Energy self-sufficiency as a feasible concept for wastewater treatment systems

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Cost issues at a microeconomic level and concerns about greenhouse gas emissions at a global level have become major driving forces towards a greater efficient usage of energy in wastewater treatment. This article describes Central European initiatives for operational optimisations, which came up with average energy saving potentials of about 30-50% for existing utilities.

In general, wastewater treatment systems are installed to reduce harmful emissions to receiving water bodies. So far, reductions of fossil energy consumption and greenhouse gas emissions to the atmosphere have been out of scope for wastewater utilities. Now Kyoto and subsequent protocols intend to impact these systems significantly by specific regulations and/or penalties associated with emissions of methane and nitrous oxide.

Any measures that impose mandatory limitations on the release of greenhouse gases (GHG) will also impact the operation of treatment facilities. Selection of treatment technology, process operation, post-processing and disposal of residual solids influence the GHG contribution of the wastewater treatment utilities.

Anaerobic digestion provides an onsite renewable energy source and is widely applied in sludge treatment in medium and large scale plants. The following work puts a focus on energy efficiency of this standard scheme of municipal wastewater treatment – biological nitrogen removal BNR and anaerobic sludge stabilisation. Wastewater treatment plants (WWTPs) are frequently ranked as the top individual energy consumers run by municipalities. Therefore energy consumption for wastewater treatment is a matter of concern on a microeconomic scale and potential savings need to be explored.

Potential in energy savings in WWTPs

Central Europe has several thousand state-of-the-art nutrient removal WWTPs, predominantly activated sludge systems. In 1994 the Swiss Ministry for Environment, Forest & Landscape published an Energy Manual for WWTPs. And in 1999 the most populous German state of North Rhine Westphalia followed suit with a rather similar Energy Manual (MURL, 1999). The declared objectives of these efforts are knowledge-transfer related to the use of energy at WWTPs, the definition of a standardised approach for energy optimisation, a reduction of operation cost and last but not least a reduction of CO_2 emissions. Hence in either case the Energy Manuals include (i) an elaborate manual describing the background of energy consumption at WWTPs, both with reference to electricity and to thermal energy; (ii) a clear strategy for the implementation of energy optimisation at WWTPs.

A two-stage approach has been suggested. The first stage represents a screening phase: Operation data is collected and a small number of key parameters are derived thereof. For instance, for large WWTPs, MURL (1999) targets electricity consumption according to Figure 1, a specific biogas yield of > 475 l/kg volatile dry solids entering sludge digestion, as well as self-sufficiency for electric and thermal energy of 90% and 99%, respectively. This is not yet complete energy self-sufficiency, but it clearly indicates that full self-sufficiency is not out of reach.

The findings of the screening stage often enable the definition of short-term optimisation measures, which typically do not even incur any investment cost. Finally, after screening a decision has to be taken on the need for a subsequent more detailed optimisation stage. In such a case there will be an in-depth analysis of each and every treatment stage and of all electro-mechanical installations. Both short-, medium- and long-term measures for energy optimization are defined and their respective economic viability is assessed.

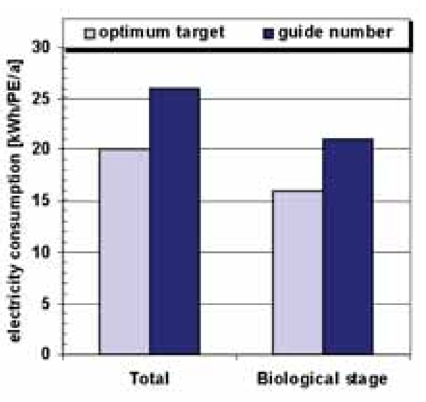


Figure 1. Targets for electricity consumption at WWTPs according to MURL (1999)

Now, after about ten years of practical application of these Manuals, a large number of WWTPs have undergone such energy optimisations. And the results are highly surprising:

Switzerland: Two thirds of all WWTPs in Switzerland have already undergone energy analysis. Because of that, energy cost has been reduced by an astounding average of 38% so far. 2/3 of this cost reduction is due to increased electricity production from biogas, 1/3 is due to "real" savings. Major efficiency increases were realised in the biological stage and with improved energy management. Current savings amount to 8 million EUR/annum. Over an investment life-span of 15 years this equals 120 million EUR.

Germany: So far 344 WWTPs in North Rhine Westphalia (NRW) have undergone energy analysis. And the findings indicate that energy cost can be reduced by an even higher margin than in Switzerland, that is by an average of 50%! Energy optimisation typically proves financially attractive for WWTPs, with potential savings being larger than the required investments. Extrapolation of findings in NRW leads to an overall savings potential in Germany equalling 3 to 4 billion EUR over 15 years.

Austria: A somewhat different path has been followed in Austria than in the two above-cited countries. Austria did not produce another Energy Manual, but

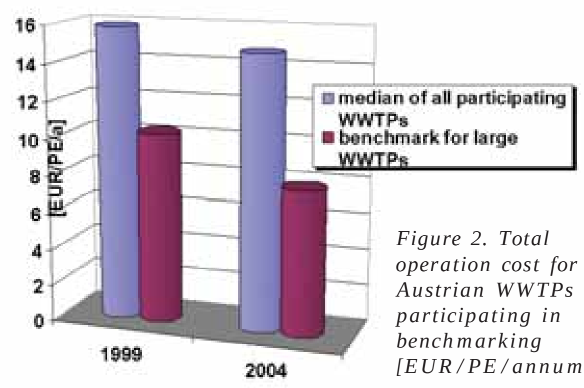


Figure 2. Total operation cost for Austrian WWTPs participating in benchmarking [EUR/PE/annum]

instead promoted benchmarking. That is, all existing WWTPs (about 950) with a total of about 20 million design PE were invited to take part in a benchmarking process, which annually compares individual cost figures with the overall national performance. Participation is voluntary and any individual data remains unknown to all other participants.

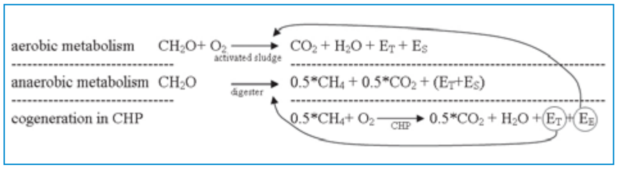
Thus a participating WWTP is informed just about its own data in comparison to the overall benchmarks, medians, etc. The first such benchmarks were developed for the year 1999 (LFUW, 2001), the latest publicly available data refers to the year 2004.

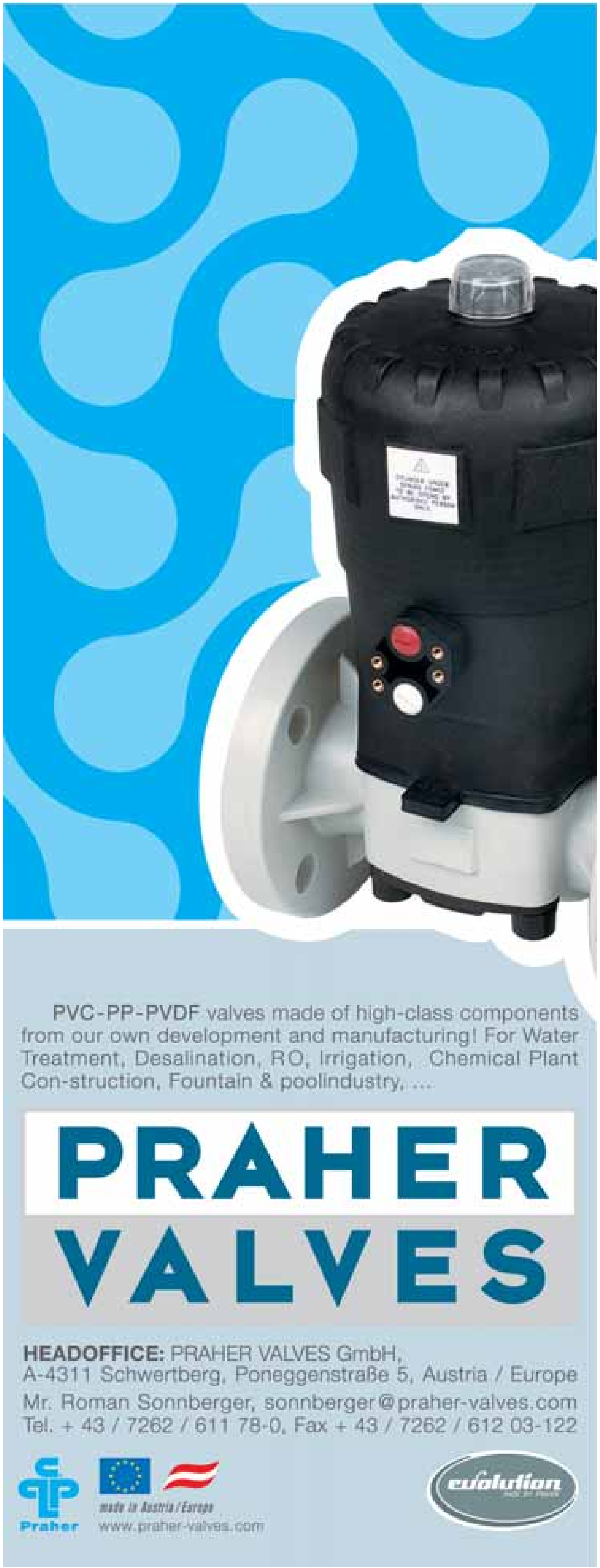
The comparison stimulates a kind of competition between WWTPs and the ambition to improve. For practical advice on possible energy optimisations, of course, the Swiss and German Energy Manuals could be used advantageously. Just how much key figures changed within this short five-year period is depicted in Figure 2. The presented total operation cost numbers include all kinds of operation cost, that is WWTP staff, administration, cost for third parties, chemicals and materials, disposal of sludge, sand and screenings, other cost and not least energy cost. Within that five-year period the relative contribution of energy cost to the benchmark has shrunk by about 30%, and thus constitutes the single most relevant factor for overall reduction of the operation cost benchmark. Consequently, the median of energy cost for large WWTPs has meanwhile fallen to about 1.0 EUR/PE/annum, with the best performing WWTPs already approaching zero energy cost.

In sum, well-run European WWTPs offer an astounding average energy saving potential of about 30-50% without the need to compromise on treatment efficiency. Hence, it would not be erroneous to assume that the worldwide existing energy saving potential at WWTPs is enormous. In the light of discussions about global warming and a need for reduced CO_2 emissions, wastewater treatment definitely is a sector where action is needed.

Energy balance of WWTPs

It is a known fact that the potential energy available in the raw wastewater influent exceeds the electricity requirements of the treatment process significantly. Energy captured in organics entering the plant can be related





to the COD load of the influent flow. Based on calorific measurements presented by Shizas and Bagley (2004) a capita specific energy input of 1760 kJ per PE in terms of 120 g COD of organic matter can be calculated. This specific organic load is subjected to aerobic and anaerobic degradation processes, partly releasing the captured energy. Three different categories of energy from carbo-hydrate degradation are differentiated – E_T thermal energy, E_S syntheses energy and E_E electricity.

Aerobic metabolism yields a large amount of energy which can hardly be put to good use. Syntheses energy generation means high excess sludge production and biogenic heat as a by-product of microbial growth is consumed for wastewater heating without significant impact due to high dilution. Anaerobic digestion generates much less syntheses energy – therefore minor biomass production – and less thermal energy, which shows more impact because of high concentrations in the solids train. A major part of the energy content remains captured in methane. This amount of energy is easily accessible for incineration technology and can be transformed by a coupled heat power plant CHP to both electrical and usable thermal energy. These energy products can be recycled to the origin of the process chain and on one hand drive the aeration system and on the other hand heat the digesters.

Obviously there are two treatment trains with different metabolism pathways and with different energy yields. The process engineering goal is a diversion of as much organics, i.e. energy, from the aerobic liquid train to the anaerobic solids train. Compliance with nutrient removal requirements remains the overriding objective, of course. In Figure 3 the main energy fluxes – separately for calorific and thermal energy – related to wastewater, sludge and biogas are displayed. The PE-specific calorific energy input to the plant of 1760 kJ/PE corresponds to 120 g COD/PE and the thermal energy flux of 14100 kJ/PE corresponds to 200 L/PE at 16.8 °C (see case study Strass). The specific biogas yield from mesophilic digestion is assumed to 26 L/PE (575 kJ/PE) and electrical cogeneration efficiency is 38%. The assumed biogas potential equals 33% of the influent calorific energy and electricity 12% of it. Significantly higher heat losses in calorific energy balance in the liquid train of about 22% compared to the digester (3%) underline difference in microbial synthesis.

METHODS

Already in the introductory section, energy values have been related to person equivalents PE in order to generate comparable performance figures. The same procedure applies to the operational data of WWTP Strass, a case study of an energy balance without relevant sources and demands of extra energy. The plant operators are much aware of measuring electricity consumptions of individual unit processes. Measured states of COD and nitrogen compounds have been analysed by means of the acknowledged biokinetic model ASM1 implemented in the SIMBA process simulator.

CASE STUDY WWTP STRASS

The municipal WWTP Strass provides a two stage biological treatment (A/B plant) to treat loads varying from 90000 to more than 200000 PE weekly averages depending on tourist seasons. In total, 31 communities are draining their sewage to this plant. The high loaded A-stage with intermediate clarification and a separate sludge cycle eliminates 55-65 % of the organic load. The A-stage is operated at half a day sludge retention time SRT, while in the B-stage the target SRT is about 10 days. N-elimination in the low loaded B-stage is oper-

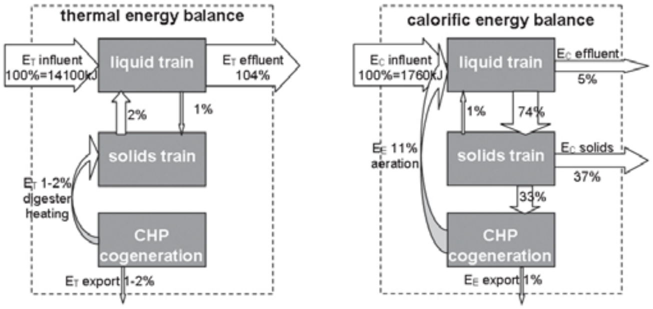


Figure 3. Flow scheme of the potential calorific and thermal energy content of wastewater in comparison with energy fluxes between the liquid train, the solids train and the CHP, respectively.

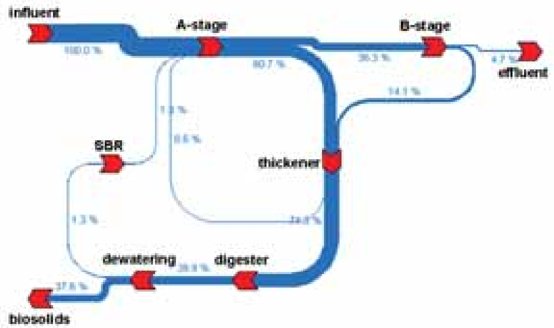


Figure 4. Simulated COD-balance of the WWTP Strass based on a 2 weeks measurement campaign in summer 2004 (average load 119866 PE_{120COD}; average flow 23771 m^3/d; Temperature 16.8°C).

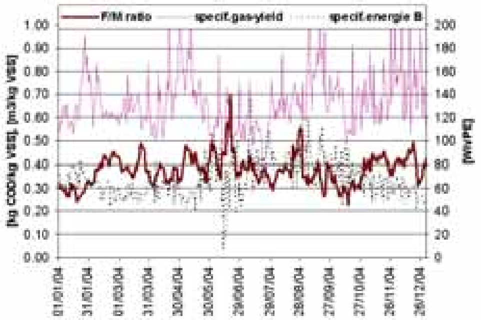


Figure 5. F/M ratio in [kg COD per kg aerobic VSS] is plotted against specific aeration energy demand and the biogas yield.

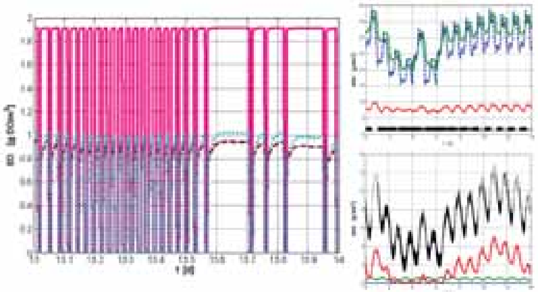


Figure 6. Simulated DO-profile during one day of on-line ammonia controlled intermittent aeration and dynamics in ammonia and nitrate concentrations during a 14 days run.

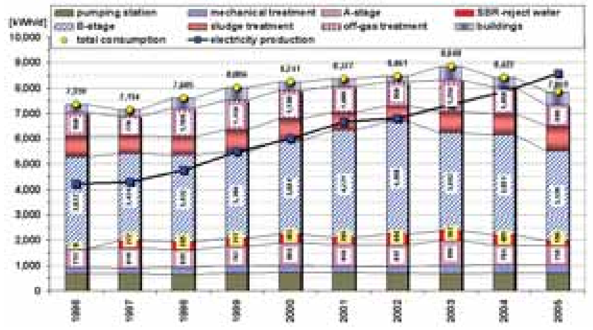


Figure 7. Energy demand of individual unit processes of the WWTP Strass.

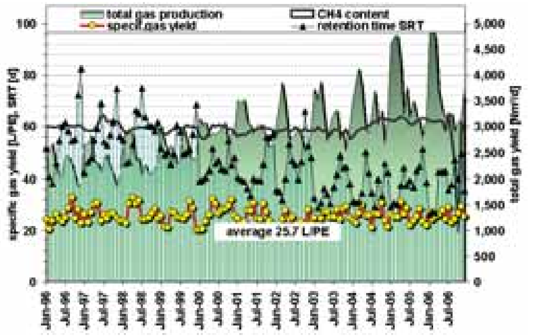


Figure 8. Specific biogas yield and methane content in correlation with retention time.

ated by pre-denitrification to achieve an annual N-removal efficiency of about 80 % at maximum ammonia effluent concentration of 5 mg/L. All activated sludge tanks can be aerated for maximum load flexibility of the system. Air-flow and aeration periods are controlled by on-line ammonia measurement. Figure 4 resumes the COD fluxes between the main subsystems of the treatment plant Strass.

Maximum transfer of organics to digesters

The biological 2-stage approach supports high-rate entrapment of organics without excessive aerobic stabilization. Within a hydraulic retention time 0.5 hours, organic compounds are removed mainly by adsorption and rapidly introduced to thickening and digestion. In the B-stage, a minimum SRT is required in order to establish a stabile population of nitrifying organisms. Aeration energy demand depends on F/M ratio, which again is governed by excess sludge flux to the digesters. Figure 5 depicts the correlation between increasing F/M ratio, decreasing energy demand for air supply and higher specific biogas yield (see fall 2004). F/M ratio obviously does not exhibit a stringent control pattern and the model predicts a saving potential of 3% in case minimum SRT depending on temperature is properly adjusted.

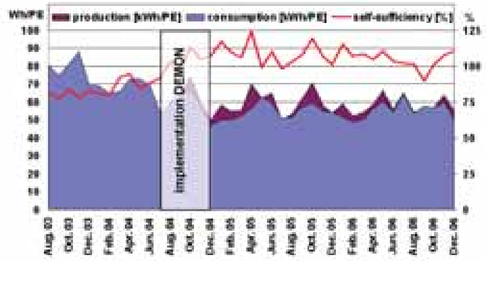


Figure 9. Percentage of plant-wide energy self-sufficiency as the difference of demand and production of electrical energy after implementation of deammonification

Intermittent aeration controlled by on-line effluent ammonia

Air supply needs to be governed by nitrification performance while heterotrophic growth should be predominantly based on nitrate reduction. That is why aerated reactor volume is stepwise increased on costs of denitrification volume depending on the actual load. Intermittent aeration is operated between two set-points of the on-line ammonia control strategy leading to extended aeration intervals in the afternoon (in Figure 6 DO of 2 mg/L in aeration zones of circulation tanks – partial depletion in-between). In case ammonia concentration continues to climb to the maximum threshold value, the complete denitrification volume gets aerated. Nitrogen profiles in Figure 6 indicate stable low ammonia (right top) and fluctuating nitrate in the effluent (right bottom).

High electrical efficiency from cogeneration

On average the electricity demand of the B-stage is still the biggest player representing 47% of the total consumption (Figure 7). Relatively high consumption rates for influent pumping (9%) and for off-gas treatment (13%) due to site constraints should be noted. The percentage of energy self-sufficiency was steadily improved starting from 49% in 1996 to 108% in 2005 by many individual measures. A big step forward in energy production was the installation of a new 8 cylinder CHP unit which provides power of 340 kW in 2001. The data in Figure 8 shows an increase in gas production due to higher load and corresponding reduction in digester's SRT, while the specific gas yield was maintained fairly constant. This high gas yield of about 26 L/PE is converted to electrical energy by the CHP unit at an average efficiency of 38%.

Energy savings from side-stream treatment

Probably the most significant individual optimisation step regards the side-stream treatment for filtrate from sludge dewatering. From 1997 to 2004 a SBR-strategy for nitritation/denitritation was operated and excess sludge of the A-stage served as a carbon source. Then the DEMON®-process for deammonification without any requirements of carbon was implemented. Higher portion of high-rate sludge in the feed to the digesters increased the methane content from about 59 to 62%. The total benefit in terms of savings in aeration energy and additional methane sums up to about 12% of the plant-wide energy balance.

CONCLUSIONS

Wastewater treatment facilities will increasingly claim their role as resources recovery plants instead of nutrient removal systems – recovery not only in terms of water and nutrients but also of energy. The presented experiences from Central Europe point towards large energy saving potentials of typically 30-50%, which are just gradually being exploited nowadays. What is feasible to reach in large-scale municipal WWTPs is underlined by the case study Strass, which already reached a positive energy balance without any relevant co-substrates. ***AW***

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