How to make a large nutrient removal plant energy self-sufficient

Latest upgrade of the Vienna Main Waste Water Treatment Plant (VMWWTP)

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Abstract

The goal to make nutrient removal waste water treatment energy self-sufficient or even energy producing has become a worldwide accepted goal of technology development. Some full scale plants have already achieved it. One of the best described energy self- sustaining treatment plants (Strass/Austria, design capacity 200.000 PE) consists of a two stage activated sludge plant (AB- technology) without primary sedimentation, anaerobic sludge digestion and deammonification of the reject water from sludge dewatering. Without adding external substrates to digestion this plant produces about 8% more energy per year than needed for operation.

The latest upgrade of the Vienna Main Waste Water Treatment Plant (VMWWTP) with a design capacity of 4 Mio population equivalents (PE) will produce about 20% more energy on a yearly basis than needed for operation due to a special process scheme. It consists of a primary sedimentation, a special two stage activated sludge process configuration where excess sludge is only withdrawn from the first stage activated sludge plant. Raw sludge is subject to mechanical thickening to ~ 8% DS for digestion at high solids concentration. The reject water will be subject to nitritation. The nitrite load is used for carbon removal by denitritation in the first stage activated sludge plant. This results in markedly reducing the energy requirement for aeration. The design of this last upgrade for energy optimisation of sludge treatment is based on the long term full scale data from the existing plant, results of mid-term pilot investigations, sound theoretical mass balance calculations and an adapted dynamic model development. All this is presented in this paper. The full scale upgrade is under construction and will start operation in 2020.

Keywords: energy self-sufficiency, COD/energy balances, sludge digestion with high solids concentration, dynamic modelling, reject water nitritation/denitritation, 2-stage activated sludge process

Introduction

The Vienna Main Wastewater Treatment Plant (VMWWTP) actually is under reconstruction and extension in order to cover the plant´s energy demand by the year 2020. The most relevant driving forces for this reconstruction have been the climate change abatement policy asking for decreased fossil CO_2 equivalent emissions and the necessity to rebuild the first step of the two step activated sludge treatment plant (start of operation in 1980) which has reached the end of its construction lifetime. The reconstruction has to be performed under full compliance with the legal requirements while the plant remains fully operational.

In order to understand the design considerations which are now in implementation it is important to describe the specific local situation in Vienna, including the legal requirements for treatment efficiency in Austria, as well as the specific climatic, morphological and hydrological conditions having strongly influenced on the development of the water supply, sewer network and treatment plant design construction. For the treatment plant design a nearly unique collaboration between the Institute for Water Quality Management at Vienna University of Technology, engineering consultants and the Vienna Sewer and Waste Water Authority from 1970 until today took place. The Institute was given the authority to decide on the process engineering based on solid scientific knowledge, pilot plant investigations and modelling performance and was responsible for meeting the legal effluent quality requirements at any time with a minimum of costs and a maximum of reliability in close co-operation with the design department of the responsible authority. The detailed design was performed by different engineering consultants also in co-operation with the Institute. This co-operation resulted in 4 doctoral theses closely related to the pilot investigations on site of the VMWWTP for the process design and operation in the past and in the future (Dornhofer K. 1998, Wandl G. 2005, Reichel M. 2015, Schaar H. 2016) and a great number of other publications.

This paper is mainly related to the thesis of Reichel M. (2015) with the title "Sludge Digestion with high dry solid matter – chances, limits, challenges" which is based on the outcome of intensive pilot investigations which were performed in order to prove and improve the design considerations for the so called EOS-Project (Energy Optimization Sludge treatment) which is now under construction and the main topic of this paper. At the same time the pilot investigations were necessary to verify and calibrate the dynamic mathematical model of the whole plant.

Effluent standards to be met

The effluent standards for the VMWWTP are in full compliance with the Austrian minimum requirements for municipal waste water treatment plants (1. AEVkA 1996) which is in compliance with the EU Urban Waste Water Directive (UWWD). The Austrian effluent standards (Tab. 1) are relevant for design considerations for VMWWTP as they differ from other national regulations in EU member states in important details. As Austria as a whole is a "sensitive area" according to EU UWWD nutrient removal is required. All standards have to be met in completely mixed daily flow proportional composite samples. Austria has not implemented waste water discharge fees like e.g. in Germany. Non-compliance with the standards in the case of negligence can be punished according to criminal law.

Tab. 1: Austrian effluent standards for municipal waste water treatment plants > 50,000 PE_{60}

COD	75 mg/l	according to EU UWWD, as 85 %ile on a yearly basis
BOD_5	15 mg/l	according to EU UWWD, as 85 %ile on a yearly basis
TN removal	>70%	yearly mean for temperatures >12 °C in the aeration tank
TP	1 mg/l	yearly mean, maximum in daily samples 2 mg/l
NH_4-N	5 mg/l	85 %ile on a yearly basis, at temp. >8 °C, max. in daily sample 10 mg/l

Specific local situation

- It exists only one waste water treatment plant in Vienna due to favorable morphology, discharge to Donaukanal (Danube)
- Temperature range in aeration tanks from 8 °C (snow melting) to 23 °C, mean ~15 °C
- Mainly combined sewer system,~ 20 % separate system, mainly gravity flow,
- Mean yearly precipitation 550 mm
- high dilution capacity in River Danube (> 1:100 even at low flow)
- mean domestic drinking water consumption 130 l/cap/d (karstic spring water pipelines)
- actual waste water flow at dry weather conditions (DW)) and pollution load: ~2 PE/cap
- actual treated waste water flow ~200 Mio m^3/year
- limited area for VMWWTP: 42 ha (without sludge dewatering and incineration)
- sludge disposal responsibility with Austrian provinces (according to Austrian Waste Legislation). Agricultural sludge application in Vienna Province impossible: ~450 km^2 of agricultural land would be necessary, total province area 415 km^2, therefore decision on raw sludge incineration in 1976.
- slow (~1 %/a) growth of population since ~15 years, continuation of trend expected

Historic development of VMWWTP

The first VMWWTP was designed in the late 1960ies as high loaded carbon removal activated sludge plant with a minimum of 70 % BOD_5 removal by W. von der Emde and went into operation in 1980.

Already at that time the idea to cover the plant´s energy demand was taken into consideration by sludge digestion with gas motors and agricultural application of sludge but was abandoned due to a change in sludge disposal strategy primarily due to reliability concerns. In 1976 it was decided to implement raw sludge incineration and ash disposal. After having solved start-up problems mainly caused by strong fluctuation of sludge production between 100 t DS/d and 350 t DS/d the incineration plant was and is properly working until today. The sludge ash is actually consolidated with cement and is used to stabilize the hillslope of the landfill.

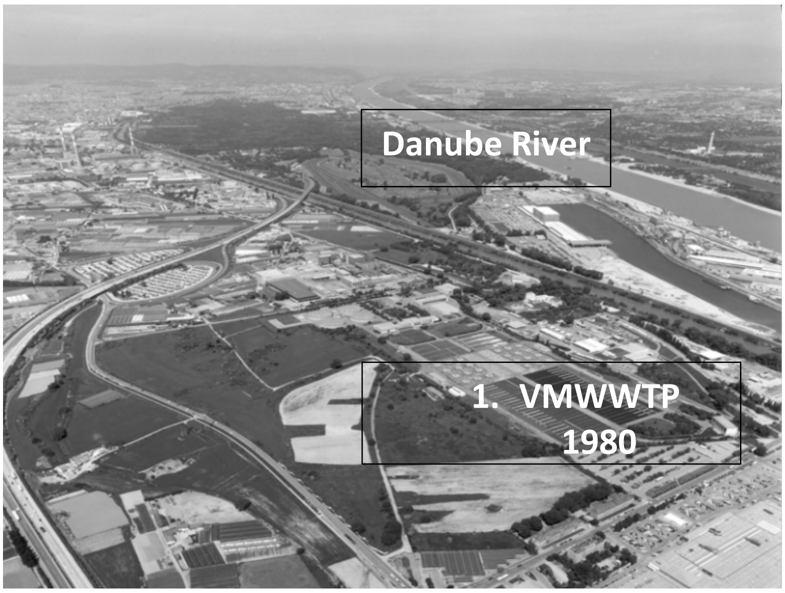

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Fig.1: First VMWWTP start of operation 1980, 3.2 Mio PE; 6 influent screw pumps, 6 lines screens and longitudinal grit chambers, 4 primary sedimentation (PS) tanks, 2 high rate activated sludge lines.

Extension 2005

Due to the new legal requirements (1. AEVkA, 1996) an extension of the VMWWTP became necessary. The extension to a 2-stage AS process went into operation in 2005. Its design concept was based on long term pilot investigation and a basic process design developed again by W. v.d. Emde. (Wandl et al. 2006).

Design data: 4 Mio PE_{60} (240 t BOD_5/d, 480 t COD/d), design loads are defined as 85 %ile on a yearly basis, the mean yearly design load is ~3.5 Mio PE
max. DW flow 9 m^3/s, max. wet weather (WW) flow 18 m^3/s.

Waste water concentrations (mean at dry weather)

Influent COD	~ 750 mg/l (yearly mean)
Influent TN	~ 60 mg/l
Influent TP	~ 9 mg/l

Table 2 shows the total tank volume for the 1-stage and 2-stage AS process with the same reliability to meet the legal requirements. The 2-stage concept needs ~ 30% less total tank volume than the 1-stage plant. The 2- stage activated sludge process therefore results in lower construction costs as compared to a 1-stage process.

Tab. 2: Volumes of the tanks for 1-stage and 2-stage VMWWTP meeting the legal requirements

	2-stage	1-stage
PST-Volume:	5 l/PE	5 l/PE
Aeration tank volume I:	10 l/PE	130 l/PE
SST-Volume I:	18 l/PE	
Aeration tank volume II:	42 l/PE	
SST-Volume II	51 l/PE	51 l/PE
Total	**126 l/PE**	**186 l/PE**

The greatest challenge was to achieve low ammonia effluent concentrations even at maximum WW flow of 18 m³/s within a temperature range of 8 to 23 °C and high nitrogen removal efficiency. The existing VMWWTP (1980) remained unchanged as the first stage and was complemented by a newly constructed second stage activated sludge plant with 15 lines (Fig. 2). While the first stage aeration tanks with a mean depth of 2.4 m remained equipped with cone aerators (1.7 kg O_2/kWh) the second stage aeration tanks were constructed with a mean depth of 5.5 m and are equipped with fine bubble aeration (>2.5 kg O_2/kWh) in order to minimize energy consumption under real operational conditions.

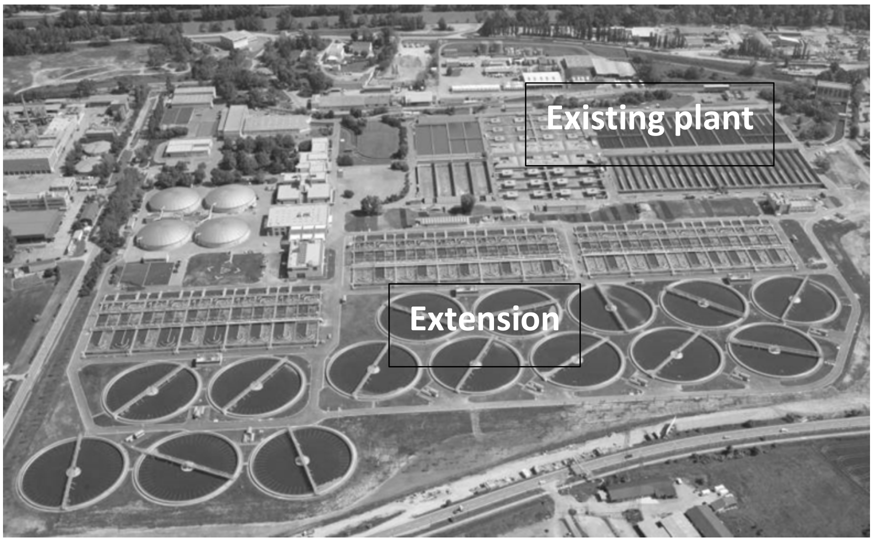

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Fig. 2: Extension of the VMWWTP; start of operation 2005; the 2nd stage is consisting of 15 lines with pre-denitrification tanks (mixed, rectangular) and 2 simultaneous nitrification/denitrification tanks with circular flow in series and a circular secondary sedimentation tank D = 64 m.

Modes of Operation

The new plant has two modes of operation in order to maximize nitrogen removal (Bypass mode) and to reliably avoiding bulking (Hybrid mode). Both modes of operation are adapted to the temperature development over the year and hence the growth rate of the nitrifiers in order to reliably meeting low ammonia effluent standards even at 8 °C. The whole excess sludge of the 2nd stage is pumped to the 1st stage. Excess sludge is only removed from the 1st stage in order to maximize sludge production by adsorption and bacterial growth and to minimize oxygen demand. In regard of the sludge management the Vienna concept is just the opposite of the AB-process developed by Böhnke, Diering (1979). The patent was based on the idea to separate the heterotrophic (A stage) from the autotrophic bacteria (B stage).

In order to stabilize nitrogen removal at >70 % even at low temperatures the plant is equipped with an external recirculation (RF in Fig. 3) of the treated effluent of the 2nd stage for denitrification in the 1st stage. This external recirculation is also used to minimize flow fluctuations which have a detrimental effect on secondary clarifiers' performance. During DW conditions the external recirculation is controlled in a way that the hydraulic loading of the first stage is kept nearly constant over time at e.g. 8 m^3/s. The maximum hydraulic load of the 1st stage is 11 m^3/s. In the case of wet weather flow the external recirculation is stopped and the flow exceeding 11 m^3/s is bypassed to the 2nd stage.

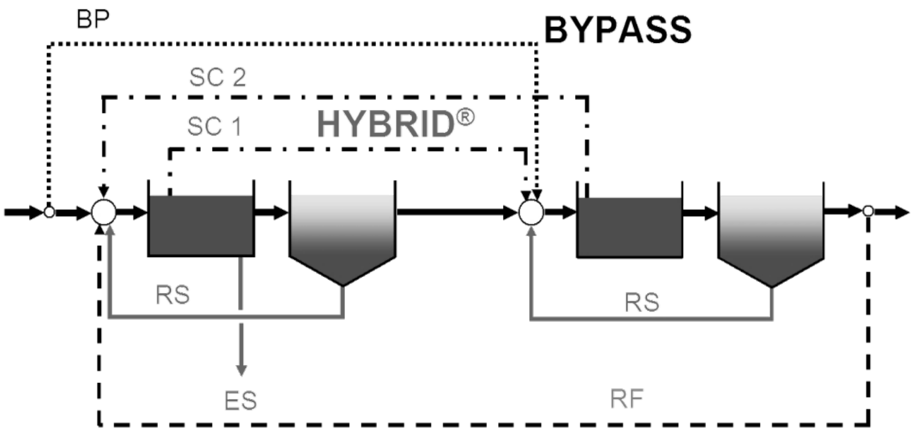

Fig. 3: Modes of operation of VMWWTP since 2005, BP=Bypass-mode, ES=Excess sludge, RF=external recirculation, RS=return sludge, SC1 SC2: activated sludge exchange during Hybrid-mode

During normal operation about 20 to 60 % of the DW flow is bypassed to the 2nd stage for improved denitrification. This bypass flow is fixed every 2 to 3 months according to the temperature development. In the case of bulking in the 2nd stage the operation switches to the Hybrid Mode, where the bypass is stopped and activated sludge of the 1st stage is added to the 2nd stage as denitrification carbon source. With these modes of operation bulking can be reliably avoided and N-removal > 80 % as yearly mean can be achieved.

The excess sludge is thickened together with the primary sludge in static thickeners and pumped to the incineration plant where it is dewatered with centrifuges and fed to the fluidized bed incinerators. The reject water from raw sludge dewatering flows to the influent pumping station.

Theoretical background: Oxygen and energy demand for 1- and 2-stage activated sludge process (AS)

Fig. 4 shows the influence of the sludge age (MCRT) and the COD balance. In a 1-stage as well as in the 2nd stage of a 2-stage WWTP with full nitrification and >70 % N-removal requirements at temperature of ≥ 12 °C a mean sludge age of about 12 days has to be selected for the design of large WWTP. In the 1st stage of a 2–stage AS plant the sludge age is ~1 day so that most of the COD removed will be transferred to excess sludge while the oxygen consumption is low. COD of the excess sludge can be interpreted as its energy content (~14 kJ/g COD) and hence methane production during digestion (1 g COD corresponds to 0.35 L of methane).

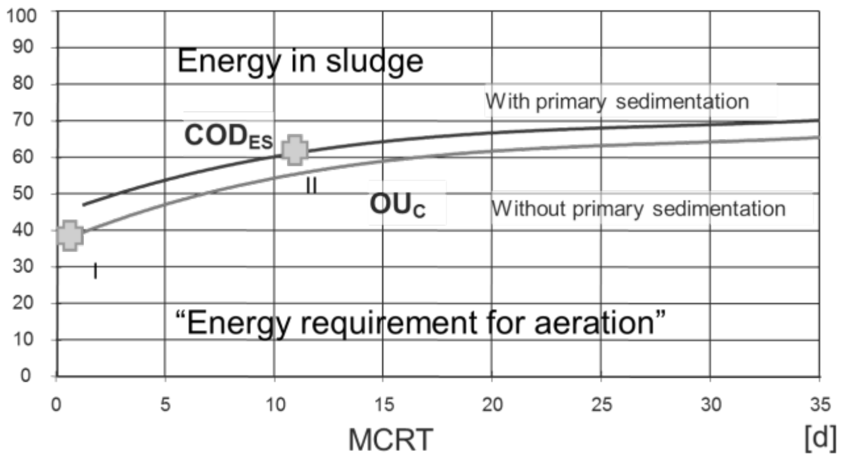

Fig. 4: Relationship between COD-balance and MCRT at 15 °C

The following Tables 3 and 4 represent the COD balance for 1-stage and 2-stage AS plants in order to show the difference (Tab.3). The theoretical background has been published by Svardal et al. (2011). The tables show the oxygen demand for COD removal, nitrification and nitrogen removal for 1 PE_{120}. The energy content of the excess sludge and of the biogas from sludge digestion is also expressed as COD. The *necessary assumptions* made for Fig. 4 and the Tables 3, 4 and 5 are in accordance with theoretical considerations (ASM 1) and full scale experience from large Austrian WWTPs and the VMWWTP.

OUC: Oxygen uptake for carbon removal
OUN: Oxygen uptake for nitrification
OUDN: Oxygen uptake for nitrogen removal

Tab.3: COD and oxygen Uptake (OU) for 1-stage AS process with PS, for $N/COD_{inf.}$= 12/120

COD Influent (N-influent 10 g N/PW/d, 85% N-removal)	120 g/PE/d
COD Effluent primary sed. (COD-removal PS = 33%)	80 g/PE/d
COD in primary sludge	40 g/PE/d
COD Effluent	*8 g/PE/d*
COD removal in aeration tank: 80 – 8 =	72 g/PE/d
OUC (60% of COD removed)	43 g/PE/d
COD excess sludge (40% of COD removed)	29 g/PE/d
COD input digester: 40 + 29 =	69 g/PE/d
COD in digested sludge	*30 g/PE/d*
COD of digester gas production (CH4) 69 - 30 =	39 g/PE/d
OUN (denitrified N-load 8,2 g N/PE/d): (12-2-8.2)*4.6	8.3 g/PE/d
OUDN: 8.2 * 1,7 =	13.9 g/PE/d

Tab. 4: COD and OU for VMWWTP 2-stage AS process with PS, $N/COD_{inf.}$= 12/120

COD influent (N influent 10 g N/PE/d, *75% N-removal*)	120 g/PE/d
COD effluent PS (COD removal by PS: 33%)	80 g/PE/d
COD of primary sludge	40 g/PE/d
COD effluent	*8 g/PE/d*
COD removal aeration tanks 80 – 8 =	72 g/PE/d
OUC (40% 1.stage/ 60% 2.stage)	29 g/PE/d
COD in excess sludge, 60 % of COD removal	43 g/PE/d
COD input digester: 40 + 43 =	83 g/PE/d
COD in digested sludge	*30 g/PE/d*
COD in digester gas production (CH4): 83 - 30 =	53 g/PE/d
OUN (nitrate in effluent 3 g N/PE/d): (12-*2*-7) * 4,6	13.8 g/PE/d
OUDN: 7 * 1,7 =	11.9 g/PE/d

Tab. 5: Comparison of Oxygen Uptake for carbon and nitrogen oxidation and of the energy demand (-) and production (+) between 1-stage and 2-stage AS plants using the data of Tab. 1 and 2

Process	OU (C+N)	aeration energy	Other energy	El. energy biogas	Sum
Dim	g O_2/PE/d	kWh/PE/a			
1-stage	65.2	- 13.0	*- 7.3*	+ 17.9	- 2.4
2-stage	54.7	- 11.4	*- 8,4*	+ 24.3	+ 4,5

For Table 5 the following assumptions have been made

- oxygenation efficiency 2.2 kg O_2/kWh for the 1-stage plant with Deammonification and 2.1 kg O_2/kWh for 2-stage plant; reject water nitritation, denitritation in 1st stage
- dissolved oxygen concentration (DO) in nitrification tank volume 2 mg/l (T=15°C)
- electrical efficiency of gas motors 4 kWh/m³ methane,
- total energy conversion efficiency of gas motor operation 90 %

Table 5 shows that the process concept of VMWWTP is able to produce more energy from digester gas than the plant´s demand while with a 1- stage AS process only about 85% of the energy demand could be recovered by sludge digestion even a 10% higher N-removal efficiency would be achievable.

Without efficient modern aeration systems and gas motors energy-positive waste water treatment plant cannot be achieved using AS process for biological treatment.

Energy Optimization Sludge Treatment Project (EOS Project) 2020

After about 5 years of operation of the extended VMWWTP a concept was developed to progress from a major energy consumer to an energy-positive wastewater treatment plant in order to respond to the climate change abatement policy and to make the plant less dependent on energy prices. After 5 years of design and pilot investigations in 2015 the construction phase started.


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Fig. 5: Layout of the EOS Project, newly constructed primary sedimentation and first activated sludge plant in order to save space for 6 sludge digesters (12,500 m³ each), gas motor station 2 gas holders, reject water nitritation and mechanical thickening

The challenges for the EOS project development have been the following:

- limited space availability,
  - digestion with high solids concentration, mechanical thickening of raw sludge
  - ammonia toxicity to methanogen
  - rheological properties of raw (8 % DS) and digested (4 % DS) sludge
  - feeding and mixing of the digesters
- gas production and composition for conversion to electric energy
- avoiding MAP precipitation in reject water system
- reject water contains up to 25 % of N-influent load, which went to incineration before
  - nitritation of reject water in order to save carbon source for N removal
  - reject water denitritation in first AS process to save aeration energy
- increased depth of the 1-step AS tanks (~ 6.5 m)
  - change from surface aerators to fine bubble aeration in first step
- development of a dynamic mathematical model for the prediction of energy management results under different loading and operational conditions
- changes of the sludge dewatering and incineration properties

Pilot investigations for digestion with high solids concentrations

In order to minimize risks for the design and operation of the EOS project a pilot plant was operated nearly 1.5 years on site and online at the VMWWTP.

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Fig. 6: Pilot plant for EOS project. Volume digester 130 m³, equipped with mechanical thickener, gas motor, reject water storage and treatment and complete sensor and control equipment

The most important results of the pilot investigations can be summarized as follows:

- Feed sludge with 8 % DS result in stable digestion operation (no ammonia inhibition)
- Mechanical thickening with addition of polymers can achieve ≥ 8 % DS
- Raw sludge with 8 % DS has a viscosity 10 to 50 times higher than digested sludge (4 %)
- Digester design (cylindrical, 35 m depth and D = 23 m) enables complete mixing by gas production alone under normal operation (sludge is fed at the bottom)
- gas production and composition is in line with the theoretical considerations, ~50 % oDS-, 37 % DS- and 60 % COD-reduction

Dynamic model development and application

Using the full scale operational data of the VMWWTP and the results of the pilot investigations it was possible to develop an adapted dynamic mathematical model of the whole plant from primary sedimentation to effluent including sludge digestion and reject water treatment.

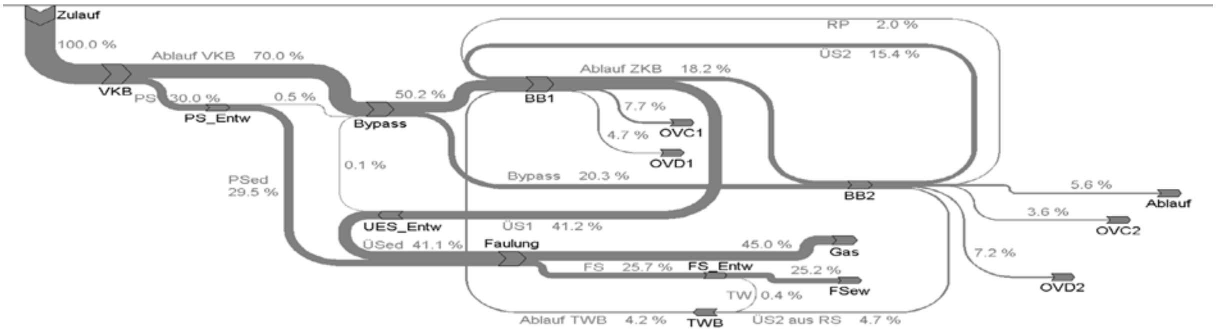

Fig. 7: Sankey diagram for the COD flow under design loading conditions (Reichel 2016)

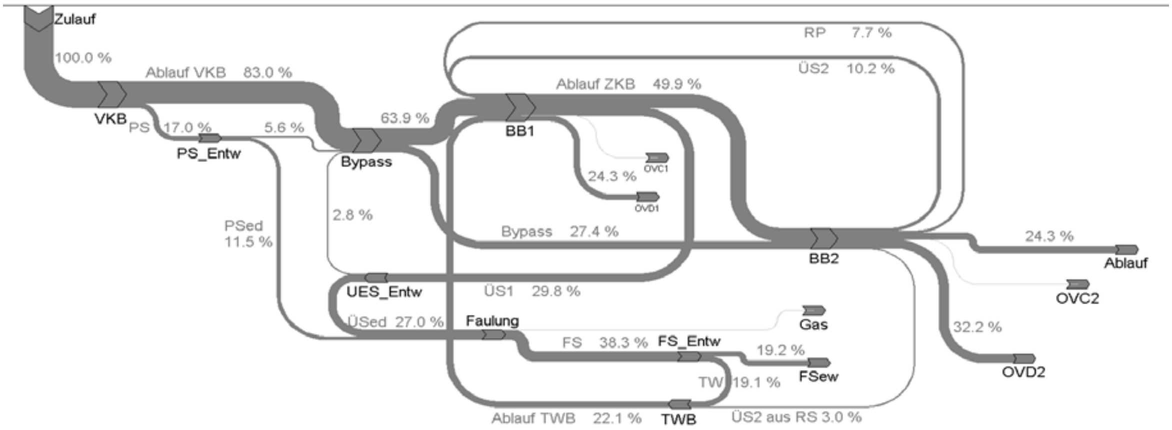

Fig. 8: Sankey-diagram for the Nitrogen flow under design loading conditions (Svardal et al. 2014)

The model developed was fed with the loading data of the whole year 2011 in order to demonstrate the influence of the variations of loading and temperature on the energy consumption for aeration, the energy production from biogas and the N removal results using different operational strategies and assuming different loading conditions. Figures 7 and 8 show the COD- and N-flows for the design loading situation (4 Mio PE as 85 %ile which corresponds to a mean load of ~3.5 Mio PE).

Reject Water treatment

After a long discussion regarding N-removal from reject water (containing ~25 % of the N influent load) it was decided to go for partial nitritation and denitritation in the 1st stage AS plant. As long as there is enough carbon source for denitrification N-removal needs 1.7 kg O_2/kg N-removed irrespective of the process applied (Deammonification or denitritation). Oxidation of ammonia to nitrite at NH_4-N concentrations >1600 mg/l is a very stable and easy process up to about 50 % conversion. Start-up phase is in the range of less than 1 week, which is very important for a large WWTP. If higher N-removal rates should be required in the future lime addition to the nitritation tank for pH control would allow to achieving up to ~80 % nitritation. The nitrite can easily be removed in the 1st stage aeration tank, replacing aeration. This results in energy saving for carbon removal in the 1st stage as the oxygenation efficiency in the reject water nitritation tank is markedly higher (α = 0.7) than in the 1st stage AS tanks (α = 0.45).

In order to avoid MAP precipitation in the pipes and tanks of the reject water treatment a controlled MAP precipitation will be performed in the digested sludge before sending it to the dewatering and incineration plant. The digested sludge will be aerated to increase the pH of the reject water resulting in MAP precipitation (Mg removal) before dewatering of the digested sludge.

Energy management

The VMWWTP will remain connected to the existing electrical grid so that excess of energy can be transferred to the grid and peak energy can be recovered from the grid. The power station has a maximum capacity of ~12 MW. The gas motors will be operated in a way that the transformation efficiency remains close to the maximum at any time.

Conclusions

Optimising design and process configuration of mechanical-biological waste water treatment plants for full nitrification and nutrient removal allows to make large plants energy self-sufficient and even energy producing without addition of external substrates.

The scientific background with COD and N-balances together with sound parameter determination from full scale operation and pilot investigations were used as the basis for the design. The development of an adapted dynamic model of the whole plant including sludge digestion and reject water treatment allowed to calculate the future energy demand and nitrogen removal efficiency for a design loading pattern over a whole year derived from the actual loading conditions of the existing plant.

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