

Energy Sustainability and Nutrient Removal from Municipal Wastewater

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ABSTRACT

The state of energy sustainability in wastewater treatment and especially nutrient removal has improved rapidly with development of new technologies and increased concerns for the environment. The ultimate goal of the wastewater treatment industry could be achieving energy self-sufficiency within a facility. The progress that has been made toward this goal with nutrient removal technologies was investigated and the challenges and opportunities facing our industry are identified in this paper.

A benchmark for energy sustainability was recently achieved in Strass, Austria, where the energy usage of 1000 kwh/million gallons (MG) treated was achieved, which was actually less than the energy generated by digester gas, . This paper presents a comparison between the U.S. and Austria of potential energy use and generation, and offer approaches that could lead to similar U.S. success in the future.

The selection of technologies and their operation impact the sustainability of facilities in two ways; energy management and carbon management. On energy management, the current U.S. energy usage ranges between 600 and 2,600 kwh/MG treated when operated with internal carbon sources. When carbon is imported, the energy usage increases by approximately 600 kwh/MG treated or more, which needs to be either reduced or supplied from the outside sources. For the purpose of energy generation, , key factors include, in-plant generation of volatile fatty acids(VFA), increased biogas yield from both enhanced primary settling with chemical addition and conditioning of feed sludge and co-digestion, where feasible . For the purpose of energy conservation, key factors included ability to operate the swing zone, step feed mode of activated sludge , side-stream treatment of recycle loads, and automation with on-line sensors. A list of challenges and opportunities are suggested for reaching a long term goal of energy self-sufficiency.

KEYWORDS

Nutrient removal, energy, carbon , fermenter, step feed, side stream treatment, biological phosphorus removal, volatile fatty acids(VFA), biogas, anaerobic digestion

INTRODUCTION

One of the major challenges in municipal wastewater treatment plant is to reliably meet ever-tightening nitrogen and phosphorus nutrient limits in a sustainable manner. The reliability requirement is driven by the need to meet tight daily or weekly limits set so as to protect the designated uses of the receiving water. Planners, engineers, and operators at facilities faced with such a challenge have a wide and possibly confounding array of possible technologies to select from. To assist, the U.S. EPA commissioned Tetra Tech to prepare a manual outlining technologies that may be employed for nutrient removal at municipal wastewater treatment plants. The technical information includes detailed process descriptions and operating factors for over 40 different treatment technologies for removing nitrogen, phosphorus, or both from municipal wastewater streams. The information also includes data on process performance and reliability that was developed from full scale operating data obtained voluntarily from 30 wastewater treatment plants located throughout the United States and in Canada (U.S. EPA, 2008).

The difficulty with most nutrient removal technologies is that they typically involve some input of energy beyond what would normally be required for municipal wastewater treatment. In addition, biological removal of nitrogen or phosphorus often requires addition of a supplemental carbon source, such as methanol, ethanol, or volatile fatty acids (VFAs). Both the extra energy and extra chemicals increase the “carbon footprint” of the wastewater treatment process, as well as raising operating costs for the plant in terms of energy costs, chemical costs, and sludge disposal costs.

CARBON AND ENERGY REQUIREMENTS VS. ENERGY SELF-SUFFICIENCY

Nutrient removal requires both addition of a carbon source and additional energy compared with conventional removal of BOD. The traditional means for achieving biological removal of ammonia nitrogen and TKN from wastewater involves first nitrification of the nitrogen to nitrite then to nitrate. That nitrification takes place under aerobic conditions, mediated by nitrifying organisms that are favored by maintaining a long sludge age. The nitrate is then anoxically reduced to nitrogen gas by denitrifiers. In denitrification, the microorganisms assimilate nitrate as a terminal electron acceptor, with some source of carbon used as food. To reduce costs and provide a more “sustainable” process, the carbon ideally should come from the influent wastewater, either by maximizing what comes in the wastewater and other in-plant sources or by generating soluble organic matter (e.g., volatile fatty acids) via fermentation. Some process configurations result in the need to provide more “external” carbon sources than others. Methanol has traditionally been used as that carbon source, although alternatives that are potentially less hazardous to workers have been suggested (U.S. EPA, 2008). The cost

of any externally-supplied carbon should be included in any assessment of the sustainability of a process.

The biological removal of phosphorus involves accumulation of polyphosphate in phosphate accumulating organisms under aerobic conditions. Those organisms must first release phosphate under anaerobic conditions while being fed with organic material. Typically, the organic is in the influent or is a volatile fatty acid (VFA) that is either present in the plant influent and/or recycle flows, or generated on-site via fermentation of primary sludge or secondary sludge. Thus, fermenter-generated VFAs can be used to support both nitrogen and phosphorus removal. The more sustainable biological phosphorous removal processes will use entirely “internal” carbon sources.

The chemical removal of phosphorous involves precipitation with ferric ion (typically supplied as ferric chloride) or aluminum ion (typically supplied as alum, or aluminum sulfate). Both chemicals are externally supplied, and the cost of providing the chemicals as well as the energy involved in producing them should be included in any assessment of process sustainability. In addition, unlike processes where primary or secondary sludge is being fermented or digested, which results in net lower sludge production, chemical addition will increase sludge production, which thus increases disposal costs.

Energy generation potential from anaerobic digestion in the U.S. vs. Austria

The only significant source of energy generation at a treatment plant is biogas from anaerobic digestion, be that thermophilic or mesophilic or both thermophilic followed by mesophilic in series. Properly designed and operating digesters have the potential to generate a significant amount of the energy necessary for meeting the energy demands.

According to U.S. EPA(2007), there are 544 treatment plants with 4.5 MGD or greater average flow, of which 296 have anaerobic digesters. However, only 70 of the facilities utilize the resulting biogas for heating or power generation. If all 544 facilities were to install combined heat and power(CHP), approximately 340 mega-watts of clean electricity could be generated and offset 2.3 million tons of carbon dioxide emissions annually, assuming 600 BTU/cf of digester gas.

In Strass, Austria(Wett et all, 2007), the power generation from biogas has finally reached the level to match and now exceed all the plant demand after successful optimization of all energy use at approximately 1000 kWh/MG treated, as shown in Table 1. This is a remarkable achievement for sustainability, and an inspiration for all in the wastewater field.

Table 1. Power generation Potential from co-generation of Biogas from anaerobic digestion in the U.S. and Austria

Parameters	U.S.	Strass, Austria
COD, g/d/PE	168- 191	120
BOD5, g/d/PE	76.5	
Energy, KJ/d/PE	2464 - 2800	1760
Wastewater, gal/d/PE	100	52.6
Gas from digestion, l/d/PE	28.3	26
Gas, KJ/d/PE	633	575
Gas, watt-hr	175	159
Power generation, watt-hr/d/PE at 34% efficiency	59.4	54.0
Power generation, kwh/MG	594	1027

In the U.S., it appears that the net power generation potential is similar to that of the case in Strass, Austria on the PE basis, or 59.4 vs. 54 watt-hr/day/person equivalent(PE). This is sufficient to meet the secondary treatment process needs but would require drastic changes in the current approach to meet the advanced level of treatment in the U.S. This paper summarizes current practice for energy in nutrient removal facilities and presents key factors that could contribute to improvements in energy efficiency and ultimately energy self sufficiency in the future.

Energy Usage- current practices

The operating and costs parameters for five facilities accomplishing nutrient removal were analyzed. The facilities employed a 5-stage Bardenpho™ process, a 3-Stage Westbank™ process, a phased isolation ditch, a 3-stage activated sludge system, and activated sludge followed by a denitrification filter. The parameters are presented in Table 2.

Table 2: Energy Usage for Nutrient Removal at Five Case Study Facilities

Name	5 stage Bardenpho	3-stage Westbank	Phased Isolation Ditch	3 Stage AS	AS with Denitrification Filter
Design Flow	10	10.5	12	30	7
Actual flow (mgd)	5.5	8.5	7	23	4.1
Annual Average effluent N (mg/L)	2.3	4.6	3.5	1.7	2.14
Annual Average effluent P w/alum	0.2 w/alum	0.2	0.4	0.47 w/alum	0.27 w/alum

(mg/L)					
Number of anoxic zones	2	1	1	1	1 (filter)
Total HRT (hr)	20	15	2	14.2	20.7
SRT (days)	25	10	12	72.5 (3 sludges)	8.1
Temperature (deg C)	23-31	13-22	16-27	18.2	20.4
Fementer?	No	Yes	No	No	No
Post-secondary filtration?	Yes	Yes	Yes	No	Yes
Swing zones with dual mixers and aerators?	No	Yes	Yes	No	No
Methanol feed?	No	No	No	Yes	Yes
Elec. Use, kW-hr/mg treated	2090	2050	670	2300	2583
Elec cost/mg treated @ \$0.08/kW-hr	\$306	\$203	\$92	\$240	\$351
Methanol feed, gal/day	0	0	0	1165	83.1
Methanol cost/mg treated @ \$1/gal	0	0	0	\$51	\$20
Total Energy + Chemical cost	\$306	\$203	\$92	\$291	\$371
Methanol feed equiv kW-hr/day @ 18.9 kW-hr/gal	0	0	0	21,979	1570
Total Energy input, kW-hr/mg treated	2,090	2,050	670	3,256	2,965
Methanol production energy, kW-hr/day @ 11.5 kW-hr/gal	0	0	0	13,400	956
Energy “footprint”, kW-hr/mg treated	2090	2050	670	3,839	3,198

All the processes provided very good nitrogen removal, as shown by the effluent total nitrogen concentrations ranging from 1.7 to 4.6 mg/L. Significant differences in energy usage are shown, with the usage inversely related to the target nitrogen concentration. The lowest nitrogen concentrations were achieved with an external carbon source, which was methanol in both cases. The other facilities obtained excellent nitrogen removal using internal carbon sources, with the lowest nitrogen concentration obtained from the phased isolation ditch which alternated aeration and anoxic zones, followed by the 5-stage Bardenpho process and step aeration.

The base electrical costs for the facilities depended on the process, ranging from a low of \$92/million gallons treated for a phase isolation ditch system using surface aerators, to a high of \$351 for operation of an activated sludge system. The use of methanol is also nominally inexpensive, adding only \$20 to \$50 per million gallons treated to the cost.

However, methanol adds a substantial amount to the “energy footprint” of the treatment process. In the case with the larger methanol dose, while the electricity use was 2300 kW-hr/million gallons, the energy included in the added methanol accounts for an additional 956 kW-hr/million gallons, while the energy assumed to produce the methanol via a syn-gas process added 583 kW-hr/million gallons, for a total additional energy input of 1539 kW-hr/million gallons treated. This calculation is based on methanol’s energy content of 22.7 MJ/kg, and the energy used to produce methanol via the syn-gas process being 13.8 MJ/kg (Atkins). By contrast, processes that use step feed or other strategies to use influent carbon rather than methanol were much more sustainable on energy, with the phase isolation ditch using less energy than the 3-stage system, which was less than the energy for the 5-stage Bardenpho.

Challenges to the future energy sustainability include development of additional sources of energy, while minimizing energy consumption at existing facilities through some radical change in approaches. Details are shown below in two areas; energy generation and energy conservation.

DESIGN FACTORS FOR ENERGY GENERATION

Carbon Requirements and Generation in Fermenter

Additional carbon is required for both nitrogen removal and biological phosphorus removal. To meet the carbon requirement, the lowest cost and most sustainable alternative is use of energy present influent (BOD, TSS and others). The next most sustainable alternative is generating additional soluble carbon internally via fermentation. The fermentation process generated volatile fatty acids (VFAs), which are ideal for supporting biological phosphorus removal, and also are an effective substitute for methanol for supporting denitrification. If influent BOD is used, the ratio of readily biodegradable COD to phosphorus should be greater than 15, while if VFAs are used, the desired VFA to phosphorus ratio is typically reported to be greater than 3. For nitrogen removal, the desired readily biodegradable COD dose is 6.6 mg per mg N or greater (U.S. EPA, 2008).

Potential sources of fermentable solids include primary sludge, MLSS from a anaerobic/anoxic zone or return activated sludge(RAS). The maximum amount of fermentation product that can be produced are in the range of 10 to 30% of the wastewater influent COD (Banister and Pretrorius, 1998; Moser-Engler et al., 1998). The VFA from fermenters were reported to be 0.15 g VFA / g VSS from primary sludge (Banister, 1998 and Moser-Engler in 1998 and 1999). Others estimated up to 0.2 lb VFA/lb VSS (Johnson and Kresge, 2003). Tremblay et. al. (2005) reported VFA production from MLSS obtained from the anaerobic zone of a UCT process as a function of SRTs; the production ranged between 0.05 and 0.14 lb/lb of VSS, with optimal production obtained at 2.5 days of SRT.

Table 3 presents the results of using fermenter-generated VFAs at three facilities. All facilities are in northern climates. The facilities either used a designed fermenter, or retrofitted primary gravity thickeners. SRT for the fermenters ranged from 5 to 8 days.

In the case of the single stage fermenter with year round operation, the anaerobic sludge fermenter treating primary sludge produced annual average VFA concentration of 202 mg/l and soluble COD of 547 mg/l in 2005, which are equivalent to 8.8 mg/l in VFA and 22.7 mg/l in soluble COD in the influent to bioreactor. The fermenter was operated at an average solids concentration of 6.1% at the SRT of 4.3 days. Actual SRT varied between 2.7 days in the summer and 5.8 days during the winter month. Ammonia N and soluble phosphorus in the supernatant were low at 19 mg/l and 7 mg/l.

Table 3: Fermentation Results at Three Full Scale Facilities

Plant	Two-stage fermenter, year-round operation	Single stage fermenter, year-round operation	Single stage fermenter, summer operation only
Average plant flow	3	8.5	28
VFA generation rate, mg/l fermenter feed	200 (winter)-450 (summer)	200	400
VFA generation rate mg/l influent	18 (20 C), 13 (13 C)	10	10
Influent P	4.11	6	5.0
Effluent P	0.12	0.14	0.3
VFA : TP	1.5 - 6	1 - 2	4

In all cases, the fermenters have shown significant production of carbon source that helped meet the process needs, while reducing the carbon foot print at these facilities. The net savings are estimated as 2200 kwh/MG treated.

Overall, VFAs obtained by fermentation are a more “sustainable” source of carbon than use of external sources. This is reflected in the following comparison (Gaulke, 2004):

VFA : Yield 0.6 for production from sludge; 1.06 g COD/g VFA; \$0.04 /Kg
Methanol : Yield = 0.3;1.5 g COD/g methanol;\$0.33/Kg
Acetate : yield 0.6;1.06 g COD/g acetate; \$0.80/Kg

Chemical addition to Primary sedimentation

It has been practiced many years with either ferric chloride or alum with two objectives; to increase biogas generation potential in the anaerobic digesters, and at the same time, to reduce the organic loading to the activated sludge thus energy requirements. The enhanced primary clarification has shown 35% reduction in BOD and 55% or higher removal of TSS in the primary clarifiers.

Solids conditioning to increase gas yield from anaerobic digestion

Typically, good operating anaerobic digesters breakdown volatile solids in the range of 35 to 40% with the remaining biosolids viewed as a disposal problem instead of a renewable energy source. The limiting step for anaerobic digestion is difficulty of breaching the cellular membrane in the sludge. New technologies have been advanced in recent years, including a mechanical cell lysis processes and the electrical focused pulse system(FP) with a 60% increase in gas production (Rittman et. al, 2008). The same technology was reported to have generated a replacement carbon source for denitrification Alder et. al (2009) in one demonstration. .

Co-generation

Since the domestic component of the wastewater in the U.S. lack the necessary energy content, this becomes an important alternate source where feasible. The brown grease has been a known source , along with other commercial and agricultural wastes, i.e., dairy wastes. This additional gas production from co-digestion is site specific, however and should be custom tailored.

DESIGN FACTORS FOR ENERGY CONSERVATION

Step Feed Activated Sludge

The Step feed activated sludge process is a desirable mode of operation for nutrient removal , due mainly to its ability to provide “good carbon” to both anaerobic or anoxic zones. By distributing the carbon, the biological reaction rate in all zones increase, which allows the zones to be smaller than would be the case without step feed. This applies to both nitrogen removal as well as phosphorus removal.

For example, by converting to the step feed mode and operation of a fermenter, the size of the anoxic zone was reduced approximately by 30% in Kelowna, BC (U.S. EPA, 2008).

Swing zones

Swing zones provide reliability for permit compliance as well as energy savings. Swing zones are equipped with both mechanical mixers as well as aeration devices in the same designated zone, in anticipation of future changes in the wastewater characteristics as well as of energy savings in normal operation. The size of the swing zone can vary between 10 to 30 % of the biological reactor. With on-line sensors (ammonia N and dissolved oxygen), the aeration devices can be turned off in a swing zone, during which only the mixers are turned on at a significant savings from not running the aeration devices.

Side Stream Flow Storage and/or Treatment of Recycle Loads – biological and non-biological processes

Side stream treatment consists of using biological and non-biological processes to treat recycle streams, with the goal of providing reliability for permit compliance as well as saving energy costs. This is typically economical at large facilities with large recycle loads from the biosolids processes that may treat not only its own sludge but also some sludge from other facilities in the same municipality.

Typical options employed include:

- biological nitrifying reactors- In-Nitri[®], biological aerated filter(BAF)
- Chemical feed – alum, lime or ferric chloride
- combined nitrification and denitrification – SHARON[®], Anammox[®], CANON[®]
- Physical-chemical processes- ammonia stripping, steam stripping, ammonia recovery process(ARP), generation of magamp(magnesium ammonium phosphate), breakpoint chlorination
- Flow equalization basin

Energy savings with sidestream processes are achieved in several ways. These include:

- reduced aeration and mixing requirements in the main plant, e.g., by reduced loads of ammonia N in the case of physical-chemical processes, such as particular stripping and ARP. This load reduction is equivalent to 80 - 90 % of the recycle loads.
- the SHARON, DEMON, and Anammox processes reduce the aeration requirement by 25% or more.
- Flow equalization reduces the peak demand for power, and thus helps energy savings by reducing the plant wide peak demand.

The final decision for use of sidestream processes depends upon the site-specific evaluation of the overall reliability for permit compliance, energy usage and operation. At the LOTT plant in Olympia, Washington, the final decision included construction of a fermenter for internal carbon generation, while sidestream treatment was not selected (Gaulke, 2004). In Strass, Austria, the DEMON process was built to treat the recycle loads from anaerobic digester and reduced energy costs significantly compared to nitrification/denitrification (Wett, 2009).

On-line sensors and automatic controls & SCADA

Advancements in sensor technologies and the control devices have enabled significant cost savings in energy in recent years. On-line sensors include improved dissolved oxygen, ammonia, nitrate, phosphate and ORP. Many effective control strategies have been developed and implemented successfully in both nitrogen and phosphorus removal. Monitoring parameters include D.O., nitrate-N, ammonia-N and ORP at select locations, which in turn are used in accordance with the established control logic to control blowers or mixers and thereby enable energy savings. SCADA with multiple sensors are used as a preference in large facility, while simple D.O.-based controls are used effectively at smaller facilities.

CONCLUSION

Sustainability depends on design and operational factors in carbon source management and energy optimization. On energy management, the current energy usage ranged between 600 and 2100 kwh/MG treated without external carbon sources. With methanol, additional energy usage increased by 600 kwh/MG treated or more. The selection of technologies and their operational factors had been focused on achieving the target limit with sufficient reliability.

New focus has been placed on reaching energy sufficiency in the long term.

The energy potential from the influent wastewater was favorably compared to that of Strass, Austria, at 59.4 vs. 54. watt-hour/day per person

The electricity generation potential however, was 594 in the U.S. vs. 1027 kwh/d/MG in Strass, Austria.

The energy usage at certain plants in the U.S. providing a state of the art nutrient removal ranged between 600 and 2,600 kwh/MG treated, thereby showing a shortfall of energy significantly at some facilities.

This shortfall, or gap needs to be removed in order to reach energy self-sufficiency and the following factors are identified and offered for energy sustainability.

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For maximum energy generation, considerations should be given to:

- chemical addition to primary sedimentation
- fermenters for in-plant carbon generation, for both N and/or P removal. This VFA from fermenter contributed up to 35% of the carbon needed at a facility and thus eliminated the need to import external carbon
- conditioning of sludge for improved gas yield
- co-digestion

For energy efficiency and conservation, consideration should be given to :

- flexible design with swing zones with both mixers and aeration devices for energy efficiency
- step aeration mode of activated sludge to reduce the reactor size and thus, allow energy efficiency
- on-line sensors and automation for efficient control of aeration devices and mixers ensures energy savings
- side stream treatment of recycle flows, where appropriate, through biological or physical-chemical processes, and
- flow equalization for recycle flows

Sustainability is enabled by installing an efficient anaerobic digester system for generation of biogas, while maximizing energy efficiency and conservation.. This is a remarkable milestone of sustainability and a challenge for the rest of the world to meet and succeed.

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