculated) and raw/treated reject water (real data).

Parameter	Unit	Wastewater	Reject water	PN/Anammox effluent	Scenario 1	Scenario 4
Flow	m^3/d	14 000	272	272	14 000	14 000
TN	g N/m^3	64	748	90	51	48
COD	g O_2/m^3	531	552	313	526	316
BOD_5	g O_2/m^3	305	170	17	302	181

2.2 ASM1 model description and calibration

A calibrated ASM1 model, representing municipal WWTP described in previous sections, was used in presented study to represent only biological part of the plant excluding primary sedimentation. This tool allowed to model autotrophic and heterotrophic reaction, with a facultative consumption of oxygen or nitrate as electron acceptor, without phosphorus removal [13]. Model was calibrated based on collected operational data and intensive measuring campaign (two weeks) under steady-state operating conditions. Model accuracy was satisfactory, despite quite poor results for nitrate concentrations, and could be used in this study. All simulations were performed for three representative temperatures: 10°C, 15°C and 20°C.

2.3 Cost calculations

To evaluate potential savings, a WWTP energy balance was created for each Scenario as for the plant current state. As model considered only processes related to carbon and nitrogen removal, energy balance was limited to energy consumption for mainstream aeration, side-stream deammonification and energy production in CHP from surplus sludge generation thanks to CAPS. In Scenarios including CAPS also coagulant and polyelectrolyte costs were included. In all cases, economical balance included amount of produced sludge and its disposal costs. Assumed energy cost was 0.093 €/kWh, which is typical value for industry in Poland.

Mainstream aeration costs were calculated based on real data of existing aeration system and oxygen demand calculated using available model. Energy use for aeration was calculated based on reactor geometry, αFSOTE, diffuser and blower characteristics (all these values were real data determined experimentally [data not published]). Energy consumption for aeration in deammonification process was assumed 0.8 kWh per kilogram of nitrogen is required in this process, as calculated by Wett [14].

Energy production in CHP units were crucial element of WWTP energy balance. Specific methane production rate was assumed 0.35 L_N per 1 g COD anaerobically degraded in digestion process [15]. Specific energy production from and CHP efficiency were assumed 3 kWh/m^3 CH_4 and 36% respectively. Additional mass of chemical sludge due to precipitation process use were calculated based on coagulant characteristics. Digested sludge disposal costs were assumed 23.3 €/ton, which is a typical value.

3 Results

3.1 Current state

Simulations results confirmed that plant has major issue with meeting the legal requirements considering effluent TN concentration (Figure 1). At cold temperatures 10°C, TN exceed limit value and reach 11.9 mg N/L. As temperature rises, TN level drops slightly below allowed value and is 9.9 and 9.7 mg N/L at 15°C and 20°C respectively. Majority of effluent total nitrogen concentration was N-NO_x fraction (~70%) as the result of insufficient carbon availability for denitrification process. No problems with nitrification process were noticed. DO concentration (1.5 mg O_2/L) was enough to oxidize most of ammonium as its concentration was around 1.0 mg N/L. Current average energy demand for mainstream aeration is 81 kWh/day which generates an annual cost of around 66 500 € (Figure 4).

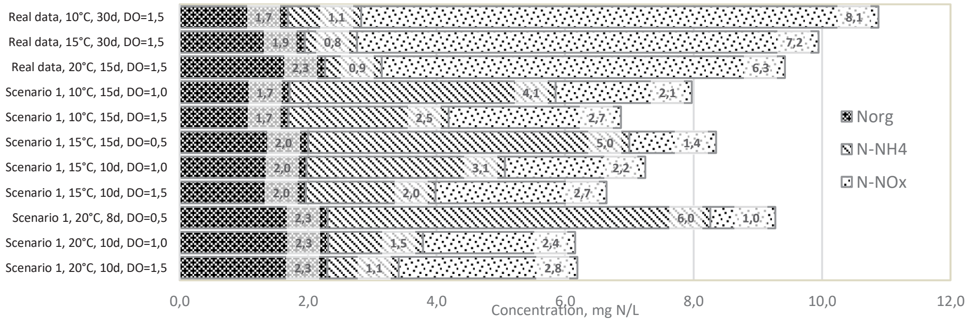

Fig. 1. Nitrogen concentration in WWTP effluent – current state and Scenario 1: implementation of side-stream deammonification.

3.2 Scenario 1 – deammonification implementation and further optimization

In this Scenario, plant was virtually equipped with a side-stream deammonification installation. As the mainstream reactor N-load has decreased by 20%, effluent quality was better and further plant optimization potential was released. In a series of simulations, various SRT and DO values were tested in whole temperature range to pick mainstream reactor setup providing lowest aeration costs and meeting TN limit. In coldest period, SRT equal to 15 days and DO = 1.0 mgO_2/L allowed to decrease TN concentration in the effluent to 7.9 mg N/L. In 15°C (SRT 10 days, DO = 1.0 mgO_2/L) and 20° (SRT 8 days, DO=0.5 mgO_2/L) TN level was 7.3 and 9.3 mg N/L respectively (Figure 1). Average energy demand for aeration (mainstream + side-stream) in optimized setup is 75 kWh/day which yearly cost around 61 100 € (Figure 4). This scenario is not best solution in terms of energy balance and cost balance (figure 3 and 5.).

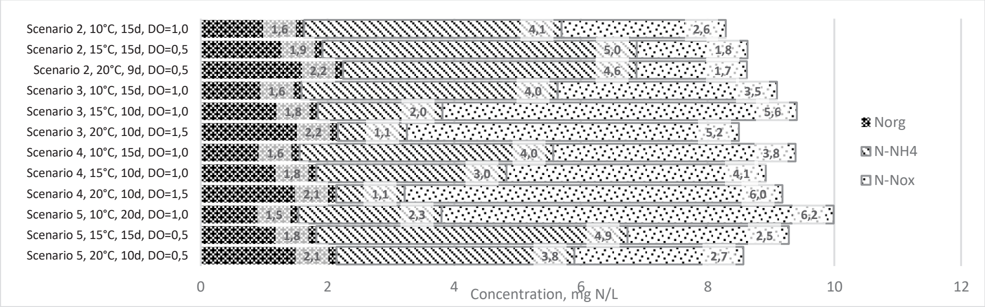

Fig. 2. Nitrogen concentration in WWTP effluent – Scenarios 2–5: side-stream deammonification, main line optimization and CAPS.

3.3 Scenario 2 - 5 – deammonification + CAPS and further optimization

In this Scenarios, beside deammonification implementation, also CAPS was used to increase energy production. Mainstream operational setup was optimized separately for each Scenario as presented in section 3.2. Figure 2 represents nitrogen concentrations in effluent for optimized parameters in each variant.

As additional chemical treatment was used, except energy cost for aeration, also chemicals price was added alongside with chemical sludge disposal costs (figure 4). Savings due to higher energy production were also included. All these values varied depending on coagulant dosage and amount of additional COD removed in primary clarifiers.

Energy calculations showed that Scenario 5 provides biggest savings in case of energy purchase (figure 3), while overall cost calculations, revealed that Scenario 3 allowed to achieve the best economical result, as appropriate balance between SRT, DO and enhanced COD removal was achieved (figure 5).

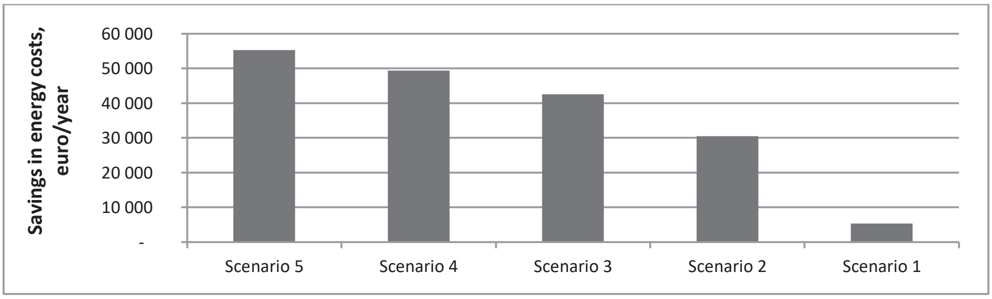

Fig. 3. Savings in energy costs in different scenarios (current state as reference, presented values are mean values from all scenarios variants).

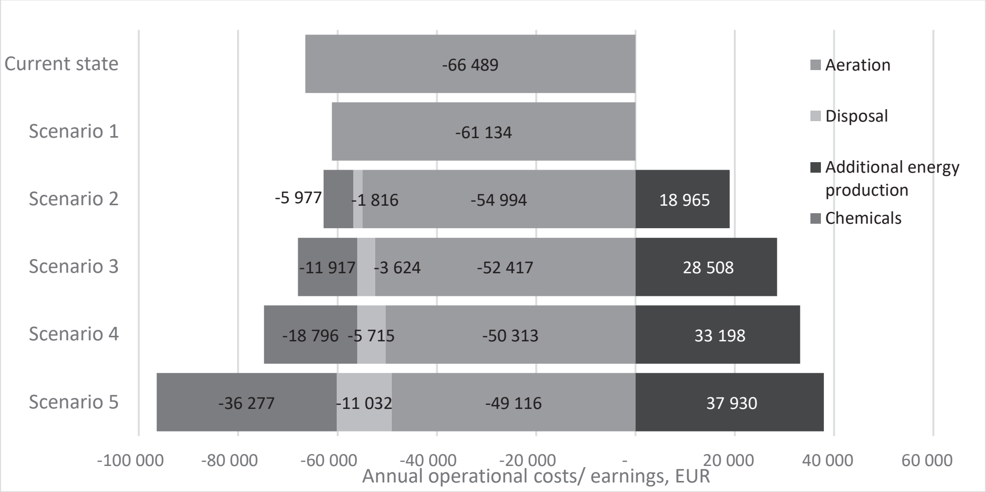

Fig. 4. Overall costs balance (presented values are mean values from all scenarios variants).

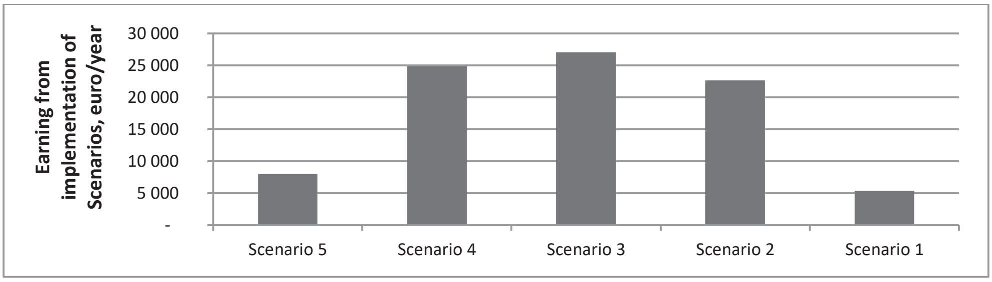

Fig. 5. Overall cost balance (current state as reference, presented values are mean values from all scenarios variants).

4 Conclusions

Following conclusions can be made:

- implementation of side stream deammonification changes wastewater composition through removal of important load of nitrogen and this opens potential for WWTP energy and cost balance optimization.
- with 20% of total nitrogen removed in deammonification, 40% additional COD can be precipitated in primary settlers in addition to COD removal without coagulants (70% overall COD removal efficiency).
- With side stream deammonification and without CAPS (Scenario 1) optimization allows for moderate savings (slightly higher that 5 000 euro/year) in energy and costs. This savings are due to lower SRT and oxygen concentrations.
- Implementation of CASP allows for much higher savings. In case of additional 40% COD removal (Scenario 5) 55 000 euro/year can be saved in energy costs. This Scenario is most energy efficient. However high doses of coagulants are required and overall savings including costs of coagulant and sludge disposal are on the level of 7 500 euro/year.
- Scenario 3 is most profitable in terms of overall costs. Overall savings in this Scenario are on the level 25 000 euro/year.

5 Assumptions and limitations

Research presented in this paper has few limitations and some assumptions had been made:

1. Phosphorus removal was not included in model. It was assumed that phosphorus will be removed biologically in every case despite high removal of organic matter in primary settlers. This assumptions was based on low phosphorus concentration in raw wastewater and steady state calculations [not presented]. Lack of phosphorus modelling has no influence on energy balance.
2. It was assumed that change in composition of wastewater due to deammonification implementation will have no influence on kinetic parameters of biomass.
3. It was assumed that all precipitated COD (scenarios 2–5) will be converted anaerobically.
4. It was assumed that pH won't change significantly due to coagulation because wastewater contains enough buffer capacity.

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