Examples of energy self-sufficient municipal nutrient removal plants

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ABSTRACT

In Austria, two municipal WWTPs (the Strass TP and Wolfgangsee-Ischl TP) operated with nutrient removal and aerobic sludge digestion are now energy self-sufficient. This is the result of a long-standing and on-going optimisation process at both plants including optimal aeration control and control of the aerobic section of the aeration tank to optimise denitrification and prevent degradation of particulate organic matter that should be degraded in the digester. Both TPs are now equipped with energy-efficient CHP units. However, it is maybe more sustainable to use the biogas as biomethane/bio-fuel than in conventional CHP at the WWTP. It is shown that energy self-sufficiency should be in reach at other municipal WWTPs, too.

Key words | energy optimisation, energy saving, energy self-sufficiency, municipal wastewater treatment

INTRODUCTION

Decades ago, when sedimentation (‘mechanical treatment’) was in many cases the only treatment step in municipal wastewater treatment plants (WWTP), the produced sludge was often anaerobically digested and energy was gained from the digester gas. If gas machines or combined heat-power units (CHP) were applied, the electricity produced from the gas exceeded by far the demand of the plant and could be sold. After introducing biological treatment for carbon removal as an ‘additional’ treatment step, it was still possible in some cases to get more energy from the gas than what was needed for all the devices at the WWTP including aeration. However, as soon as ammonia removal – which today has to be seen as the minimum standard for water protection – was required, the additional energy demand for the oxygen transfer for nitrification which is in the same range as that for oxidation of carbonaceous matter resulted in a demand for electro-mechanical energy higher than what could be produced from the digester gas. Moreover, due to larger aeration tanks and therefore higher sludge age, less organics have been transferred into the anaerobic digester with the excess sludge and therefore less ‘biogas’ has been produced at WWTPs after the introduction of nitrification at municipal WWTPs. Even nitrogen removal by denitrification does not help very much to improve the energy balance of a conventional WWTP (activated sludge process) with primary sedimentation and anaerobic sludge digestion. Whilst some oxygen can be ‘recovered’ by denitrification which reduces the oxygen demand, the aeration tank additionally necessary for denitrification has to be stirred and the specific load of organics in the excess sludge which is transformed to methane in the anaerobic digester is certainly not higher than in the case of nitrification only.

During the last few years, many papers have been published on energy minimisation or ‘optimisation’ of WWTPs (e.g. Nowak 2003; Svardal & Kroiss in press). Energy minimisation, however, must never negatively affect treatment efficiency as water quality protection is more important for sustainable development than the possible reduction in energy demand (Svardal & Kroiss in press). This must be seen against the background that the energy costs are only in the range of about 5–10% of the total yearly costs (construction and operation) of municipal WWTPs (Nowak 1999). Accordingly, at existing WWTPs, at first the wastewater treatment process has to be optimised towards better performance in terms of quality of the effluent and the waste sludge, and then the treatment plant operators can go for savings of energy, chemicals, etc.

The target of ‘energy self-sufficient sewage plants’ has also been reported (Fievez 2009; Kolisch et al. 2009).
Austria, two municipal WWTPs (the Strass TP – also called AIZ – and the Wolfgangsee-Ishl TP) operated with nutrient removal are now energy self-sufficient. This is the result of an optimisation process that has lasted at both plants for about two decades.

Both of these treatment plants are activated sludge plants with nutrient removal with phosphorus effluent concentrations well below 1 mg P/L and about 80% nitrogen removal, for which no external carbon source is needed. Both plants are equipped with primary sedimentation. In the oxidation-ditch type aeration tanks of both plants fine-bubble diffusers are installed. They are both operated with a combination of pre-denitrification and intermittent nitrification-denitrification by means of an optimised aeration control system. Both plants are equipped with mesophilic anaerobic sludge digesters. The energy from the biogas is used in combined heat-power (CHP) units. Both plants have previously been presented or mentioned in literature (Nowak et al. 1996; Wett et al. 1998; Nowak 2003; Wett 2006; Wett 2007; Svardal & Kroiss in press).

ENERGY SELF-SUFFICIENCY AT THE STRASS WWTP

Description of the plant

The Strass WWTP is designed as a two-stage activated sludge plant, a so-called A–B-plant, with a very high-loaded first stage with solids retention time (SRT) below 0.5 days. COD removal in this high-loaded stage is around 50%. The SRT or ‘sludge age’ in the second, low-loaded stage (aeration tank volume of 10,740 m³) is about 12 to 14 days and the temperature varies between 9 and 18 °C. The aeration is controlled not only by DO probes but also by means of an online ammonia analyser. If the ammonia concentration exceeds a certain value in the effluent from the aeration tanks, the second aeration tank in line, which is normally intermittently aerated, is then aerated permanently. If this is not enough for full nitrification (NH₄-N below ca. 4 mg/L), the aeration in the ‘pre-denitrification tanks’ is switched on in addition and the internal recycle is deactivated.

The following operational data are related to the years from 2005 to 2007. In this period, the mean influent load was about 146,000 pe₁₂₀ (=population equivalents related to 120 g COD/(pe.d)). Due to winter tourism, the influent load equals about 220,000 pe during winter season, whereas during the rest of the year, the influent load is sometimes less than 90,000 pe. The N:COD ratio of the influent is around 0.07 on average. The extent of nitrogen removal of the plant is around 83% on the yearly average, and about 86% on the average of all days with more than 12 °C in the effluent. The solids retention time in the digesters is around 36 days. Due to the two-stage biological process, a lot of biomass with a lot of nitrogen is transferred to the digesters, and therefore the nitrogen load as ammonia in the reject water from sludge dewatering is very high. Nitrogen from the reject water is removed by deammonification (‘anammox’) to a high extent. For deammonification, at this plant the DEMON process has been developed (Wett 2006). The digester gas is utilised in the conventional CHP units with an electrical efficiency of now close to 40%.

Energy production and energy consumption at Strass TP

Since 2008, pre-conditioned organic substrate (food leftovers) is directly fed into the digester together with excess sludge of the treatment plant in order to increase the electricity production from the biogas. Accordingly, the results presented here are from the period of 2005 to 2007, when no external organic substrate was utilised to enhance energy production. Figure 1 shows the energy balance of that period.

According to Figure 1, on the average of the years from 2005 to 2007, 21.4 kWh/(pe₁₂₀.a) of electric energy were produced from the gas from sludge digestion. Peak energy demand has still to be taken from the grid; surplus electrical energy from the plant, however, is fed into the grid. So, 3.2 kWh/(pe.a) could be fed into the grid, and 1.7 kWh/(pe.a) were provided from the grid. In total, 19.9 kWh/(pe.a) of electricity were consumed at the
WWTP of which 9.1 kWh/(pe.a) used for aerating and stirring the aeration tank, the 'rest' (10.8 kWh/(pe.a)) used for all the other treatment steps and devices including the influent pumps which consumed 1.9 kWh/(pe.a).

Over the whole period of three years, 6.3% more electricity was produced through the anaerobic digestion of the excess sludge from both stages from the biogas by means of CHP units than was needed in the plant. Figure 2 shows the fluctuation of electricity production and electricity consumption in the period from August 2003 until the end of the year 2007.

It can be seen from Figure 2 that approximately in September 2004 energy self-sufficiency was reached. However, it also can be seen that in some months more electrical energy was needed than provided by CHP. In 2009 (and 2010), the electricity production was sometimes up to 200% of the demand of the plant for electrical energy.

Svardal & Kroiss (in press) have shown by theoretical considerations that a municipal WWTP of this type (two-stage activated sludge with a high-loaded first stage and deammonification of the reject waters from anaerobic digesters) can produce about 1 kWh/(pe.a) more of electric power than is needed for the operation of the plant. Hence, the results of this plant are not really surprising.

**ENERGY SELF-SUFFICIENCY AT WOLFGANGSEE-ISCHL TP**

**Description of the plant**

The Wolfgangsee-Ischl WWTP is a single-stage activated sludge system with primary sedimentation and anaerobic sludge digestion. The aeration tanks (5,100 m³) are equipped with fine-bubble aeration and stirring devices. The treatment plant was put into operation in the mid-1980s and afterwards only upgraded by changing and optimising mechanical devices.

In 2009, the mean influent load was about 40,000 pe related to 120 g COD/(pe.d). Due to summer tourism, in the months of July to September, the influent load equals around 50,000 pe, whereas during the rest of the year the influent load is in the range of 33,000 to 40,000 pe. Originally, the plant was designed for 100,000 pe, but only for carbon removal – and for phosphorus removal, because the recipient flows later into a lake. However, because it was clear during plant design that at least in the beginning of the operation of the plant, the influent load would be much lower than 100,000 pe, the aeration tanks were designed in a way that makes nitrification and denitrification practicable. Hence, the aeration tanks are operated with a combination of pre-denitrification and intermittent nitrification-denitrification. The temperature varies between 7 and 17 °C.

The N:COD ratio of the influent is in the range of 0.09 and 0.10 g N/g COD on average. COD removal by primary sedimentation was found to be about 37% (Nowak 2003). In the aeration tank, the SRT is about 8 days in summer and about 12 days in winter. The extent of nitrogen removal of the plant is around 76% on the yearly average, and about 80% on the average of all days with more than 12 °C in the effluent. This plant is equipped with two large digesters operated in series with a solids retention time of almost 80 days in total. The digester gas is mainly used in conventional CHPs. A second CHP unit was installed about 2 years ago. The reject water from sludge dewatering is not treated separately, but only equalised by means of a storage tank. The digested sludge is dewatered by means of a chamber filter press and used in agriculture.

**Energy production and energy consumption at Wolfgangsee-Ischl TP**

In 2002, the energy management of this plant was reported with data from the years 1999 and 2000. During that period about 72% of the demand on electric energy was provided by an older CHP unit with an electric efficiency of about 31%. As there was only one CHP unit not all biogas could be used all the time (Nowak 2003). Afterwards a second, more efficient CHP unit was installed with an electric efficiency of about 34%. Now, all biogas can be utilised for electricity production and, moreover, the energy demand of the plant was further reduced by optimisation.
Figure 3 shows the energy balance of Wolfgangsee-Ischl TP for the 1-year-period of September 2009 to August 2010. On the average of this 12-month-period, 20.6 kWh/(pe\_120.a) of electrical energy were produced from the digester gas. Like at the Strass TP, surplus electric energy from the plant is fed to the grid. For the peak energy demand, electricity as well as natural gas is taken from the grids. Natural gas is used in order to avoid peaks in the demand from the grid which would be costly. According to Figure 3, 2.2 kWh/(pe.a) of electric power were fed into the grid, while 0.4 kWh/(pe.a) were taken from the grid. With the natural gas taken from the gas grid another 0.4 kWh/(pe.a) of electrical energy were produced by means of the CHP units. In total, 19.2 kWh/(pe.a) of electricity were consumed at this WWTP of which 11.5 kWh/(pe.a) were used for aeration and the stirring of the aeration tank, and 7.7 kWh/(pe.a) of electric energy were used for all the other treatment steps and devices.

Over this 1-year-period (09/2009 to 08/2010), the overall-surplus of electricity production was 7%. Figure 4 shows the electricity production in relation to the consumption of electric energy for every month from May 2009, when energy self-sufficiency was reached for the first time, until August 2010. How much of the energy produced is used inside the plant and what has been fed into the grid is also presented. It can be seen that not all months produced more electric power than was needed at the plant.

A MODEL TO EXPLAIN ENERGY SELF-SUFFICIENCY AT WOLFGANGSEE-ISCHL TP

Unlike the treatment system of Strass TP, it is not easy to explain why energy self-sufficiency could be accomplished at Wolfgangsee-Ischl TP, a typical activated sludge plant with primary sedimentation and anaerobic sludge treatment without any further treatment steps that might further reduce energy consumption such as separate treatment of reject waters from sludge handling.

For a better understanding, the model for estimating energy demand and energy production that was already presented in the previous presentation (Nowak 2003) has been adjusted to the current energy balance of this plant. At first, an approximate COD mass balance for the Wolfgangsee-Ischl TP was derived from the operational data and from theoretical considerations (Figure 5). This tool for balancing COD has been presented previously (Nowak et al. 1999; Nowak 2003).

![Figure 3: Energy balance of Wolfgangsee-Ischl TP for a period of 12 months (September 2009 to August 2010).](image1)

![Figure 4: Energy production in relation to energy consumption (as electricity) at Wolfgangsee-Ischl TP in the period May 2009 to August 2010.](image2)

![Figure 5: Approximate COD balance for the Wolfgangsee-Ischl WWTP (activated sludge plants with primary sedimentation and mesophilic anaerobic digestion).](image3)
With a COD removal of the treatment plant of 96%, the specific effluent COD is about 5 g/(pe.120.d). With reference to previous work (Nowak et al. 1999), the COD load in the stabilised sludge removed from the system (COD\text{XD}) was assumed to be 29 g COD/(pe.d). Furthermore, it was estimated that the ratio of oxygen consumption for carbon degradation (OUC) to the COD removed in the activated sludge (AS) system (\(\eta_{\text{COD}} = 73 \text{ g COD/(pe.d)}\)) equals 0.57.

This ratio was found at another plant at SRT of about 10 days (Nowak et al. 1999). Accordingly, the COD in the digester gas (COD\text{gas}) can be estimated to be 47 g COD/(pe.d) and the estimated specific methane production is therefore 16.5 NL CH\(_4\)/(pe.d).

Table 1 gives the parameters that have been applied to the model based on Nowak (2003) adjusted to the current energy situation at Wolfgangsee-Ischl TP. It was assumed that under operating conditions 50% of the load of the oxygen consumption for carbon removal (OUC) is used for denitrification as oxygen consumption for the degradation of carbonaceous matter with nitrate as electron acceptor (OUCD). This value can be reached in the case of effective pre-denitritification and if the anoxic reactor section is somewhat more than 50% of the total aeration tank. To avoid calculating unrealistically high nitrogen removal, it was assumed that the nitrogen removal efficiency does not exceed 93%.

Figure 6 shows the results from the estimations with this model. For the energy demand other than for the aeration tank (aeration and stirring), the extremely low specific value of 7.7 kWh/(pe.a) as found at Wolfgangsee-Ischl TP in the respective period (see Figure 3) was taken into account. The model used here was calibrated on the operational results of Wolfgangsee-Ischl TP and therefore the results from this model are in accordance with the data. It can be seen, however, that as a result of these theoretical considerations the energy balance of a single-stage activated sludge plant with primary sedimentation is strongly dependent on the N:COD ratio of the influent and on the COD removal in the primary clarifier. It can also been seen that for a typical COD removal of 33% in the primary clarifier and an influent N-to-COD-ratio below 0.10 g N/g COD, energy self-sufficiency should be feasible – provided that the energy demand for ‘other’ than the aeration is as low as it is at Wolfgangsee-Ischl TP. Accordingly, it can be derived that what is possible at Wolfgangsee-Ischl TP should also be in reach at similar municipal WWTPs.

**CONCLUSIONS**

The example of Wolfgangsee-Ischl TP demonstrates that with permanent optimisation of the electricity consumers energy self-sufficiency can be reached at average municipal WWTPs. It has to be pointed out, however, that at this plant the COD influent load in summer is about 50% higher than in winter. Because of this relatively higher load in summer, the aeration tank volume is most of the
time optimally used, which is certainly an advantage in terms of minimisation of energy consumption. In this respect, the Strass TP has a disadvantage in minimising energy consumption, as COD influent loads are high in winter and low in summer. This negative effect is equalised by the two-stage wastewater treatment system with deammonification of the reject waters which help to minimise energy consumption for aeration. Another advantage of the Wolfgangsee–Ischl TP with respect to the energy balance is the large volume of the anaerobic digesters, which certainly helps for a far-reaching degradation of the organic compounds of the sludge and to increase biogas yield. At both plants, energy self-sufficiency was achieved as soon as new energy efficient CHP units were installed. Besides on-going optimisation, another important reason for reaching energy self-sufficiency at both plants is the optimal control of aeration to avoid too high DO concentrations and too large aerobic sections to prevent degradation of particulate organic matter.

Finally, it has to be pointed out that producing electricity in a conventional CHP plant is maybe not the best choice for utilising the energy content of biogas. Tilche & Galatola (2008) found that from the sustainability point of view the use of bio-methane as bio-fuel is most likely the best option. An interesting alternative for upgrading the value of the biogas is to gain bio-methane from the biogas by means of pressure swing adsorption (PSA). With this technology, the methane content in the remaining ‘rest gas’ is around 14%. To use this rest gas in a proper manner, it can be remixed with biogas to a methane content of about 27%, which is high enough to be used in a micro gas-turbine to produce electricity and heat. In this way, about 80% of the methane in the biogas is upgraded to bio-methane and the other 20% are still used in a CHP unit. Another option is to use the biogas directly as a fuel in a near-by industry for example in a steel works.

REFERENCES


