Analysis of routes for energy recovery and efficiency improvement at municipal Wastewater Treatment Plants

PROJECT REPORT

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Table of content

Abstract

Energy use for wastewater treatment is typically among the major contributors to the total energy use faced by urban water and wastewater utilities. However, substantial energy and financial savings can be uncovered through operational changes and capital investments at wastewater treatment plants. This report presents examples of energy efficiency improvements at different WWTPs in Europe. It covers important issues as benefits of energy efficiency at WWTPs as well as basic strategy steps that should be taken by managers to successfully implement changes leading to higher energy efficiency at the plant.

1. Introduction

A significant amount of municipal energy use occurs at wastewater treatment facilities. With pumps, motors, blowers and other equipment operating 24 hours a day, seven days a week, wastewater facilities can be among the largest consumers of energy in a municipality and thus among the major contributors to the municipality’s total GHG emissions. These economic and environmental costs can be reduced by improving the energy efficiency of wastewater treatment plants by selecting energy efficient processes and less energy consuming equipment and operations. This can be achieved by capturing the energy in wastewater to generate electricity and heat or/and by the reduction of the energy consumption of processes and equipment. Increased energy production at wastewater treatment plants by burning biogas from anaerobic digesters in a combined heat and power system and capturing heat from plant effluents by heat pumps allows wastewater facilities to produce some or all of their own electricity and space heating, turning them into “net zero” consumers of energy.
The potential energy stored within different wastewaters is variable, ranging from 4.92 to 7.97 kWh kg COD^{-1}, which exceeds the energy requirement of its treatment (Heidrich et al., 2011).
Considering that the fact that energy consumption represents a substantial cost to the wastewater utilities, it is essential to periodically conduct energy verifications (audits) and realize some changes in operations and infrastructure that can lead to energy savings. The cost of energy can represent the main item of operating expenditures at WWTPs (Guerrini et al., 2017).
According to The European Benchmarking Co-operation (2016) the median electricity consumption for wastewater treatment was 33.4 kWh/p.e.. A WssTP (2011) report presents energy consumption values in Europe for wastewater treatment by the activated sludge process of 0.15-0.7 kWh/m^3. The average energy consumption for Germany, the UK, the Netherlands, and the United States is 0.67, 0.64, 0.47 and 0.45 kWh/m^3, respectively, and for Italy a consumption between 0.40 and 0.70 kWh/m^3 was measured, depending on the type of plant (Global Water Research Coalition, 2010; Cantwell et al, 2010).

This study describes a strategy, which implemented by managers and operators, may significantly reduce energy consumption at WWTPs. It identifies opportunities at different steps of a WWTP with the focus on the main technology line (primary, secondary and tertiary treatment) to help achieve gradual improvements in energy efficiency mainly through optimisation of existing process operations.

2. Strategy for energy improvements at WWTPs

Continuous improvement of energy performance requires establishing effective energy management practices and processes to support the energy program. Any organization, regardless of size, function, or mission can develop an effective energy program if they are willing to make the commitment.
These guidelines for energy management can assist the organization in improving its energy and economic performance.

STEP 1: Commitment to energy efficiency improvement
No matter the size or type of organization, the common element of successful energy management is commitment. Organizations seeing the economic returns from better energy management continuously strive to improve their energy performance. Their success is based on regular assessment of plant energy performance and implementation of steps to increase energy efficiency.
In order to establish an energy program, managers should form a dedicated energy team with its leader and institute an energy policy.

Leader key duties can include:
• Coordinating and directing the overall energy program

• Increasing the visibility of energy management within the organization
• Drafting an Energy Policy
• Assessing the potential value of improved energy management
• Creating and leading the Energy Team
• Securing sufficient resources to implement strategic energy management
• Ensuring accountability and commitment from core parts of the organization
• Identifying opportunities for improvement and ensuring implementation (including staff training)
• Measuring, tracking, evaluating, and communicating results
• Obtaining recognition for achievements

The Energy Team should execute energy management activities across different parts of the organization and ensure integration of best practices. In addition to planning and implementing specific improvements, the team should measure and track energy performance and communicate with management, employees and other stakeholders.

STEP 1 also includes the institution of an Energy Policy which provides the foundation for successful energy management. It should articulate the organization's commitment to energy efficiency for employees, shareholders, the community and other stakeholders.

The Energy Policy should:
• Set an objective — have a clear, measurable objective that reflects the organization's commitment, culture and priorities.
• Establish accountability — institute a chain-of-command, define roles in the organization, and provide the authority for personnel to implement the energy management plan.
• Ensure continuous improvement — Include provisions for evaluating and updating the policy to reflect changing needs and priorities.
• Promote goals — provide a context for setting performance goals by linking energy goals to overall financial and environmental goals of the organization.

<u>STEP 2: Assessment of plant energy performance</u>
Understanding current and past energy use is important to identify opportunities for improved energy performance and gaining financial benefits.
Identify activities and operations that consume the most energy or are inefficient. The Energy Team and facility operators can use information from the energy audit to identify the most energy-intensive and/or inefficient activities and operations in the facility. This step may require comparisons with the rated efficiency listed on equipment nameplates, or comparisons with similar models of equipment to get an idea of typical energy consumption.
Assessing performance is the periodic process of evaluating energy use for all major facilities and functions in the organization and establishing a baseline for measuring future results of efficiency efforts.

Evaluating energy performance requires good information on how, when, and where energy is being used. Collecting and tracking this information is necessary for establishing baselines and managing energy use.
Analyzing data to determine energy use trends can help an organization gain a better understanding of the factors that affect energy performance and identify steps for reducing energy consumption.
Energy audits are comprehensive reviews conducted by energy professionals and/or engineers that evaluate the actual performance of a facility's systems and equipment against their designed performance level or against best available technology. The difference between these is the potential for energy savings.

The main steps for conducting technical assessments and audits are:
- assemble an expert team
- plan and develop a strategy

- create a final report

There are a variety of ways data can be analyzed depending upon the needs of the organization Key aspects include:

- Data Collection and Management
  - Gather and track data — collect energy use information and document data over time.
- Baselining and Benchmarking
  - Establish baselines — determine the starting point from which to measure progress.
  - Benchmark — compare the energy performance of your facilities to each other, peers and competitors, and over time to prioritize which facilities to focus on for improvements.
- Analysis and Evaluation
  - Analyze — understand your energy use patterns and trends.
  - Technical assessments and audits — Evaluate the operating performance of facility systems and equipment to determine improvement potential.

Assessing energy performance help to:
- Categorize current energy use by fuel type, operating division, facility, product line, etc.
- Identify high performing facilities for recognition and replicable practices.
- Prioritize poor performing facilities for immediate improvement.
- Understand the contribution of energy expenditures to operating costs.
- Develop a historical perspective and context for future actions and decisions.
- Establish reference points for measuring and rewarding good performance.

<u>STEP 3: Set a target</u>

Based on results of energy assessments and audits, the Energy Team should identify, evaluate, and prioritize potential energy improvement projects and activities. The team can make a list of all projects that could be implemented to increase energy efficiency. These projects may involve operational changes or equipment modernization (e.g., replacing a pump).

Performance targets drive energy management activities and promote continuous improvement. Setting clear and measurable goals is critical for understanding intended results, developing effective strategies, and achieving economic benefits.

Well-stated goals support daily decision-making and are the basis for tracking and measuring progress. Communicating and setting goals can motivate staff to support energy management efforts throughout the organization.

To develop effective performance goals:

- determine scope — identify organizational and time parameters for goals.
- estimate potential for improvement — review baselines, benchmark to determine the potential and order of upgrades, and conduct technical assessments and audits.
  Examples of criteria that could be used in priority ranking include: capital costs, maintenance costs, potential for energy reduction, maintenance required, existing need for equipment upgrade, return on investment, regulatory requirement, ease of implementation.
- establish goals — create and express clear, measurable goals, with target dates, for the entire organization, facilities, and other units.
  Setting goals helps to:
  - set the tone for improvement throughout the organization
  - measure the success of the energy management program
  - help the Energy Team to identify progress and setbacks at a facility level
  - create a sense of purpose, and motivate staff
  - demonstrate commitment to reducing environmental impacts
  - create schedules for upgrade activities and identify milestones

- estimate potential for improvement to set goals- it is important to have an informed idea of what level of performance is achievable and the amount of resources needed.
  There are a variety ways to determine potential. The method to choose will depend on a number of factors, such as: available resources, time, the nature of energy use at your facilities, and how the energy program is organized.
  Methods used by leading energy programs include:
  - ✓ Reviewing performance data - assessing performance and setting baselines should help to identify differences in energy use between similar facilities, giving a limited, point-in-time, view of your potential improvement. Performance data spanning a longer period of time will be more useful for understanding improvement potential.
  - ✓ Benchmarking - Benchmarking provides a yard stick for evaluating opportunity when enough data is available to show trends in energy use.
  - ✓ Evaluating past projects and best practices - evaluate past projects and best practices at higher performing facilities to determine the feasibility of transferring these practices to other parts of the organization.
  - ✓ Reviewing technical assessments and audits - identify opportunities to reduce energy use identified during technical assessments and audits of poorer performing facilities to serve as a strong basis for quantifying the potential for improvement.
  - ✓ Comparing goals of similar organizations - reviewing performance goals of other organizations can help to guide and inform you of the potential for your own organization.
  - ✓ Linking to organization-wide strategic goals - strategic as well as operational goals, such as cost reductions, can also help inform the goal setting process.

STEP 4: Create Action Plan

Successful organizations use a detailed action plan to ensure a systematic process to implement energy performance measures. Unlike the energy policy, the action plan is regularly updated, most often on an annual basis, to reflect recent achievements, changes in performance, and shifting priorities.
While the scope and scale of the action plan is often dependent on the organization, the steps below outline a basic starting point for creating a plan:

- Define technical steps and targets
  - Create performance targets - for each facility, department, and operation of the organization to track progress towards achieving goals.
  - Set timelines - for actions, including regular meetings among key personnel to evaluate progress, completion dates, milestones and expected outcomes.
  - Establish a tracking system - Create a system to track and monitor the progress of action items. This system should track and measure energy use and project/program activities.
- Determine roles and resources

Work with the Energy Team to communicate the action plan to all areas of the organization.
Identify internal roles. Determine who should be involved and what their responsibilities will be.

STEP 5: Implement Action Plan

Gaining the support and cooperation of key people at different levels within the organization is an important factor for successful action plan implementation in many organizations. In addition, reaching the goals frequently depends on the awareness, commitment, and capability of the people who will implement the projects.
To implement action plan, the following steps should be considered:

- Creation of a communication plan — develop targeted information for key audiences about your energy management program.
- Raising awareness — build support at all levels of your organization for energy management initiatives and goals.

Most people are unaware of how their everyday actions and activities at home and work affect energy use and impact the environment. Increasing overall awareness can be an effective way to gain greater support for energy initiatives.

- Building of capacity — one can expand the capacity of its staff through providing training, access to information, sharing of successful practices, procedures and technologies, and sharing of lessons learned. Investing in training and systems to share successful practices helps ensure the success of the action plan by building the overall organizational capacity. Many organizations have found that informed employees are more likely to contribute ideas, operate equipment properly, and follow procedures, helping to guarantee that capital investments in energy improvements will realize their potential.
- Motivate — incentives should be created to encourage staff to improve energy performance to achieve goals. Offering incentives for energy management is one way many organizations create interest in energy initiatives and foster a sense of ownership among employees. Examples of how organizations motivate staff and employees include:
  -Internal competition — use tracking sheets, scorecards, etc. to compare performance of similar facilities and foster a sense of competition.
  -Recognition — Highlight and reward accomplishments of individuals, departments, and facilities.
  -Financial bonus and prizes — Offer cash bonuses and other rewards if goals are met.
  -Environmental responsibility — Use environmental messages to promote a sense of environmental and social responsibility.
  -Financial responsibility — Use financial messages to promote a sense of fiduciary responsibility.
  -Performance standards — Tie employee performance standards to energy goals
- Track and monitor — Use the tracking system developed as a part of the action plan to track and monitor progress regularly. A tracking system is the means by which an energy program's activities are monitored. The system should be centralized and available for all to use in gauging progress toward established targets, milestones, and deadlines. Maintaining a tracking system enables you to assess necessary steps, corrective actions, and identify successes. Periodic review of the activities outlined in the action plan is critical to meet energy performance goals. In order to track and monitor: perform regular updates, conduct periodic review, identify necessary corrective actions.

STEP 6: Evaluate Progress

Evaluating progress includes formal review of both energy use data and the activities carried out as part of the action plan as compared to performance goals. Evaluation results and information gathered during the formal review process is used by many organizations to create new action plans, identify best practices, and set new performance goals.
Key steps involved include:

- Measure results – Comparison of current performance to established goals.
- Review action plan – Understanding of what worked well and what didn't in order to identify best practices.

Regular evaluation of energy performance and the effectiveness of energy management initiatives allow energy managers to:

measure the effectiveness of projects and programs implemented,
make informed decisions about future energy projects,
reward individuals and teams for accomplishments,
document additional savings opportunities as well as non-quantifiable benefits that can be leveraged for future initiatives.

STEP 7: Recognize Achievements

- Providing and seeking recognition for energy management achievements is a proven step for sustaining momentum and support for energy improvement programs.
- Providing recognition to those who helped the organization achieve these results motivates staff and employees and brings positive exposure to the energy management program.

- Receiving recognition from outside sources validates the importance of the energy management program to both internal and external stakeholders, and provides positive exposure for the organization as a whole.
- Key steps in providing and gaining recognition include:
  - Providing internal recognition — to individuals, teams, and facilities within your organization.
  - Receiving external recognition — from government agencies, the media, and other third party organizations that reward achievement.

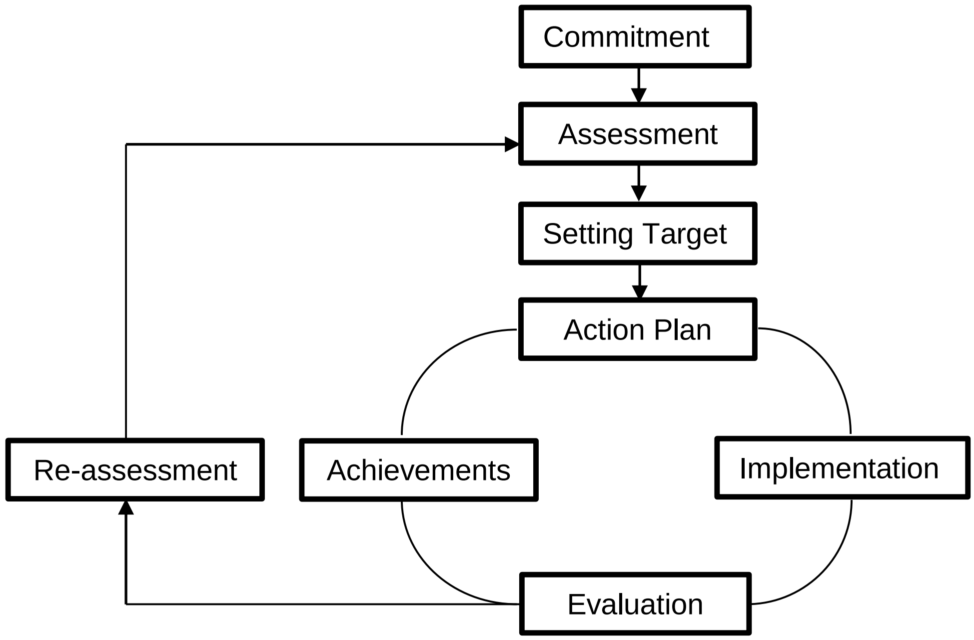


Figure 1. Guidelines for energy management strategy

3. Energy recovery

Energy recovery is not a core of the current report but due to the fact that it is an important aspect of energy efficiency at WWTPs, it is shortly described.

3.1. Biogas production

Anaerobic digestion (AD) is a well-developed and robust technology for energy recovery from sewage sludge. AD is a series of biological processes (hydrolysis, acidogenesis, acetogenesis and methanogenesis) in which microorganisms break down biodegradable material in the absence of oxygen. The two principal products of anaerobic digestion are digestate and biogas, which contains 60-70 percent CH_4 by volume, 20 to 30 percent CO_2, and small amount of N_2, H_2, H_2S, water vapor and other gases. The biogas produced in a digester is the main energy source in WWTP. Biogas at 65% methane content has the energy potential of 6.5kWh/m^3.
Wastewater treatment plants with sludge digestion consume about 40% less net energy than WWTPs without anaerobic digestion. Gas production can fluctuate over a wide range, depending on the volatile solids concentration in feed, biological activity in the bioreactor as well as on operation parameters. Typical values of biogas production vary from 0.75 to 1.12 m^3/kg of volatile solid destroyed, while the low heating value of biogas is approximately 22,4 kJ/m^3. The biogas can be used for heating and/or electricity generation. Combined Heat and Power (CHP) technologies which generate both electricity and heat from biogas at the same time is the most adopted technology in the existing self-sufficient WWTPs.

There is a strong evidence that up to about 15% of wastewater energy demand can be offset by biogas generation and CHP, and this may be higher where existing levels of take-up are low (Brandt et al., 2010).
Enhancement of anaerobic digestion efficiency is a common practice to increase the energy self-sufficiency of WWTPs. The optimizations of AD include pretreatments of sewage sludge aiming to higher biodegradability of sludge. Based on the lysis system employed, sewage sludge pretreatment methods can be divided in mechanical, thermal, chemical and biological as well as different combination of them. The most common technologies available on the market are mechanical and thermal pretreatments. Thermal hydrolysis (THP) technologies like Cambi, Biothelys, Exelys are the most spread technologies used to improve anaerobic digestion in WWTPs. For example, in the first WWTP in North America which applied CAMBI technology (Washington DC, USA), a 50 % higher biogas production in a shorter HRT (12-15 days) was observed.
Another option is co-digestion of sewage sludge with other biodegradable waste which provides a range of economic and environmental benefits. Co-digestion of organic waste in combination with municipal wastewater sludge does not only allow WWTPs to be energy-neutral but also reduce the cost of municipal and industrial organic waste management. Co-digestion of sewage sludge with six different co-substrates (e.g. food waste, lacto-rich waste, FOG) has been implemented in Mossberg (Germany) for 10 years. Due to the high ratio of co-substrates, the heat and energy production is significant higher than the internal demand of WWTP. Excess energy produced in Mossberg plant is fed into the grid, while excess heat is used to dry dewatered sludge from other WWTPs.
The optimization of anaerobic digestion process parameters like sludge-specific loading rate, sludge retention time as well as organic loading rate can also be the key towards energy self-sufficient WWTP.
Another way of increasing biogas production is the application of the thermophilic operation of AD instead of mesophilic mode (described in chapter 5.1).

Summarizing the energy efficiency can be increased through several approaches: (i) enhancing COD retention with pre-conditioning unit; (ii) thermal pre-treatment of sludge; or (iii) thermophilic digestion. Combinations of any two options will increase the energy efficiency to 50% approximately.
Even higher production of electricity can be obtained by combined application of following technologies and processes: (i) enhancing primary settling tank performance to harvest more COD to anaerobic digester; (ii) sludge pre-treatment to increase the VSS destruction to 60% in mesophilic anaerobic digester; (iii) thermophilic digestion to achieve ~60% of VSS destruction; (iv) high efficiency of electricity generators (≥40%); (v) co-digestion e.g. adding FOG (fat, oil, and grease) to anaerobic digesters (Cao, 2001).

3.2. **Heat pumps in treatment plant effluents**

Promising sources of heat for use in heat pumps (HP) are the effluents from municipal wastewater treatment plants. The heat from HPs can be used for heating of residential, social and administrative buildings of the plant and/or neighbouring infrastructure. Heat pumps using wastewater are widely applied in Europe, USA, Japan, South Korea, and China (Kalnin 1994). These heat pump units are reliable and economical sources of heat.
Compared to other traditional sources of heat for HPs like groundwater, geothermal heat, outdoor air, wastewater exhibits relatively high temperatures during the heating season (winter). The temperature of wastewater in European cold climate countries during the winter time is usually in the range of 10–15^{0}C. Wastewater therefore offers an ideal basin for the use of heat. On contrary, during the summer time when temperatures can be above 20^{0}C, it can be used for generation of cold for air-conditioning.
The variations of the amount of wastewater are a second characteristic feature. In the typical combined sewerage systems, the ratio between night minimum during dry weather and the maximum during rain period is up to 10. Therefore this should be taken into account with greatest importance when planning and dimensioning wastewater energy installations.

Normally, as a basis the daily mean value during dry weather is taken and a reduction factor for daily variations is included. For the thermal use of wastewater heat in buildings, the wastewater flows in surges. Retention is therefore a precondition for a heat recovery.
Often, the construction of a new wastewater treatment or upgrading of an existing plant with HP can be implemented without substantial reconstruction of the WWTP. The mode of operation of the wastewater treatment plant is not affected by adding the HP system in the effluent of the plant.
The efficiency of the HP is dependent on the temperature difference between the heat source and the consumer.
The efficiency of the HP significantly depends on the temperature of the heat source. In the summer time, the temperature of the wastewater is high. As a result, the conversion efficiency is high. In this case, the HP can heat the water at low energy costs. In the winter period, the temperature of the wastewater is lower, and the energy consumption is significantly increased.
HPs at wastewater treatment plants reduce the emissions of heat into the environment.

Since late eighties, heat extraction from wastewater has been employed in Norway. HIAS WWTP in Hamar is one of the national leading utilities for heat pump energy recovery in wastewater treatment plants having more than 30 years of experience. In 2010 the system was renovated. Oslo Water and Sewage Works (VAV) has also had a HP installation for many years in the raw wastewater tunnel to their biggest WWTP outside the city.

Heat pump systems can deliver an effect of 3 MW. The heat pump is only in use during the winter season, when heating is necessary. The annual energy delivery from the heat pump system is approx. 4000 MWh, while heat pump consumption is 6000MWh per year (Frijns, 2011).

3.3. Energy recovery from various high temperature streams by heat exchanger

All WWTPs employing high temperature sludge treatment processes (i.e. anaerobic digestion, both thermophilic and mesophilic, thermal hydrolysis, thermal drying) should look into the possibility of implementing heat exchangers to recover energy from all streams (sludge, reject water, condensate, etc.) containing high temperatures. The recovered energy can be used for heating water for different purposes or for heating of raw sludge being fed to a high temperature treatment process.

4. Energy efficiency improvement

A conventional municipal WWTP consists of three principal treatment steps: primary (suspended solids removal), secondary (organic pollution removal, nitrogen and phosphorus removal) and tertiary (polishing step and advanced nitrogen removal) stages. The primary treatment phase includes wastewater collection and pumping, screening, grit removal (alternatively called pre-treatment) and sedimentation in primary sedimentation tanks. These processes are low energy demand ones (except for wastewater pumping). Data on the primary treatment process energy consumption given in the literature vary widely. Energy consumption of raw wastewater pumping depends mainly on the pumping height and ranges from 0.02 to 0.1 kWh/m^3 in Canada, from 0.045 to 0.14 kWh/m^3 in Hungary and from 0.1 to 0.37 kWh/m^3 in Australia (Bodik and Kubaska, 2013).

Aeration in the secondary treatment step represents the highest energy consumption at WWTPs. Besides aeration, also mixing of activated sludge in denitrification basins and recirculation (pumping) of sludge are very important energy consumers in this phase. Conventional activated sludge treatment systems consume in average 0.46 kWh/m^3 (Australia), 0.269 kWh/m^3 (China), 0.33–0.60 kWh/m^3 (USA) and 0.30–1.89 kWh/m^3 (Japan) (Bodik and Kubaska, 2013). On the other hand, oxidation ditch as a part of secondary

treatment step has higher energy demand of 0.5–1.0 kWh/m^3 (Australia), 0.302 kWh/m^3 (China) or 0.43–2.07 kWh/m^3 (Japan) (Mizuta and Shimada M, 2010; Plappally and Lienhard, 2012; Water Environment Federation, 2009, Yang et al, 2010).
Tertiary (advanced) wastewater treatment consumes relatively higher amount of energy due to intensification of nutrient removal processes (nitrification, denitrification, and bio-P-removal) or other energy intense processes, e.g. UV disinfection. In Japan, for example, the advanced wastewater treatment processes are highly energy intensive with energy demand ranging from 0.39 up to 3.74 kWh/m^3. In the USA tertiary treatment consume 0.43 kWh/m^3, on average. This value is similar to the energy consumption given in the literature for Taiwan (0.41 kWh/m^3), New Zealand (0.49 kWh/m^3), and Hungary (0.45–0.75 kWh/m^3).

Figures 2, 3, 4 and 5 present energy profiles for 3 steps processes in kWh/m^3, unit processes in kWh/year, in kWh/p.e. year^{-1} and kWh/day at the most common WWTP (with predominant activated sludge).

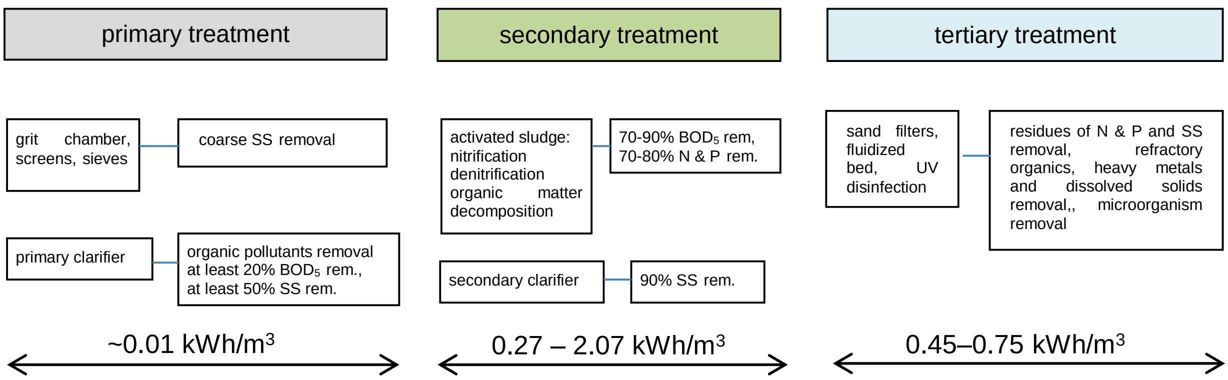


Figure 2. General scheme of wastewater treatment processes and energy use.

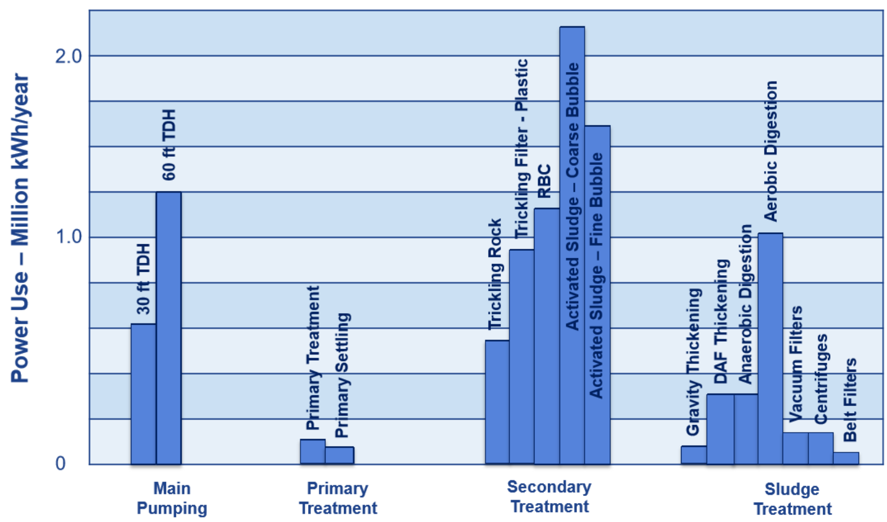


Figure 3. Typical energy use profile (for 10 mgd = 37 854.1 m^3/day). Source: Energy Conservation in Water and Wastewater Facilities - Manual of Practice no 32. WEF, McGraw-Hill Professional, 2009.

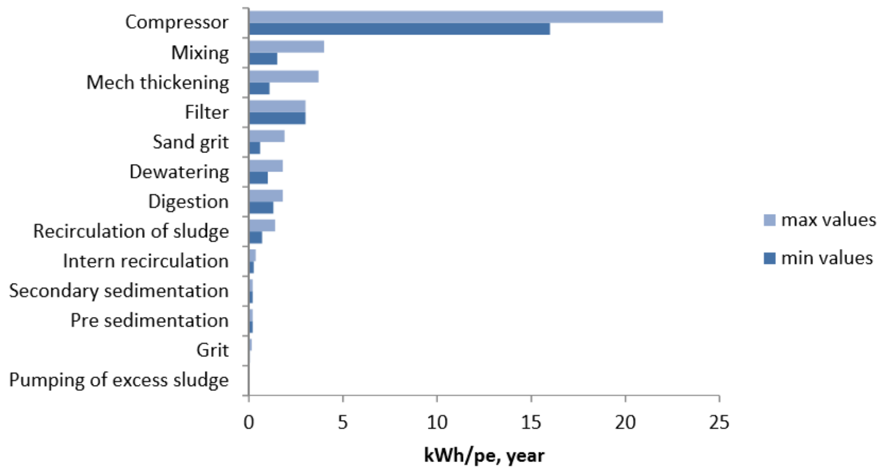


Figure 4. Energy consumption by process (kWh/pe/ year). (Wennerholm, 2014).

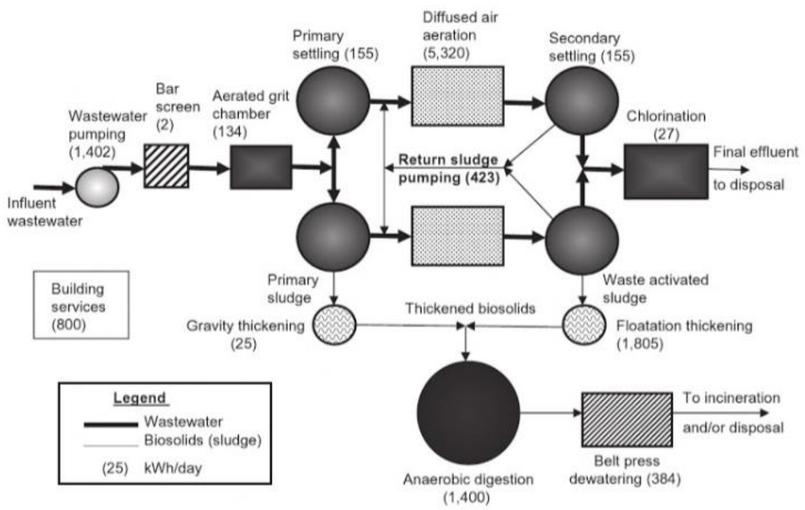


Figure 5. Daily electricity consumption for a 37 854.1 m^3/d facility, (Cao, 2001).

Table 1. presents the electricity consumption of individual units, energy distribution and specific energy consumption of the individual units calculated based on data of Figure 5.

Table 1. Electricity consumption distribution and specific electricity consumption of individual units, (Cao, 2001).

No	Unit/ equipment	Electricity consumption kWh/day	Distribution of total electricity consumption, %	Specific electricity consumption kWh/m^3
1	Lifting pump	1402	8.2	0.04
2	Bar screen	2	0.01	negligible
3	Grit chamber	134	0.8	negligible
4	Primary clarifier	155	0.9	0.01
5	Aeration	8766 (5320+3446)[1]	51.2 (31.1+20)[1]	0.23 (0.14+0.09)[1]
6	RAS pump	508	3.0	0.01
7	Secondary clarifier	155	0.9	0.01
8	Chemical mixer	552	3.2	0.01
9	Filter feed pump	822	4.8	0.02
10	Filtration	385	2.2	0.01
11	Chlorination	27	0.1	negligible

12	Gravity thickening	25	0.1	negligible
13	Floating thickening	2022	11.8	0.05
14	Anaerobic digester	1700	10.0	0.05
15	Belt dewatering	457	2.7	0.01

[1] the number outside of the brackets is the electricity consumption needed for both COD removal and nitrification, while the first and the second numbers in the brackets are the individual electrical consumption for COD removal and nitrification, respectively.

The data shows that specific electricity consumption for aeration is 0.23 kWh/m^3 for both COD removal and nitrification, which is 51% of the total specific electricity consumption, and 0.14 kWh/m^3 for COD removal only, which is 31% of the total specific energy consumption.

Distribution of energy use in the treatment chain including inlet pumping station, treatment processes and sludge disposal is 25, 60 and 15%, respectively. As shown in table 2 the treatment processes give the best opportunity for energy efficiency improvement.

Table 2. Wastewater energy saving matrix

	Wastewater treatment stages		
	Inlet pumping	Wastewater treatment	Sludge treatment and disposal
Energy use in %	25	60	15
pumping	X		X
primary settling		X	
mixing/coagulations		X	
nutrient removal		X	
RAS pumping		X	
thickening/dewatering		X	
digestion/co-digestion		X	
sludge drying		X	
biogas / CHP		X	
solar power		X	
mini hydro-turbines	X		
wind turbines			X

Similar distribution of energy at WWTP is given by Parsons et al, 2012 (Table 3). Here also potential energy saving is indicated.

Table 3. Distribution of energy consumption and energy savings potential at a WWTP with activated sludge system (based on Parsons et al, 2012).

Treatment step	Energy consumption share	Energy saving potential	Comments
Wastewater collection (pumping)	10%	5-10% by improving existing pumps. Up to 30% by better maintenance and closer adjustment to the load size.	Dependent on the share of gravity induced collection
Treatment (aeration)	55%	20-50% by better alignment of control parameters with the discharge standards e.g, improvement/installation of on-line system control.	Mostly for aeration of wastewater
Sludge treatment and disposal (centrifugal and press dewatering, sludge pumping)	35%	30% energy efficiency can be achieved by application of conventional mesophilic anaerobic digestion with CHP. Pre-treatment of sludge or	Energy can be produced by anaerobic digestion of the sludge

		thermophilic digestion can increase efficiency to 50%. Further application of integrated advanced processes with co-digestion, high efficiency CHP can increase the energy efficiency up to 80%.	

Due to the fact that treatment processes, including primary, secondary and tertiary treatment, are the biggest energy consumers at WWTPs (Table 1-3) this report mainly focuses on their performance and energy use.

4.1. Inlet and pre-treatment units

Inlet wastewater pumping can represent up to 30% of wastewater treatment energy demand. Wastewater pumps suffer a higher wear rate because of grit, rags, debris and other solids. Managing these issues saves energy by avoiding pumping against partial blockages and maintaining pumps and their systems close to best efficiency. Pump designers size casings for efficient flows over the duty range, but pump flow speeds are much higher than pipe velocities.
Good practice to minimise head loss and ensure efficient flow in and out of pumps can be summarized as:

- design sumps and intakes according to best practice;
- keep suction pipework short, the ideal length is zero,
- keep suction pipework speeds low; between 1 and 2.5m/s,
- avoid adjacent bends in perpendicular planes; this promotes swirls,
- site pumps low down relative to suction well levels to reduce NPSH (Net Positive Suction Head) losses and avoid cavitation,
- ensure flooded suctions to eliminate priming and air entrainment problems,
- sudden contractions on the suction side are not usually a problem provided that edges are rounded and vortices are avoided,
- locate the pump for easy access for maintenance,
- expand pipe size with a taper at the pump discharge flange if possible,
- avoid sudden expansions as they create instability,
- discharge velocities can be higher; between 1.5 and 3.5m/s,
- use swept bends if possible and avoid sharp edges with high velocities,
- use appropriate valves for check and isolation duties,
- incorporate facilities for flow and head measurement.

Moreover good design practice for energy efficient wastewater pumping should cover:

- steep benching in pump sumps and intakes to avoid sediment,
- access and means for removing scum, sediment and debris,
- short, simple and self-venting layout for pump station pipework,
- selection of pump and impeller type to suit worst case flow conditions,
- swept bends and tees and no valves if possible in delivery pipework,
- any unavoidable pipework constraints covered by rodding or flushing points,
- arrange for automatic back-flushing if possible.

The last item refers to pumps with free discharge or where air valves can be incorporated in the discharge pipes so that when the pump is switched off the flow reverses for a short time. This flows back through the pump, clearing the vanes of any ragging, and into the sump which can clear the sump floor around the pump suction.

Operation of wastewater pump systems also involves extra measures. Regular routines can help to avoid some problems:

- regular “fill and draw” cycles to flush out sewers and pump sumps,
- regular drain down cycles to “snore” levels to avoid scum rafts,
- performance checks should be more frequent than drinking water pumps.

The last item should include chipped or bent impeller blades, partial blockages, and the condition and clearances around wear rings, which all affect efficiency.

Pumps and pumping common energy saving potential ranges between 5-30%:

- 5-10% by improving of existing pumps
- 3-7% through upgrading to new pumping technology (pump technology is mature)
- gains up to 30% are possible through maintenance improvement and closer matching of pumps to their duties (such as using VSDs)

4.2. **Primary treatment**

Primary treatment processes remove suspended solids either by settling (sedimentation tanks or sludge blanket tanks) or by flotation (dissolved air flotation-DAF). The clarification method used is usually a function of the characteristics of the raw wastewater to be treated.
Primary treatment consumes about 11% of the total energy consumption of the plant (Tchobanoglous et al., 2006).
Flocculation plays an important role in clarification. It is a low energy consuming process and can be either hydraulic or mechanical. Energy input depends on the size of floc required for the clarification process.
Sludge removal in settling tanks is mechanical, in sludge blanket clarifiers hydraulic and in flotation clarifiers either mechanical or hydraulic.
DAF clarifier method requires an air injection system which is energy consuming and comprises water recycle pumps (8-12% of plant flow), compressed air plant and absorbers (packed or unpacked) operating at high pressure.
The concentration of removed solids (sludge) in the clarifiers varies over a wide range. It depends on the clarifier type and sludge removal method used. The higher the concentration the lower the water loss and smaller the capacity of the sludge treatment plant.

The primary treatment process involves mainly energy for stirring and pumping of screenings, grit and primary sludge.

Energy can be saved by managing the scrapers in clarifiers (primary or secondary) on the basis of the influent flow rate and the return sludge flow rate or in combination with the suspended solids concentration in the aeration tank or of the return sludge, instead of on the basis of a fixed flow rate (usually rain weather flow). To this aim scrapers should have an adjustable speed and adjustments in the operating system (process control) are required.

The main parameter influencing primary processes and energy production are:

- KWh/kg TSS removed – the higher content of organic matter in the primary sludge production (higher removal from wastewater), the higher energy production
- KWh/kg P chem removed (if P removal applied).

However, primary treatment process optimisation influences energy production at the plant indirectly. A new approach is being implemented at many WWTPs, where primary sludge production is increased by chemically enhanced primary treatment (CEPT) or by employing fine sieves or drum filters instead of sedimentation tanks, to obtain as much organic matter as possible for anaerobic digestion (Zaborowska et al, 2017). The higher primary sludge production, the higher energy gain by increased biogas production. At the same time, one must remember to secure a denitrification step with enough easily degradable organic matter in the primary treated effluent.

4.3. **Secondary treatment**

A large proportion of the wastewater treatment plants across Europe work with the activated sludge process as the main secondary treatment stage. The energy requirements to operate this process are high. Values of 0.15-0.7 kWh/m^3 are given by WssTP, 2011. Delivering of the oxygen for the nitrifying organisms to oxidised ammonium via nitrite to nitrate and to break down the organic matter containing carbon to form carbon dioxide and water is a clue of the process. Oxygen consumption by nitrification is 4.57 kgO_2/kgN. Diffusion of oxygen plays an important role. Applied diffusors have different ability to create air bubbles. Bubbles produced per unit volume of air and the bubble diameters differentiate the systems. The smaller diameter bubbles provide more surface area for better oxygen transfer efficiency (OT). OT indicates the percentage of oxygen in air that is transformed from the pressurized air to the mixed liquor under ideal conditions. Table 4 presents typical OT values for common diffuser types defined at 4.5 m submergence.

Table 4. Oxygen transfer efficiency (OT) for different diffuser types (after van Haandel and Lubbe, 2007).

Diffuser type	**Air flow rate (Nm^3 h^{-1})**	**OT (%) at 4.5 m submergence**
Ceramic discs	0.5-6	25-35
Ceramic domes	1-4	27-37
Ceramic plates	3.5-8.5	26-33
Rigid porous plastic tubes	4-7	28-32
Non-rigid porous plastic tubes	1.5-12	26-36
Perforated membrane tubes	1.5-7	26-36
Jet aeration	100-500	15-24

The capital cost of a fine-pore aeration system will probably be higher, but annual cost of the system will be less than for coarse-bubble aerators. Fine-pore systems can reduce energy costs for aeration by 40 to 50%. The payback time for replacing coarse-bubble systems with fine-pore aeration is 5 to 7 years for most WWTPs. If mechanical aeration is replaced, payback time is 4-5 years.
Important is also arrangement of the diffusers – spiral roll or total floor. For the same aeration tank configuration and diffuser type, the total floor coverage will produce higher oxygen transfer efficiency and use less energy than spiral roll layout.

Proper maintenance and cleaning of blowers also contributes to lower energy consumption.

Shortening sludge age can significantly reduce aeration energy. A short sludge age as used in the so called high-rate processes may allow almost complete utilization of biodegradable material at higher temperatures, but solids retention time is too short for extensive decay and associated endogenous respiration. Hence, the oxygen consumption in these processes will be low, whereas the sludge production is high and the fraction of active (biodegradable) sludge is also high (organically rich sludge should gain more biogas).
At the same time, when optimizing sludge age it is necessary to adjust the retention time in the way that microorganisms will not be washed out from the system. Shorter sludge age can also be insufficient to sustain the nitrification process at normal wastewater temperatures. The short sludge age solids will be will be more difficult to settle. Alternatively chemicals might be needed to promote flocculation and reduce suspended solids in the effluent to meet discharge standards.
The added costs of chemicals and energy for handling of additional quantities of sludge must be compared to expected energy savings due to less aeration and higher biogas production during sludge digestion.

Due to oversized equipment, inefficient operation and lack of controls, supplied oxygen is usually much too high comparing to process needs. Excess supply of air is not only wasted

energy but can also cause sludge settlings problems and sludge carryover into plant effluent. The basic function of an aeration control system relies on monitoring of wastewater treatment variables and data feedback to the control center where a computer adjust the operation of the aeration system. The simplest control system is based on continuous measurement of dissolved oxygen (DO) by a DO sensor in the aeration tank. The instrument readouts are used to automatically adjust operation of aeration system in accordance with the data received by the controller and the standard requirements of the plant. If an existing aeration system was retrofitted with monitoring and automatic controls to maintain set-point concentration of dissolved oxygen in the aeration tank, aeration energy could be lowered by at least 20%. For successful control of dissolved oxygen level in the tank operators must keep the sensors properly maintained and calibrated.
Nowadays there are also available more advanced online control systems based on additional measurements and sensors. The bacteria responsible for biological nitrification exhibit significant biological diversity. Many can operate at low DO concentration. Thus, relying on automation of DO alone may not result in the most energy efficient system. Advanced control systems use multiple measurement parameters as ammonia, nitrite and nitrate. It was reported that through on-line DO and NH_4-N measurement, dynamic aeration control can save up to 30% of the original aeration energy. Furthermore, sensor-based intermittent aeration can save 15% of aeration energy (Wett, 2007).
Moreover, instead of monitoring and control based on DO concentration in the aeration basin, another innovation can be used as alternative measurements of biological activity and use this information for process control. These are respirometry, critical oxygen point control, and off-gas monitoring.

The aeration rate can be reduced by decreasing the dissolved oxygen concentration set-point of the system which is usually way too high. As a rule of thumb for completely aerated and well mixed tanks a minimum of approx. 0.8 mg/L and a maximum oxygen concentration of approx. 2,0-2,5 mg/L can be applied.

Application of intermittent aeration control increases the control range and makes it possible to adjust the aeration input more accurately to the actual oxygen need of the system. Intermittent aeration control application can reduce energy up to 5%.

Aeration energy can be lowered by about 1% by the use of exhaust air that can be transported to the aeration tank through an air blower instead of being treated by filters. This measure is only applicable for continuous aeration operation.

By applying bump aeration (intensive aeration during a very short time) during nonaerated periods almost no oxygen is transferred, but the sludge is still mixed. As a consequence propellers might become redundant, thereby reducing the energy consumption.

Energy can be saved by optimising the propeller operation on the basis of the measured liquid flow velocity in the tank. Continuous measurements are not feasible due to the difficulty in measuring the velocity profile over the tank. The velocities can be measured periodically and the operation of the propellers can be adjusted. For this purpose the propellers require variable frequency drive operation, high/low speed operation or blade operation, and adjustments in the operating system are required.

Another important energy factor during activated sludge systems operation is the return activated sludge (RAS). A portion of the biological sludge removed from the secondary (final) clarifier is recycled to the aeration basin to maintain a high mixed-liquor suspended solids (MLSS) level. RAS pumping typically consumes 5-10% of the wastewater treatment energy demand. The required RAS rate is normally dependent on the flow of wastewater. However, other parameters, such as the settleability of the sludge (commonly measured as SSVI) and the concentration of solids in the mixed liquor present in the aeration tank could be used to control the RAS flow rate. By reducing the RAS pumping rate, less energy is used. Range of potential savings can be up to 55% of RAS pumping energy consumption (see chapter 5.2).

To summarize there are several ways to increase energy efficiency of secondary treatment:
- application of fine-pore aeration systems
- proper maintenance of the aeration system
- optimize sludge age
- application of aeration system control (optimize the position and numbers)
- calibration of sensors
- application of intermittent aeration
- reduction of the oxygen concentration set-point
- application of exhaust air
- managing return sludge flow rate

The most important process performance indicators influencing energy efficiency in the secondary treatment processes are:

energy use	kWh/m^3
oxygen consumption	kWh/kg COD rem (normally in the range of 0.5-1.0)
OCP (Oxygen Consumption Potential)$_{red}$	%; kg/pe/day
energy aeration	kWh/pe/day, kWh/kg oxygen need; % of total energy need
energy mixing	kWh/pe/day % of total energy need
energy/reduced parameter	kWh/kg reduced parameter: kWh/kg COD $_{removed}$, kWh/kg NH$_4$ $_{removed}$, kWh/kg TN $_{removed}$, kWh/kg P $_{bio\ removed}$

4.4. Tertiary treatment

Various types of tertiary treatment are applied, in combination if needed, to meet requirements for receiving waters phosphorus and/or nitrogen reduction. Tertiary and advanced treatment can be completed by a wide variety of processes. There are many treatment processes, such as activated carbon adsorption processes, membrane separation processes, and biological aerated filter. They may be followed by disinfection and/or advanced processes to inactivate pathogens or complex organics such as pharmaceuticals.

Filtration is in the list among the biggest energy consumers at WWTP (see Figure X). Filtration is an energy demanding process, about 7-12 % of total energy need. Sand filters are designed to remove excess suspended solids, BOD and P. The type of filter used (e.g. cartridge, sand or diatomaceous earth [D.E.]) can have a significant impact on energy consumption because each one places different levels of resistance on the circulation system. Resistance is related to energy efficiency because of its impact on water flow. Of the three filter types, cartridge filtration offers the least resistance to flow, which is partially due to the absence of valves. Although sand and D.E. filters function more effectively as solids accumulates, a dirty filter can increase the pump's workload. In fact, the difference between a clean and a dirty filter can nearly double the pump's energy use.

Because of concerns related to security, safe handling, and effluent toxiciy associated with chlorine, UV radiation has become increasingly popular over the years as an alternative to chemical disinfection. Energy requirements for UV depend on the number, type, and configuration of lamps used to achieve the target UV dose for pathogen inactivation. One of the most important factors affecting UV dose delivery is UV transmittanc e (UVT) of the water being disinfected. UVT is affected by the level of pretreatment. Filtered wastewater has a much higher UVT than unfiltered water. Microorganisms that move quickly through the reactor far from the lamp will receive a lower dose than microorganisms that have longer exposure to the UV radiation and are closer to the lamp. Other factors affecting UV dose delivery are temperature, lamp age, and lamp fouling.
Because UV disinfection is complex and based on many factors, dose estimation methods

are complicated and typically involve computational fluid dynamic modeling or bioassays. Dose can be maintained at a minimum level or can be controlled based on water quality (i.e., lowered during periods of improved quality) which can save energy.
A study funded by the Pacific Gas and Electric (PG&E) company found that the energy cons umed by UV disinfection can account for approximately 10 to 25 percent of total energy use at a WWTP facility (PG&E, 2001). Energy required for low-pressure lamps ranged from approximately 0.026 to 0.66 kWh per m^3. Disinfection by UV or filter membranes required for medium pressure systems ranged from 0.121 to 0.147 kWh/m^3. PG&E (2001) reported that UV disinfection performance in relation to input energy is not linear. An increasing amount of energy is required to obtain marginal reductions in total coliforms counts.
Leong et al. (2008) reported that the energy demand for low-pressure, high-output systems is similar to that of low-pressure low-intensity systems. Thus, low-pressure, high output lamps may be a good option for reducing the number of lamps and footprint while keeping the energy requirements low.

Tertiary treatment also includes treatment of side-streams like reject water from dewatering of anaerobic digested sludge. One of the processes that can be applied to treat this highly nitrogen loaded stream, increasing the main treatment line capacity and saving energy cost for aeration is **deammonification**. It is a biological treatment process for the degradation of ammonium from wastewater, by converting ammonium into nitrogen gas under anaerobic circumstances by using nitrite. This process is autotrophic and does not require the addition of a carbon source. The process consists of two steps: nitrite formation from ammonium and the combining of nitrite and ammonium to nitrogen gas. The process is applicable for highly concentrated wastewaters such as reject waters. Low C/N ratio and high temperatures are a requisite. The first step of deammonification which relies on oxidation of half amount of ammonium to nitrite is partial nitritation, while the second step converting nitrite and remaining ammonium is the **Anammox** process (ANaerobic AMMonium Oxidation). In this process ammonia is oxidised using nitrite as electron acceptor and carbon dioxide as an energy source by anaerobic-oxidising bacteria under anaerobic conditions. Oxygen and carbon substrates are not required, CO_2 is not emitted, and little excess sludge is produced as the yield is very low. This process is recognized as one of the most startling biotechnology. Application of Anammox can lead to savings up to 90% reduction of the operation cost, compared to conventional nitrification/denitrification (Jetten et al., 2005). Full-scale data from Strass WWTP in Austria indicates that the electricity consumption for nitrogen removal in side stream sludge dewatering reject water was 1.16 kWh/kgN, what is significantly lower compared to 6.5 kWh/kgN in main stream treatment (Wett, 2007). After application of Anammox in side stream, oxygen consumption for ammonia removal was reduced by 50%, corresponding to approximately 12% savings of the total electricity consumption of the whole plant.

Anaerobic nitrogen removal has a special meaning when enhanced primary treatment in the main treatment line is applied (Zaborowska et al, 2017). Better primary clarification and a higher sludge removal efficiency results in an unfavorable BOD/N ratio and can cause problems with respect to the denitrification. Application of energy conserving side stream techniques for nitrogen removal can provide a solution (see chapter 4.6).

Tertiary process performance indicators are:
for solids removal: kWh/kg $TSS_{removed}$
for ammonia removal: kWh/kg $NH4_{removed}$
for TN removal: kWh/kg $TN_{removed}$
for solids and P removal: kWh/kg $TSS_{removed}$, kWh/kg $P_{removed}$
for pathogens removal: kWh/log reduction
for hazardous pollutants (eg estradiol) removal: kWh/$estradiol_{removed}$

4.5. Sludge treatment and disposal

There are many sludge treatment processes and ways of sludge disposal depending on sludge type, origin and local possibilities. The most common sludge treatment options in Poland are:

- Dewatering only – for e.g. incineration
- Digestion and dewatering – for land application, landfill or incineration
- Dewatering and composting – for land application or landfill
- Dewatering and drying – for fuel
- Digestion, dewatering and drying – for fuel or land application.

Thickening and dewatering typically takes 5-10% of a WWTP energy demand. Both thickening and dewatering involves removal of water from the sludge.

<u>Sludge thickening and dewatering</u>
Sludge treatment in the first steps involves two main processes that may have different configurations - sludge thickening and dewatering.
Sludge thickening functions, such as solids capture, affects loads imposed back on the wastewater treatment processes such as primary settling tanks. The balance of sludge removed from treated wastewater may also affect thickening as waste activated sludge (WAS) is usually difficult to thicken or dewater and often needs a centrifuge. Maximising primary sludge draw-off can help sludge handling and maximise digester biogas potential (see chapter 4.2).
Thickening can be achieved by gravity, by centrifugal force (centrifuges) or by filtering (belt or drum). Dewatering is performed by use of a centrifugal force in a centrifuge or by physical force in a press.
Sludge thickening can attain between 3 and 8% dry solids (DS) content, dewatering is used when 20 to 25% or more is required.
All sludges as primary, secondary and digested have different characteristics and require different thickening/dewatering processes application. Processes are assisted by polymer addition.
Energy is used in the feed pumps, the thickening/dewatering machines, the discharge pumps, the polymer dosing equipment and the reject water recycle or treatment plant. By replacement of high energy demanding thickening facilities energy efficiency improvement can be obtained, as well as the effect of thickening which in turn again will contribute to lower energy consumption in further treatment steps.

Table 5. Hierarchy of sludge treatment processes by potential energy efficiency (Brandt et al, 2010)

←Low energy use			High energy use →
Drum thickeners	Belt thickeners	Belt presses	Centrifuges

<u>Anaerobic Digestion</u>
Anaerobic digestion including biogas handling typically takes 10-15% of a sewage treatment works energy demand, but on the other hand may be able to generate up to 100% of the sewage treatment works energy demand.
Traditionally digestion known as mesophilic anaerobic digestion (MAD) is carried out at mesophilic (32°C to 38°C) temperatures in the absence of oxygen. Different type of sludge (substrates) are pumped to a mixing tank and then to the digester where the content is heated up to the required temperature and with an average retention time of 15 days or more. The biogas can be combusted and used for heating or with a gas engine to produce electricity and heat; it can also be upgraded (CO_2 removal), compressed and used as fuel for vehicles.

There are few methods that can be applied to increase the energy efficiency of MAD:
- adjustment of the retention time in the digester,

- feed of different additional substrates and/or varying ratios of primary sludge and waste activated sludge.
- change of operation mode from mesophilic to the thermophilic (TAD) range (55ºC). TAD can increase the reduction of organic matter (volatile solids) by about 20% and thereby increasing the biogas production by ~20%, compared to MAD.
- installation of a pre-treatment step that can make feed to the digester more readily digestible (i.e. physical or thermal methods with 20% higher biogas production).

Potential steps that could be considered for existing as well as new AD plants to increase energy efficiency are:
- increase primary sludge production (see chapter 4.2)
- optimise the retention time in the digester to generate maximum amount of biogas
- use low energy mixing technologies and carefully design mixing system taking into account sludge rheology
- ensure constant feed and that feed pumps gas collection tank and engines match to the digester size so that the maximum potential of the sludge is used to generate gas.
- use heat pumps to generate heat to keep the temperature in the digester without use of biogas (see also chapter 3.1).

Sludge drying

The cost of disposal of sewage sludge is dependent on the catchment served and environmental considerations. Sludge drying allows land disposal without odour (if sludge digestion before applied) and with much reduced risk of increasing polluted run-off into water courses from farmland, even in wet weather. However, drying of sludge is energy intensive. For most applications to land drying is used to attain more than 45% DS in the sludge. Drying of dewatered sludge usually requires combustion-level temperatures and hence a fuel supply, either biogas from digestion or natural gas from the grid.
Sludge handling and dryer design is complex. Operation is at least semi-automatic to reduce any safety risks and operators need plant-specific training. Dried sludge dust is also a problem with explosion risks.

Drying technologies can be classified into four groups, depending on the way the energy is supplied to the sludge:
- Convection or direct dryers
- Conduction or contact or indirect dryers
- Radiation dryer (solar)
- Combined systems (convection and conduction in the same dryer) and hybrid systems (convection and conduction dryers put is series).

Table 6 Presents specific energy consumption of different dryers.

Table 6. Specific drying rate and specyfic energy consumption of differen drying type systems (Arlabosse et al., 2011).

Dryer type	Specific drying rate (kg m^{-2} h^{-1})	Specific energy consumption (KWh ton^{-1})
Belt dryer	5 - 30	700 - 1140
Direct drum dryer	3 - 8	900 – 1100
Flash dryer	0.2-1	1200 - 1400
Disk dryer	7-12	855 - 955
Paddle dryer	15 - 20	800 - 885
Thin film dryer	25 - 35	800 - 900
Solar dryers- greenhouses		30-200
Combined and hybrid systems		700 -900

In order to improve energy efficiency of the drying process one should consider:

- Dewatering of the sludge to the highest DS content to reduce drying energy demand in further steps.
- monitor sludge conditions to optimise process control,
- pre-heat sludge using waste heat from on-site processes,
- if the sludge is incinerated after drying the combustion heat can be used for drying the sludge feed or pre-heating combustion air.

4.6. New WWTPs

Optimise configuration
When designing a WWTP (new one or renovated) minimisation of the wastewater head elevation and the return and recirculation flows should be incorporated. By choosing a smart configuration the hydraulic energy losses (minimise flow resistance and water heads) can be minimised.

Gravity transport
For new WWTPs the construction should aim to utilise gravity transport as much as possible. This reduces the energy consumption for pumping stations. Depending on the specific situation a (partly) underground construction is an option, to optimise the height of the waterline. The higher costs (including the pumping of groundwater during construction) have to be considered in relation to lower energy costs for utilities over a longer period of usage.

Optimise transport system
By optimising the process control over the pumping stations in the transport system, for example by Real Time Control, the supply of wastewater to the WWTP can be distributed more evenly. This has a positive effect on the energy consumption in the total treatment process.

Advanced pre-treatment
By application of fine sieves/filters instead of primary clarification more BOD can be removed from the wastewater and converted into biogas through digestion. Note that sufficient BOD has to be available in the wastewater to comply with the requirements for nitrogen removal. By improving the digestion process an increase in the nitrogen load in the rejection water can be encountered; in this case advanced side stream reject water treatment can be applied.

Upflow Sludge Blanket Filtration (USBF).
The USBF process is a sludge/water separation technique with a V-shaped construction. In this configuration no scraper is required and the return sludge pump requires a lower head of discharge compared to conventional clarifiers. Both differences allow lower energy consumption, but a thorough comparison with conventional clarification has to be made.

Sequencing Batch Reactor (SBR).
By applying batch wise treatment of wastewater, energy can be saved with respect to recirculation. This operation mode is only applicable for dry weather flow systems or for systems with a very low rain weather flow to dry weather flow ratio. SBR systems can be built modularly, for larger WWTP's more SBR units are required.

Energy exchange.
The temperature of warm side-streams can be used to heat or cool down office buildings or the wastewater in WWTPs. For WWTPs levelling of the influent temperature can be achieved. The effect of temperature levelling of the influent on the energy consumption is dependent on the specific circumstances at the WWTP.

Anaerobic wastewater treatment
Most of the above proposals involve implementation of better control of existing processes. They would be feasible on relatively short time and at comparatively low cost. The more radical proposal with greater potential benefits is to replace current aerobic systems treatment with low temperature anaerobic processes.
Stephenson and Aunger et al, 2009 states that there will be a revolution in the main unit operation used at WWTP. A major development will be the application of anaerobic processes to mainstream flows. Ambient temperature anaerobic treatment of wastewater will be possible by fortification of the influent wastewater stream temperature by heat coming either from sludge generated on-site or other imported organic waste. The major benefit will be reduced aeration costs. Also another author Caffoor, 2010 suggests that the major change to wastewater processing will be the move to low temperature anaerobic treatment and the use of anaerobic membrane bioreactors.

It has been estimated that by 2030 aerobic treatment consuming 0.15-0.7 kWh/m^3 could be replaced by anaerobic treatment producing 1.7 kWh/m^3 (WssTP, 2011; GWRC, 2010).
Wett et al., (2007) proposes the following solution: enhanced primary treatment with organic polymer addition for increasing biogas production in AD, activated sludge process with short SRT and HRT to adsorb colloidal and soluble COD for more biogas production, dynamic control of aeration and pH, thermal pre-treatment of sludge, high efficiency generators or fuel-cell for electricity generation, and application of Anammox (see chapter 4.4) in the side-stream.
Although a move to anaerobic treatment is the dominant proposal for low-emission wastewater treatment, an alternative approach was suggested by Hofman et al, 2009. This consisted of an optimized primary treatment step, including P recovery, followed by dynamic membrane reactor, then nitritation and sand filters for the effluent (Liu et al, 2009). The sludge would be dried using waste heat and used as a fuel source for incineration or co-firing (for example) a cement furnace. This design has not yet been tested in practice.

5. Examples of energy improvements in wastewater treatment

5.1. **Conversion of MAD to TAD**

Anaerobic digestion is one of the most widely used methods for treatment of sewage sludge. It reduces the total mass and stabilize the sludge. Additionally, the production of biogas makes the process profitable. Anaerobic digestion is a process in which microorganisms break down biodegradable organic material in the absence of oxygen. Mesophilic anaerobic digestion (MAD) is operating at 35-40^o C in the digester, while thermophilic anaerobic digestion (TAD) is the same process but operating at temperature ≥ 50^o C. If sludge hygienisation (pathogen inactivation) is an objective, the temperature is ≥ 55^o C.

Biogas production and sludge degradation
During anaerobic digestion 40-60% of the organic solids are converted into biogas containing some 60-70% methane. The biogas can be used to generate heat or electricity (or both) or it can be upgraded to biomethane and used as a vehicle fuel or introduced to the natural gas grid. Application of TAD increases degradation of organic matter in sludge and consequently increases biogas production. Additionally, a reduced amount of sludge to be disposed of can be achieved. Application of thermophilic process to existing digester(s) increases capacity of existing digesters or reduces digester volume for new digesters.

Process performance and operational experiences
Operational data are from TAD plants in the U.S., Norway, the Czech Republic, Sweden, Denmark and Germany with a broad range of operating conditions. Most plants have been converted from mesophilic to thermophilic operation, and many plants in the U.S. and in Norway are employing the draw-and-fill mode to improve pathogen inactivation and achieve controlled hygienisation.

TAD can increase the reduction of organic matter (volatile solids) by about 20% and thereby increasing the biogas production by ~20%, compared to MAD.
The amount of total solids (TS) for final disposal can be reduced by 10-15% compared to MAD operation, and by increased TS content of dewatered sludge (improved dewaterability), the total sludge volume to be disposed of can be reduced by 25 – 30% compared to MAD.
The percentage of volatile solids reduction can be further increased by pre-treatment of the sludge before thermophilic digestion, employing:
-Disintegration of waste activated sludge
-Enzymatic and/or thermal pre-treatment
-Chemical and/or thermal hydrolysis.
Many of the proposed pre-treatment methods are still lacking reliable data from full scale operation.
Improved dewaterability and reduced foaming are experienced with most TAD plants. Process stability is not a problem with good process control (frequent analysis of volatile fatty acids (VFA) and alkalinity).
Strong odours are normal from TAD sludge at the higher temperatures. Cooling of sludge is therefore necessary prior to subsequent treatment, and the first step should be heat exchanging of hot digested sludge with cold raw sludge fed to the digesters. This will also improve the energy balance of the process.
Increased water content in the biogas from TAD plants may require improved water removal, depending on gas utilization.

Cost estimations compared to MAD
There are few data on investment costs of new TAD plants, but they should not differ much from the investment cost of similar MAD plants. Converting from MAD to TAD normally involves fairly low investment costs related mainly to heat exchangers, boilers, sludge pumps, some piping and valves, etc. Operation costs are nearly unchanged when treating the same amount of sludge. Increased energy consumption is balanced by increased biogas production (provided utilization of all the gas produced) and reduced amounts of sludge for dewatering and final disposal.

Application
U.S.A
There are many plants in U.S.A. converted from mesophilic to thermophilic operation over the last 15 years, such as:
Hyperion Wastewater Treatment Plant (WWTP) in Los Angeles
Terminal Island WWTP in Los Angeles
Columbus WWTP in Columbus
Blue Plains Advanced WWTP in Washington D.C.
The main objective of conversion is to comply with Class A standards for pathogen control in sludge (biosolids). For this purpose a lot of digester process configurations have been developed including parallel and in series combinations as well as thermophilic and mesophilic combinations.
The Czech Republic
Three WWTPs in the Czech Republic have converted their digesters to thermophilic operation in the last 10 years. Prague Central WWTP is the biggest one (5,8 m^3/s) with 12 digesters of 4800 m^3 each (6 primary and 6 secondary digesters) and only the primary digesters are heated to 55 °C. The main objectives of thermophilic operation in that country are:
Increasing capacity of existing digesters
Increasing the biogas production for increased combined heat and power generation.
Norway
Five WWTPs in Norway have thermophilic operation of their digesters, and the ”new” Bekkelaget WWTP in the City of Oslo (max capacity 3,0 m^3/s) was designed for thermophilic operation and put in operation 10 years ago with 2 digesters of 8000 m^3 volume each.

Several more WWTPs are in the planning or implementation phase of converting from mesophilic to thermophilic operation of their digesters. Main objectives for the conversion are:

- Complying with sludge pathogen standards similar to those in the U.S.
- Increasing the biogas production for increased production of heat and electricity and also the production of biofuels for vehicles (public transport).

The thermophilic operation of anaerobic digesters accomplishes an efficient hygienization of sewage sludge. It significantly increases degradation of organic matter in sludge resulting in a reduction of the sludge amount for final disposal. During the process a higher production of biogas can be achieved, making the process more profitable. The thermophilic process is applied in many countries around the world, and there is an increasing interest. Especially, conversion from mesophilic to thermophilic operation is often used as it involves low costs and is easy to perform.

5.2. **RAS pumping**

Below is presented a case study from UK WWTP in Hendon where returned activated sludge rate was reduced from a fixed flow to a lower fixed flow giving energy savings at the level of 320kWh/d.

Table 7. Increase in energy efficiency by RAS pumping rate reduction at Hendon WWTP (after Brandt et al, 2010).

Location:	Hendon, UK
Sector:	WWTP
Size	225 205 PE
Works Owner or Operator:	Northumbrian Water
Energy Provider:	Cost £0.066/kWh
Process:	Biological
Component	Activated Sludge Plant
Specific energy problem:	Cost of pumping RAS
Process/Plant changes:	Fixed RAS flow reduced from 1330m3/d to 660m3/d
Energy Efficiency gains:	Saving 320 kWh/d
Cost / Benefit analysis:	Saving £9 000/year (ca 42 000PLN/y)

5.3. **Sludge thickening/dewatering**

Table 8 presents the data of improved energy efficiency achieved by replacing the decanters by belt thickening at Hapert WWTP in the Netherlands. Belt thickeners having higher energy efficiency than decanters, resulted in 230,000 kWh/y energy savings.

Table 8. Modernisation and energy efficiency improvement at Hapert WWTP.

Location	Netherlands
Sector	WWTP
Works owner or operator	Waterboard De Dommel
Size	71 000 PE, 14 500 m3/d, 1 000 tonSS/y
Process	Biological
Component	Replacement of decanter by belt thickener in sludge thickening process
Specific energy problem:	Low energy efficiency of decanters
Civil/Physical Changes:	Improvement of thickening at lower energy demand
Risks and Dependencies	Experience at other WWTPs that thickening results may get worse

Implementation:	Two decanter replaced by two belt thickeners
Energy Efficiency gains: kWh & kWh/m	Improvement energy demand of thickening from 250 to approx. 100 kWh/ton SS; 230.000 kWh/y.
Comparison of energy demand	246.121 kWh – Decanter, 94.617 kWh – Belt thickener
Spec. Energy demand	256 kWh/ton SS– Decanter, 97 kWh/ton SS– Belt thickener
Cost / Benefit analysis:	Investments: 223 000 euro
Other benefits	Increase in DS from 4.8% to 6%.

5.4. **Aeration systems**

Data from New York State shows that removing of coarse-bubble and mechanical aeration equipment and installing fine-pore systems at WWPTs that use activated sludge could save from 300 million to 500 million kWh of electricity per year.
Sludge age reduction from 12 to 3 days could save from 100 million to 200 million kWh annually. Installing aeration system controls that automatically adjust the output of air blowers or compressors in response to the concentration of dissolved oxygen in the aeration basins could further reduce electricity use from 100 million to 150 million kWh per year.

5.5. **Aeration and control system 1**

Energy savings with a new aeration and control system are presented for a mid-size Swedish wastewater treatment plant.

Within this study it was investigated how much energy and money that could be saved by implementing new aeration equipment and aeration control in Sternö wastewater treatment plant (WWTP).

Sternö WWTP was built in 1997 and dimensioned for 26 000 population equivalents. The plant has two parallel biological treatment lines with pre-denitrification. During the study, one of the treatment lines was used as a test line, where new aeration equipment and control system was implemented. The other line was used as a reference line, where the aeration equipment and control was maintained as before.

The new aeration equipment that was implemented to support the test line was an AtlasCopco screw blower, fine bubble Sanitaire low pressure diffusers and measurement equipment. Two control strategies were tested: oxygen control and ammonium control.

The results show that 35 % points of the test line energy consumption was reduced with the new screw blower. The diffusers saved another 21 % points and by fine tuning the controllers, the oxygen concentrations and the air pressure a further 9 % points could be saved. The ammonium control gave no energy savings, since the lowest allowed DO set-point (0.7 mg L^{-1}) kept effluent ammonium below the ammonium set-point of 1 mg L^{-1}. The final energy savings of the test line was 65 ± 2 %.

Each aeration equipment upgrade increased the energy savings with:
- Blower 35 %.
- Diffusers 32 %.
- Oxygen control with decreased DO concentrations and air pressure 21 %.

The final savings correspond to 13 % of the total energy consumption of Sternö WWTP. These savings are equivalent to annual savings of 178 MWh, which decreases the energy costs by 200 000 SEK per year. The payback period of the implemented aeration equipment and control was 3.7 years (Larsson, 2011).

5.6. **Aeration and control system 2**

In 2009 at “Dębogórze” WWTP (450 000 RLM) in Gdynia, Poland a new computerized control and supervision system has been installed. IT network consists of 21 object controllers (drivers) and 4 operator stations. Each driver supports one dedicated area of technological equipment. Each controller is equipped with a graphical interface that allows operator for:
- constant observation of technological parameters and state of technological devices.
- change settings
- local manual control
- diagnosis of damage.

The automation and control of aeration system of biological reactors includes:
- control of the nitrification process performance based on the readouts of ammonia nitrogen sensors installed on the discharge ducts from individual rectors.
- automatic adjustment of the oxygen level depending on the concentration of ammonium nitrogen in the outflow of the reactors - master control system sets the oxygen concentration, which should be maintained in the individual oxygen zones.
- automatic control of the oxygen level in the oxygen zones provides the oxygen sensors - the amount of air supplied to the individual zones is regulated by electric dampers, while the master control system ensures the proper performance of the blowers.

The control strategy allows the blower to operate at a rate that suits the actual process needs and protects against unnecessary wastewater oxidation at times of reduced oxygen demand. This makes it possible to obtain the better denitrification efficiency and consequently further reduce the oxygen demand. Thanks to a new strategy of the aeration control it was observed a decrease of the energy consumption of about 15-25% comparing to years before modernization (2009) (Remiszewska, 2014). The Figure 6 shows the energy consumption for aeration in the following years.

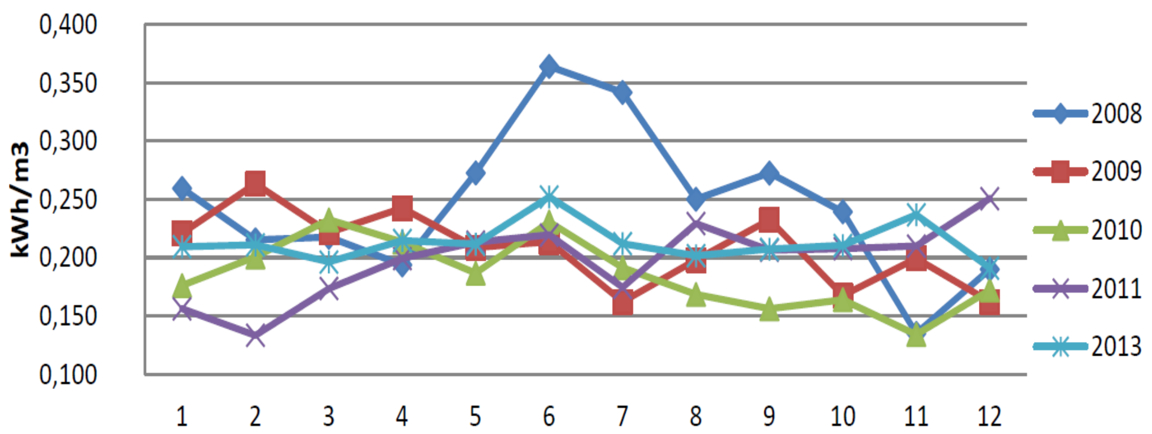


Figure 6. Energy consumption for aeration, 2008 before modernization, 2009-2013 after modernisation, Dędogórze WWTP (Remiszewska, 2014).

Table 9 and 10 presents energy consumption in the following years after new aeration control system was installed. One can see that along the time and increasing number of PE only slight increase in energy use for aeration in kWh/day can be observed while units energy consumption for aeration remain nearly at the same level.

Table 9. Total and aeration energy use in kWh/day and kWh/PE/day at Dędbogórze WWTP, Poland (data provided by Gdynia Waterworks).

year	2013	2014	2015	2016
P.E.	427 600	444 000	476 000	463 000
Energy use in kWh/day				
total	35 888	36 865	38 967	39 497
aeration	11 969	11 912	12 733	13 257
Energy use in kWh/PE/day				
total	0.084	0.083	0.082	0.085
aeration	0.028	0.027	0.027	0.029

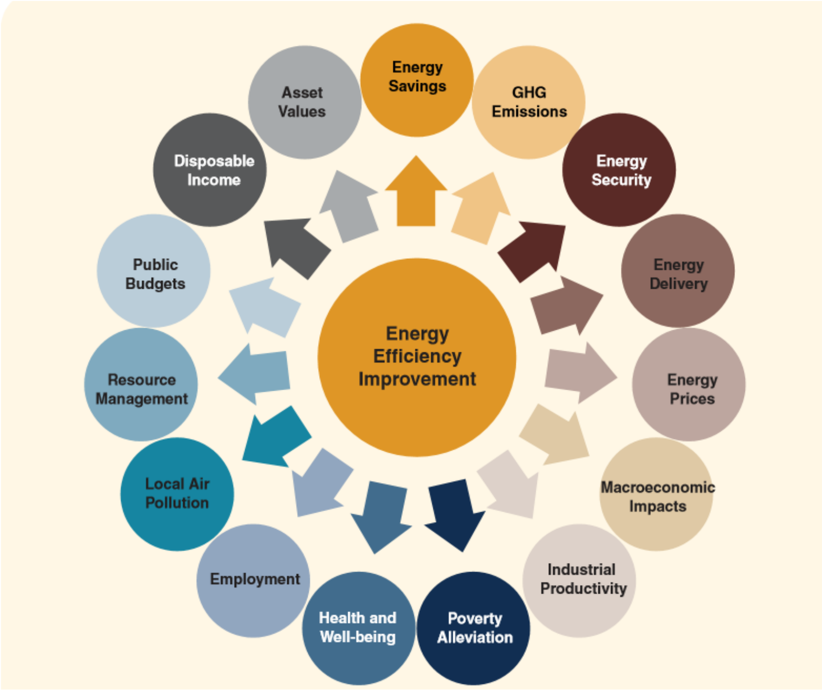
Table 10. Energy use and unit energy consumption at Dębogórze WWTP, Poland (data provided by Gdynia Waterworks).

	2013		2014		2015		2016	
	energy use in kWh/year	unit energy consumption	energy use in kWh/year	unit energy consumption	energy use in kWh/year	unit energy consumption	energy use in kWh/year	unit energy consumption
total	13 396	0.65 kWh/m^3	13 456	0.68 kWh/m^3	14 223	0.71 kWh/m^3	14 456	0.69 kWh/m^3
		7.98 kWh/kgN $_{rem}$		8.07 kWh/kgN $_{rem}$		8.22 kWh/kgN $_{rem}$		8.26 kWh/kgN $_{rem}$
		1.53 kWh/kgBOD $_{rem}$		1.44 kWh/kgBOD $_{rem}$		1.50 kWh/kgBOD $_{rem}$		1.57 kWh/kgBOD $_{rem}$
aeration	4 369	0.21 kWh/m^3	4 347	0.22 kWh/m^3	4 648	0.23 kWh/m^3	4 852	0.23 kWh/m^3
		2.6 kWh/kgN $_{rem}$		2.6 kWh/kgN $_{rem}$		2.7 kWh/kgN $_{rem}$		2.8 kWh/kgN $_{rem}$
		0.50 kWh/kgBOD $_{rem}$		0.47 kWh/kgBOD $_{rem}$		0.49 kWh/kgBOD $_{rem}$		0.53 kWh/kgBOD $_{rem}$

6. Benefits of energy efficiency

Improving energy efficiency in wastewater facilities can produce a range of environmental, economic, and other benefits, including:

- Reduced air pollution and GHG emissions. Improving energy efficiency in water and wastewater facilities can help reduce GHG emissions and air pollutants by decreasing consumption of fossil fuel-based energy.
- Reduced energy costs. Local governments can achieve significant cost savings by increasing the efficiency of e.g. pumps and aeration equipment at a wastewater treatment plant. Facilities can also use other approaches to reduce energy costs, such as shifting energy use away from peak demand times to times when electricity is cheaper or using CHP systems to generate their own electricity and heat from biogas.
- Support economic growth through job creation and market development. Investing in energy efficiency can stimulate the local economy and spur development of energy efficiency service markets. Furthermore, facilities that reduce their energy costs through efficiency upgrades can spend those savings elsewhere, often contributing to the local economy
- Demonstrate leadership and indicate example for others to follow. By implementing energy efficiency projects at wastewater facilities, a local government can demonstrate not only the money saved, but the environmental co-benefits that are obtained from reducing energy use. Installing energy-efficient products (e.g., more efficient pumps), may facilitate broader adoption of these technologies and strategies by the private sector— particularly when communities publish the economic and environmental benefits of their actions.
- Improve energy security. Improving energy efficiency at a wastewater treatment facility reduces electricity demand, avoiding the risk of brownouts or blackouts during high energy demand periods and helping to avoid the need to build new power plants.
- Extend the life of infrastructure/equipment. Energy efficient equipment often has a longer service life and requires less maintenance than older, less efficient technologies.
- Protect public health. Improvements in energy efficiency at wastewater facilities can reduce air and water pollution from the power plants that supply electricity to those facilities, resulting in cleaner air and human health benefits. Equipment upgrades may also allow facilities to increase their capacity for treating wastewater or improve the performance of treatment processes, reducing the potential impacts of sea level rise, treatment failures, and risk of waterborne illness.



Figures 7. Multiple benefits of energy efficiency (EPA, 2013).

7. Conclusions

For successful energy management at WWTP a well-structured guideline for implementation of energy optimisation is the basic management tool. This report indicates seven main steps which should be taken by plants managers to develop a strategy for creating an energy management program focused on continuous improvement of energy performance.
The report illustrates that the potential for energy recovery and energy savings are enormous. It can be used to obtain ideas about energy efficiency measures in an existing situation and can be used as a checklist to assess whether energy efficiency measures are sufficiently incorporated in a design.
Aerobic wastewater treatment systems are areas with most potential for energy efficiency increase. Simple gains of up to 50% are possible in aerobic wastewater systems by aligning control parameters with the discharge consent.
There is enough energy contained in municipal wastewater to operate the wastewater treatment plants. Energy self-sufficiency of municipal wastewater treatment plants in the nearest future is not out of reach. Revolutionary progress in energy efficiency depends on development of novel technologies e.g. anaerobic nitrogen removal in the main stream.

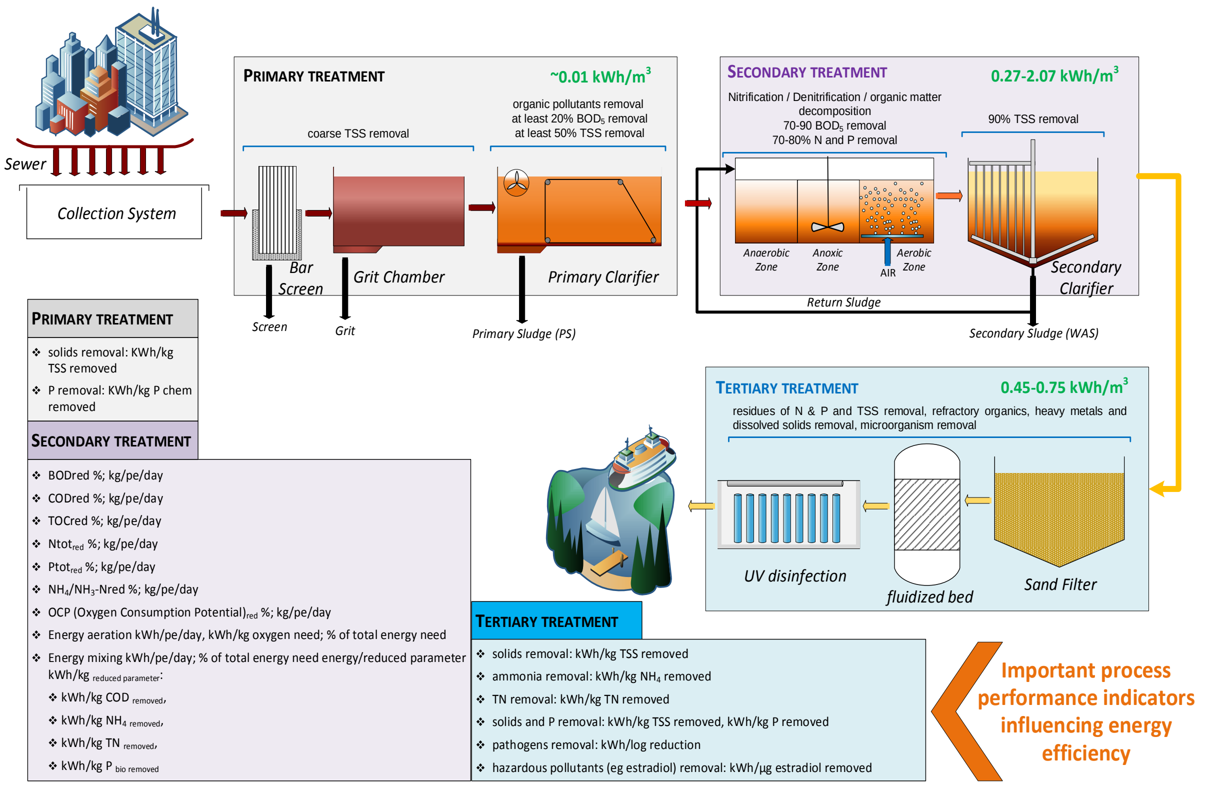


Figure 8. Energy use and process performance indicators influencing energy efficiency at 3 steps treatment process WWTP with activated sludge.

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About the Project

The goal of ETV4Water is to promote ETV as a tool facilitating market uptake of new technologies that improve energy efficiency of municipal wastewater treatment plants. The project aims to build capacity for SMEs primarily from Poland and Norway, but also others, to jointly develop an offer of innovative environmental technologies for water sector that will be credible to purchasers through performing verifications under the EU ETV Programme and relevant to the actual needs of the users.

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