Benchmarks for the energy demand of nutrient removal plants

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Abstract The energy demand of municipal wastewater treatment plants for nutrient removal equipped with primary clarifiers, activated sludge system, anaerobic sludge digestion, and CHP is evaluated theoretically, on the basis of COD balances. Operational experience from energy-efficient Austrian treatment plants confirms that the demand on external electrical energy can be kept as low as 5 to 10 kWh/(pe.a) depending on the N:COD ratio in the raw wastewater. A low N:COD ratio helps to keep not only the effluent nitrogen load low, but also the energy demand. Measures to minimise the energy demand at treatment plants and to reduce the nitrogen load are discussed.

Keywords Activated sludge; COD balances; energy demand; municipal wastewater; nutrient removal

Introduction
In many EU countries, the total personnel costs including administration are the most important cost factor in the operation of municipal WWTPs. The energy costs and the costs for chemicals for phosphorus precipitation and for sludge conditioning are considerably lower (Nowak, 2000). However, with respect to a sustainable resources management and to social aspects, the personnel costs have to be judged completely different from costs for energy and chemicals. While having people employed at public services might be a political decision, the consumption of energy and chemicals causes environmental impacts and mostly a depletion of natural resources. In view of this background, the use of energy as well as of chemicals should be kept as low as possible.

In practice, the activated sludge process is by far the most important treatment technology for nutrient removal. The following considerations have been carried out for nutrient removal plants with an average load of about 50,000 pe, with primary clarifiers and with mesophilic anaerobic sludge digestion including gas utilisation for electricity production.

COD balances of activated sludge plants
Mass balances are very useful when applied to the biological WWTPs. Figure 1 shows estimates for the COD balances of activated sludge plants with 20% and 40% COD removal by primary sedimentation.

The input to this system which is equal to the output under steady-state conditions is represented by:
- the influent COD (COD$_i$),
- plus the COD introduced into the system by the growth of the autotrophic nitrifying bacteria (COD$_{XA}$).

The output of the system equals to the sum of:
- the effluent COD (COD$_o$),
- the oxygen consumption for the degradation of carbonaceous matter (OUC),
- the COD in the digester gas (COD$_{gas}$) where 1 g COD corresponds to 0.35 NL CH$_4$,
- and the COD of the sludge removed from the system to be disposed of (COD$_{XD}$).
The unit of the values presented in Figure 1 is g COD/(pe.d). These values are based on several assumptions deduced from Austrian experience. On the base of a specific BOD₅ load of 60 g/(pe.d), the per-capita COD load in municipal wastewater is about 110 to 120 g/(pe.d) (Andreottola et al., 1994; Nowak et al., 1996). In this example, a value of 110 g/(pe.d) has been chosen for the influent COD load. CODₙₐₜ is about 2 g/(pe.d) depending on the load of nitrogen to be oxidised, and the effluent COD was estimated to be 7 g/(pe.d). In previous work (Nowak et al., 1996), it has been shown that the COD load in completely stabilised sludge varies only slightly at different municipal WWTPs, between about 23 and 29 g COD/(pe.d), when related to 110 g COD/(pe.d) in the influent. In these examples (Figure 1) a specific COD load in the stabilised sludge removed from the system (CODₓₜₘ) of 26 g COD/(pe.d) has been assumed.

Because 4 of the input and output values (CODᵢ, CODₙₐₜ, CODₒ and CODₓₜₘ) of the COD balances in Figure 1 can be assumed to be constant, also the sum of the other 2 output values (OUC and COD₉ₐₙ₉) can be regarded as being fixed. Long-term experience exists about the ratio of oxygen consumption for carbon degradation (OUC) to the COD removed in the AS system (ηCOD) of municipal WWTPs for nutrient removal. This parameter ηCOD equals the COD in the influent to the AS system plus CODₙₐₜ minus the effluent COD (Nowak et al., 1999). From this experience, the ratio OUC/ηCOD is about 0.6 at municipal AS plants with conventional primary sedimentation (33% COD removal) at SRT about 15 d and average temperature conditions (15°C in the aeration tank). With a lower COD removal efficiency of the primary clarifiers, the ratio OUC/ηCOD tends to be lower.

At nutrient removal plants without primary sedimentation, values of about 0.5 have been found for the ratio OUC/ηCOD at the same conditions as above (Franz et al., 1996).

In these examples (Figure 1) the parameter COD₉ₐₙ₉ was calculated from the other input and output values presented above. In practice, the COD of the digester gas can be estimated by the gas production and the CO₂ content of the digester gas, for 0.35 norm-litre of methane gas correspond to 1 g of COD. Figure 1 clearly shows that, the more organic matter (COD) is removed by primary sedimentation, the lower is the oxygen demand for carbon removal and the higher is the production of digester gas.

An approach to estimate the minimum energy requirement

More than half the power consumption of a municipal WWTP is required for the aeration of the aeration tank. Several assumptions have to be made to estimate the energy demand for

Figure 1  COD balances for activated sludge plants with primary sedimentation and mesophilic anaerobic digestion: a) 20% COD removal, b) 40% COD removal by primary sedimentation
the aeration as well as the gain of energy from the digester gas. Furthermore, the oxygen consumption for nitrification and the “recovery” of oxygen by denitrification have to be taken into account. In Table 1 all assumptions made here are listed.

Concerning nitrogen removal, it was assumed that about 1.3 g N/(pe.d) are eliminated from the wastewater system with the stabilised sludge (Nowak et al., 1996). There are some nitrogen losses as NH₃, perhaps 0.3 g/(pe.d), in the course of sludge handling. Together roughly 1.6 g N/(pe.d) are removed from the wastewater by ways other than denitrification. The “rest” of the nitrogen, influent load minus 1.6 g/(pe.d), is denitrified or found in the effluent. Furthermore, it was supposed that under operating conditions 40% 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 the electron acceptor (OUCD) (Table 1). This corresponds to an anoxic reactor section close to 50% of the total aeration tank. To avoid calculating unrealistically high nitrogen removal, it was assumed that the nitrogen removal efficiency does not exceed 90%. In the case of membrane aerators, the oxygenation capacity is, at the best, about 2.2 to 2.5 kg O₂/kWh under operating conditions (Frey, 1992). Assuming a value of 2.35 kg O₂/kWh and a DO of 1.5 mg/L in the oxic zones, the energy demand for the aeration amounts to 0.50 kWh per kg of oxygen consumed at 15°C. The calorific value of methane gas (CH₄) is 10.0 kWh/Nm³ of which about 32% can be transformed into electricity by means of combined heat-power units (CHP) or into mechanical power, in the case of direct coupling of the gas engine and blower. Because not all digester gas can be used all the time, an energy gain of 2.8 kWh of electrical energy per Nm³ of methane gas is assumed.

Figure 2 shows the results from these estimations where the energy demand (or gain) is related to the mean influent load. It has to be pointed out that these values can be achieved only if the aeration is designed properly, is well maintained and operated economically, and the recovery of energy from the digester gas is done effectively.

In Austria, a minimum nitrogen removal of 70% on the yearly average of all days with more than 12°C in the effluent is required by law from all municipal WWTPs with a design capacity of more than 5,000 pe. Correspondingly, in Figure 2, the results for the energy demand of the aeration tank are presented only as far as the nitrogen removal rate does not drop below 70%. In domestic wastewater the N:COD ratio is about 0.09 to 0.10. At a N:COD ratio of 0.10, the COD removal in the primary clarifiers may not exceed 26% to keep the nitrogen removal efficiency above 70% (Figure 2). By “conventional” primary sedimentation (HRT > 1.5 h) about one third of the organic load (COD or BOD₅) is removed. Therefore, AS plants for nutrient removal are often designed and operated with a short retention time of about 0.5 h in the primary clarifiers to reduce the COD removal. However, this provokes a higher energy demand for carbon degradation and a lower gas

### Table 1 Assumptions for estimating the energy demand for the aeration (aeration tank) and for the energy gain from digester gas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
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<tbody>
<tr>
<td>Ratio OUC/ηCOD</td>
<td>Linear increase from 0.5 without primary clarifier to 0.6 at 33% COD removal in primary clarifier</td>
</tr>
<tr>
<td>Nitrogen removed from the plant with the sludge (and during sludge handling as free ammonia)</td>
<td>1.6 g N/(pe.d)</td>
</tr>
<tr>
<td>Extent of nitrification</td>
<td>Full nitrification (NH₄-Nₓ = 0)</td>
</tr>
<tr>
<td>Ratio OUCD/OUC *)</td>
<td>0.4 kg/kg</td>
</tr>
<tr>
<td>Maximum nitrogen removal</td>
<td>90%</td>
</tr>
<tr>
<td>Specific energy demand for the aeration</td>
<td>0.5 kWh/kg O₂ consumed</td>
</tr>
<tr>
<td>Gain of electrical energy from the digester gas</td>
<td>2.8 kWh/Nm³ CH₄</td>
</tr>
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*) OUCD oxygen consumption for the degradation of carbonaceous matter with NO₃ as electron acceptor
production (Figure 2). A high specific nitrogen load in the influent causes a high energy
demand, not only due to increased nitrification, but also as a consequence of the need for
enhanced denitrification in order to keep the NO$_3$-N concentration low in the effluent.

Except for the aeration, the demand on electrical energy of energy-efficient AS plants is
in the range of 6 to 13 kWh/(pe.a) mostly depending on the head of the influent pumps and
on the complexity of sludge treatment. For the further estimations a value of 9 kWh/(pe.a)
was used. Figure 3 exhibits that an energy-efficient WWTP for nutrient removal with reuse
of the digester gas may require only around 3 to 5 kWh/(pe.a) (0.15–0.23 kWh/kg BOD$_5$) of
electrical energy from the grid, if a lot of organic material can be removed from the waste-
water by sedimentation (35 to 40%) and if the N:COD ratio of the influent is about 0.06 to
0.08. Nutrient removal plants with an influent N:COD ratio of 0.10, however, need at least
9 kWh/(pe.a) (= 0.4 kWh/kg BOD$_5$) of “external” electrical energy (Figure 3).

The energy demand of existing nutrient removal plants

The energy demand of 12 nutrient removal plants in Austria

In a study of the expenditures on the operation of municipal WWTPs (Nowak, 2000), the
operational data from 1997 of 12 plants for nutrient removal equipped with primary
clarifiers and anaerobic digesters were evaluated. The demand on external electrical energy

Figure 2  Energy demand for the aeration (aeration tank) and energy gain from digester gas as a function of
the COD removal by primary sedimentation and of the N:COD ratio of the raw wastewater (The results for
the energy consumption are drawn in only as far as the N removal rate exceeds 70%)

Figure 3  Energy demand from the grid in kWh$_{el}$/pe.a of energy-efficient WWTPs as a function of the
COD removal by primary sedimentation and of the N:COD ratio of the raw wastewater (The results for the
energy consumption are drawn in only as far as the N removal rate exceeds 70%)
of these 12 plants was between 9 and 60 kWh/(pe.a) (Figure 4). The mean value for the electrical and/or mechanical energy obtained from digester gas was 12 kWh/(pe.a). 5 of the treatment plants of this study purchased between 9 and 13 kWh/(pe.a) related to the mean influent load ranging from 25,000 to 100,000 pe. Detailed analyses revealed savings potentials of 2 to 4 kWh/(pe.d) of electrical energy, even for these plants.

Energy management of a benchmark plant

The WWTP of Wolfgangsee-Ischl is equipped with primary clarifiers, an AS system operated with a combination of predenitrification and intermittent nitrification-denitrification, anaerobic digesters and a CHP unit (Nowak et al., 1996; Nowak et al., 2001). In the years of 1999 and 2000, the mean influent load was about 41,000 pe related to 110 g/(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. The N:COD ratio of the influent is 0.082 on the average. COD removal by primary sedimentation is about 37%. The extent of nitrogen removal of the plant is around 75% on the yearly average, and about 80% on the average of all days with more than 12°C in the effluent. Figure 5 shows the energy balance of the WWTP of Wolfgangsee-Ischl in 1999. The digester gas is partly used in a gas engine directly coupled to a blower. If more heat is required in winter, natural gas is purchased – besides electricity – to produce heat as well as electric power. In 1999, 19.3 kWh/(pe.a) of electrical and mechanical energy were consumed in total, of which 13.9 kWh/(pe.a) were produced from digester gas. Thus, only 5.4 kWh/(pe.a) (≈0.25 kWh/kg BOD₅) of electrical (and mechanical) energy were required from external suppliers.

For the aeration 10.0 kWh/(pe.a) were needed. It has to be mentioned that in 1999 the demand on external energy was about 3 kWh/el/(pe.a) lower than in 1997, as in 1998 the 12-year-old membranes of the aerators were renewed. In Table 2, values for the energy demand of the other electrical equipment of the Wolfgangsee-Ischl TP, of another WWTP (Agis, 2001), and benchmarks recommended as a rule of thumb are presented.

Measures to minimise the energy consumption

Measures at the treatment plants

The reasons for elevated energy consumption of nutrient removal plants are manifold. Here, only the major causes observed in practice are discussed.

Low oxygenation capacity due to ageing of the membrane aerators. Practice has shown that membrane aerators loose their optimum oxygenation capacity after about 6 years of
operation. From Austrian experience, the costs for changing the membranes amount only to about half of the yearly energy costs for the aeration. Thus, it is economical in any case to renew the membranes, before the specific demand on pressurised air increases.

Insufficient aeration control. Unnecessarily high oxygen concentrations in the aeration tank are linked with elevated energy consumption. Denitrification helps to keep the energy consumption of the aeration low, not only because nitrate can be used instead of oxygen for the degradation of carbonaceous matter, but also because the DO has to be kept reasonably low in the aerobic zones to make sure that the anoxic zones or phases are large enough. In any case, an adequate concept for aeration control is needed.

Excessive energy demand for mixing the aeration tank. Cascades of the aeration tank that are intended to be stirred have to be designed properly with respect to hydraulics. Then, stirring devices with low specific energy demand can be installed. Otherwise, a lot of energy has to be spent on stirring to prevent sedimentation of the activated sludge.

Additional treatment units. Every additional treatment step causes additional expenditure and an additional energy demand. At any rate, all designed electrical equipment should be checked for its energy demand before it is installed.

Measures to reduce the N:COD ratio in the influent
As presented above, the N:COD ratio of the raw wastewater has a major influence on the energy demand of a nutrient removal plant. The higher the N:COD ratio, the more energy
has to be taken from the grid. Moreover, at higher values for the N:COD ratio, the COD removal by primary sedimentation has to be reduced to meet the limit values for nitrogen removal. This causes additional energy demand. In view of this background, it should be considered to relate the energy consumption to the nitrogen load, as proposed by Balmér (2000). In any case, all measures to keep nitrogen from entering the biological treatment step not only help to decrease the effluent nitrogen load, but help to save energy.

Groundwater infiltration has to be avoided, as it is often linked with the entry of sizeable loads of nitrate into the sewer system. This is mostly denitrified within the sewerage, and therefore not measured in the influent of the treatment plant. But, it causes a reduction of the organic influent load. This is advantageous on the one hand, because the COD loading of the plant is reduced, but on the other hand the N:COD ratio increases. At any rate, nitrate from groundwater diminishes the extent of nitrogen removal and of EBPR.

A separate treatment process for the highly concentrated reject waters, like ammonia-stripping (Thorndahl, 1994), denitrification via nitrite (Wett et al., 1998), or the anammox process (van Dongen et al., 2001), may help to decrease the demand on organic matter for nitrogen removal to some extent. However, the capability of such a treatment step to reduce the overall expenditure has to be ascertained for each individual case. A separate management of urine, as proposed by Larsen and Gujer (1996), would reduce the N:COD ratio considerably, since urine contains more than 75% of the nitrogen load in domestic sewage. However, such a change in technology can only be achieved stepwise.

Conclusions
Nutrient removal from municipal wastewater in activated sludge plants is not necessarily linked with high energy consumption. Theoretical considerations as well as practical examples of Austrian WWTPs reveal that the demand on electricity of activated sludge plants equipped with anaerobic digesters for the aeration (of the aeration tank) is in the range of 9 to 13 kWh/(pe.a). For the other electrical equipment about 7 to 12 kWh/(pe.a) – depending on the head of the influent pumps – are required. Around 12 to 14 kWh/(pe.a) of electrical or mechanical energy can be obtained from digester gas. Accordingly, the minimum demand on external electric (and mechanical) power of nutrient removal plants is in the range of 5 to 10 kWh/(pe.a). To reach this range it is essential to pay attention to the energy consumption not only throughout plant operation, but also in the course of the design procedure to avoid unnecessarily high energy requirement later on.

The energy requirement of nutrient removal plants is strongly dependent on the N:COD ratio in the raw wastewater, due to the oxygen consumption for nitrification, and also because of the need for reduced COD removal by primary sedimentation in the case of a high N:COD ratio. Thus, a low N:COD ratio is not only advantageous in regard to nitrogen removal, but also with respect to a low energy demand. For a nutrient removal plant with an N:COD ratio of 0.10 in the influent, a minimum demand on external electric power of 9 kWh/(pe.a) can be deduced from theory, whereas for treatment plants with N:COD ratios of about 0.08 the energy requirement from the grid can be as low as 5 kWh/(pe.a). To prove this in practice, more energy-efficient WWTPs should be investigated. For the evaluation and verification of operational data, it is highly recommended to use mass balances like the COD balance, as presented here.

References


