Sustainable biogas production in municipal wastewater treatment plants

Nathalie Bachmann

SUMMARY

This report deals with anaerobic digestion (AD) of sewage sludge, an energy- and nutrient-rich by-product of wastewater treatment plants (WWTP). The objective is to promote sustainable practices and technology, focussing on energy efficiency of biogas production and utilisation. An overview of the AD process in WWTP is given, along with standard energy performances, nutrient recycling and different process options and their impacts. It is not intended as a detailed technical guideline for project managment.
The report is aimed at energy policy and decision makers as well as WWTP operators and was produced by IEA Bioenergy Task 37, an expert working group that addresses challenges related to the economic and environmental sustainability of biogas production and utilisation.

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Table of contents

1. Introduction

Anaerobic digestion (AD) is a proven technology for sewage sludge treatment and which allows generation of renewable energy from the same process. During AD, microorganisms break down the organic matter contained in the sludge and convert it into biogas, a mixture of mainly methane and carbon dioxide, which can be used for electricity, heat and biofuel production. At the same time, the sludge is stabilised and its dry matter content is reduced. The benefits of AD of sewage sludge are widely recognised and the technology is well established in many countries. Today, a high proportion of biogas produced in AD plants is from those on municipal wastewater treatment sites (see Table 1) and there is still an enormous potential to exploit worldwide.

Table 1: Biogas production in WWTPs in Task 37 member countries (IEA Bioenergy Task 37, 2014 b)

Country	**Reference**	**Total biogas production** From agricultural residues, industrial wastewater, biowaste, landfills and sewage sludge	**Biogas production in WWTPs** only from sewage sludge	
	Year	**GWh/y**	**GWh/y**	**% of total production**
Australia		n.a.	n.a.	n.a.
Austria	2013	570 3)	n.a.	n.a.
Brazil	2014	613 3)	42 3)	7 %
Denmark	2012	1.218 1)	250 1)	21 %
Finland	2013	567 2)	126 2)	22 %
France	2012	1273 3)	97 3)	8 %
Germany	2014	41.550 2)	3.050 2)	7 %
Ireland		n.a.	n.a.	
Norway	2010	500 1)	164 1)	33 %
South Korea	2013	2.578 1)	969 1)	38 %
Sweden	2013	1.686 1)	672 1)	40 %
Switzerland	2012	1.129 1)	550 1)	49 %
The Netherlands	2013	3.631 1)	711 1)	20 %
United Kingdom	2013	6.637 3)	761 3)	11 %

1) Energy generated as gross gas production
2) Energy generated as electricity, heat, vehicle fuel or flared (excluding efficiency losses)
3) Electricity generation only (excluding efficiency losses)
n.a.: data not available

Sewage sludge is produced in wastewater treatment plants (WWTPs) as part of the water cleaning process (Figure 1). The sludge contains the particles removed from the wastewater, which are rich in nutrients and organic matter, leaving the water clean for its release into nature. Growing population centres and expanding industry, which are increasingly well served by wastewater treatment facilities, result in rapid growth of sewage sludge production.

As important consumers and generators of energy, WWTPs are one of the numerous players influencing developments towards energy sustainability. The present brochure aims to encourage sustainable and efficient production, conversion and utilisation of biogas in municipal WWTPs, including the closing of nutrient cycles, whenever this is legally and technically possible. It is addressed to energy policy- and decision makers as well as WWTP operators. It allows understanding context and interactions involved in the treatment processes, but it is not meant as a technical guideline for project management. Specialists must also be involved for detailed studies and implementation of new treatment concepts and technologies. The three main objectives of the brochure are:

- To acknowledgement the importance of AD in WWTPs
- To provide information about benefits and challenges
- To encourage optimisation of biogas production and utilisation

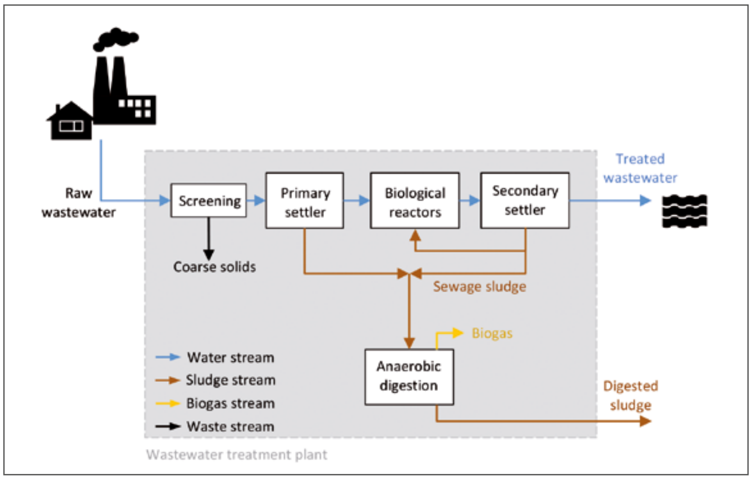

Figure 1: Schematic illustration of a typical wastewater treatment plant with AD

2. Biogas production in wastewater treatment plants

2.1 Feedstock

The principal feedstock for AD in WWTPs is sewage sludge. In general, it is composed of primary and secondary sludge, also called mixed sludge. Greases from the grease trap (usually found at the entrance of the plant) are often also digested. Screenings are not suitable for AD as they contain coarse materials that may be harmful to pumps and stirring systems. In addition, other organic materials such as organic waste from households or from industries may be digested in the anaerobic reactor of the WWTP (depending on national legislation); this is then called co-digestion.

Primary sludge, also called raw sludge, is produced by gravitational sedimentation in the primary settler. It has a high content of organic matter and is easily degradable. Under optimum digestion conditions, a methane yield of 315 – 400 Nm³/t organic dry matter (ODM) can be expected (based on VSA, 2010 and Zhang, 2010).

Secondary sludge, also called excess sludge or activated sludge, results from the biological treatment of wastewater. It has a smaller degradable fraction than primary sludge and thus a lower biogas yield. Under optimum digestion conditions, a methane yield of 190 – 240 Nm³/t organic dry matter (ODM) can be expected (based on VSA, 2010 and Zhang, 2010).

Co-substrates are organic substrates which are co-digested with the main feedstock, with the objective to increase the biogas production and/or as a treatment path for the concerned co-substrates. More information about co-digestion is given in chapter 4.2.2.

2.2 Process steps

The biogas part of a WWTP comprises a series of steps, in short, starting with sewage sludge pretreatment, followed by the AD process and biogas production, and ending with post-treatment of the digested sludge and the gas, as schematised in Figure 2.

Sewage sludge preparation

The sewage sludge resulting from primary and secondary water treatment is gathered for AD. Before entering the digesters, the sludge is sometimes sieved and is then thickened to a dry solids content of up to 7% in order to avoid too high energy consumption for heating due to excessive water content. Optionally, the sludge can be pretreated by disintegration technologies with the aim to improve the gas yield (see chapter 4.2.1.).

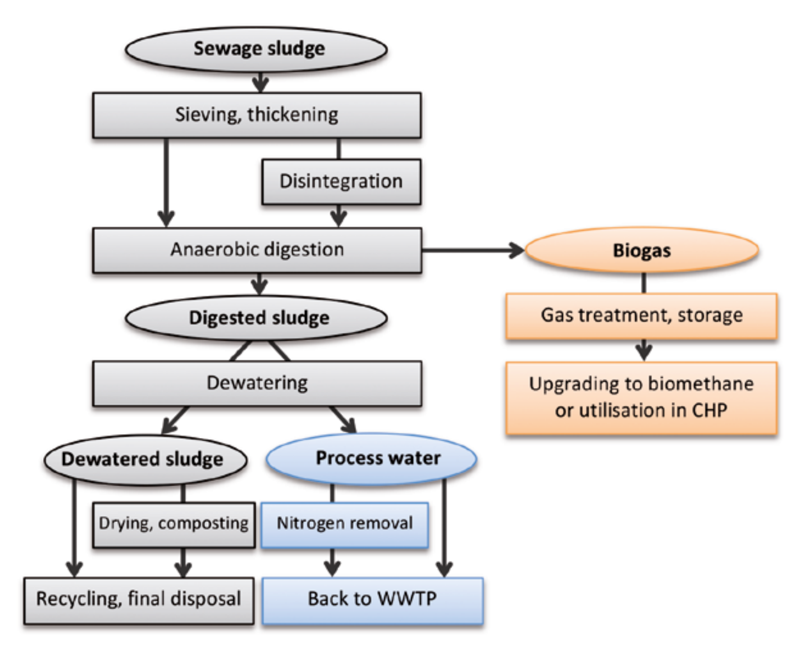

Figure 2: Main steps of AD in WWTP

Anaerobic digestion process

The sludge is pumped into the anaerobic continuously stirred tank reactors (CSTR) where digestion takes place, usually at mesophilic temperature (35 – 39 °C). During a retention time of around 20 days, microorganisms break down part of the organic matter that is contained in the sludge and produce biogas, which is composed of methane, carbon dioxide and trace gases.

Gas treatment and conversion

The raw biogas needs to be dried and hydrogen sulphide and other trace substances removed in order to obtain a good combustible gas and avoiding corrosion or unwanted deposition in the combustion equipment. For biogas produced from sewage sludge (as well as from landfills), particular attention must be paid to the concentration of siloxanes, which can lead to deposits in combustion equipment and deterioration of performance. Generally, removal of siloxanes by adsorption on activated carbon is sufficient.

After cleaning, the biogas can be upgraded to biomethane or it can be combusted in a combined heat and power (CHP) plant to generate electricity and heat simultaneously.

Treatment of digested sludge

As about one third of the solid matter in the sludge is transformed into biogas during the process (equivalent to about 50% of the organic matter), the digested sludge becomes very liquid again and must be thickened another time after leaving the digester. Depending on the further utilisation of the sludge, the latter is pressed, centrifuged or even heat dried in order to remove as much water as possible. When the digested sludge is further used in agriculture, composting of the sludge may be carried out gaining further fertilizing value with this process (practiced for example in Spain, Italy, France, Belgium). Otherwise, the sludge may be transported to an incineration plant or landfill. The final disposal or recycling of the sludge mainly depends on legal boundaries and costs (see chapter 2.4).

Treatment of digester liquids

A highly loaded liquid fraction results from the dewatering of the digested sludge, and this is reintroduced to the start of the WWTP. In particular, an ammonium concentration of 500-1500 mg NH4-N/L is very high (Fux et al., 2004), compared to 50-100 mg/L in raw wastewater. Hence a nitrogen removal process can be applied before mixing with the raw wastewater arriving at the start of the treatment process (see chapter 4.2.5).

2.3 Impact of anaerobic digestion on sewage sludge

The properties of sewage sludge are modified during anaerobic digestion, with mainly positive consequences for the sludge management that follows the process. The major impacts are described below.

Stabilisation, sanitation and odour reduction

AD enhances stabilisation of the sewage sludge: at the end of the process the biological activity is very low because all easily accessible biomass has been degraded by microorganisms. Further, the amount of pathogens and weed seeds in the sludge are reduced (for details see Utilisation of digestate from biogas plants as biofertiliser, Lukehurst et al., 2010). Once the sludge is stabilised, the odour emissions also decrease significantly, which is a particular advantage in case of agricultural utilisation.

Improvement of dewatering

Sewage sludge is easier to dewater after digestion. The efficiency of a mechanical dewatering process is improved by 15 to 25% compared with that for sewage sludge before digestion (Jeitz, 2012), making it possible to reach 35% dry matter content in the digested and dewatered sewage sludge. The improvement results from alterations to flocs and particles in the sludge during the AD process. Dewatering is also discussed in an IEA Bioenergy Task 37 publication on digestate processing (Drosg et al., 2015).

Reduction of dry matter

The transformation of the organic matter into biogas during AD leads to a reduction in the total dry matter content in the digested sludge. The volume of organic matter is reduced by about 50%, which is equivalent to a reduction in total dry matter of about 25 - 33%. If the digested sludge is dewatered or dried, a significant reduction of the final sludge volume can be achieved. In consequence, transport and eventual disposal fees may be reduced.

Improvement of fertilisation value

Sewage sludge serves as fertiliser in many countries and is thus a substitute for mineral fertilisers. During the AD process, biochemical changes take place that alter the organic compounds in the sludge and improve its fertilisation value. For example, a part of the organic nitrogen is converted to ammonium, which is more easily accessible for plants. The impact of AD on nutrient value and availability is described in Lukehurst et al., 2010.

Lower heating value

If sewage sludge is incinerated, this is usually accompanied by recovery of the waste heat. The heating value of sewage sludge depends in the first place on its water content, but also on the ratio of mineral matter to organic matter in the sludge. As the quantity of organic matter decreases during AD (but the quantity of mineral matter stays the same), there is a reduction of the heating value of the sludge with the result that the amount of recoverable heat decreases by about 32-47% (based on Fytili et al., 2008).

2.4 Situation in Task 37 member countries

All Task 37 member countries have experience with AD of sewage sludge. Some interesting examples are described in Case Studies that can be found on the Task 37 website www.iea-biogas.net, for example:

- REVAQ Certified digestate from waste water treatment plants in Sweden (IEA Bioenergy Task 37, 2015)
- Biowaste and sewage sludge recovery: separate digestion, common gas upgrading and heat supply (IEA Bioenergy Task 37, 2014 a)

Legal boundaries concerning the final disposal and recycling of sewage sludge (digested or not) differ considerably in the member countries, which influences the upstream management of sewage sludge, particularly the amount of sludge dewatering. In this context, a short description of the legislative framework in the European Union (EU) and Task 37 member countries outside the EU is described below.

In the European Union, the Sewage Sludge Directive (86/278/EEC) (European Union, 1986) encourages the use of sewage sludge in agriculture whenever harmful effects on soil, vegetation, animals and humans can be

Table 2: Main final recycling and disposal paths of sewage sludge in Task 37 member countries

Country	Use in agriculture	Landfilling	Incineration	Others
Australia	✓	✓	✓	Stockpile, composting
Austria, Denmark, Finland, France, Germany, Ireland, Norway, Sweden, UK	✓	(✓)[1]	✓	Forestry, silviculture, land reclamation, composting
The Netherlands, Switzerland, South Korea			✓	
Brazil	✓	✓	✓	Lagoons, disposal in surface waters[2]

[1] Austria, Denmark, Finland, France, Germany, Ireland and Sweden have reduced landfilling of sewage sludge drastically, and is close to zero today (Eurostat, 2014).

[2] (Stout, 2001)

excluded. About 37% of sewage sludge produced is actually applied to agricultural land; other main pathways are land reclamation and restoration (12%) and incineration (11%) (Fytili et al., 2008). Landfilling is also still practised, but according to the Landfill Directive (99/31/EC) (European Union, 1999), all Member States must reduce by 2016 the amount of biodegradable waste going to landfills to 35% of 1995 levels. In consequence, the amounts of sewage sludge going to landfills are being reduced significantly.

In Australia, there is no specific sewage sludge recycling and disposal regulation. Guidelines are set out on a state by state basis for land application of biosolids. The use as an agricultural fertiliser is allowed on condition that biosolids have been treated for sufficient pathogen removal, that potential contaminants are below threshold levels and that the agricultural land/crop accepting biosolids is deemed appropriate.

In the Netherlands, Switzerland and South Korea, the use of sewage sludge in agriculture is completely prohibited. Concerns about the potential long term impact of heavy metals, pathogens and organic pollutants have led to the strict legislation. Instead, the sludge is delivered to waste incineration plants, cement factories, industrial furnaces or sludge incinerators. The consequence is that sludge has to be efficiently dewatered or dried in advance. For example, the use in a cement kiln requires minimum 90% of dry solids. However, the dried sludge becomes a valuable and renewable energy source with a calorific value similar to lignite (Bachmann, 2009).

In Brazil, where 39% of the wastewater produced is actually treated (SNIS, 2014), federal legislation defines the criteria and procedures for wastewater sludge uses in agricultural areas, with the purpose of bringing benefits to the plantation areas and avoiding the risks for human health and the environment (resolution 375 from August 29th, 2006).

An overview of different practices is given in Table 2.

3. Sustainable biogas production in WWTPs

3.1 Context and objectives

Sustainable energy production takes on increasing importance in the light of dwindling resources and the world's increasing energy consumption. Biogas technology is one of the options for deployment in conversion of organic residues to renewable energy and valuable fertiliser. It is playing an important role in achieving the ambitious targets set by the European renewable energy directive, 2009/28/EC (European Union, 2009), which states that 20% of the final energy consumption has to be provided by renewable sources by 2020.

As important consumers and producers of energy, WWTPs are one of the numerous players influencing the development towards energy sustainability. The present brochure aims to encourage sustainable and efficient production and utilisation of biogas in WWTPs, including the closing of nutrient cycles, whenever this is legally and technically possible.

It is recommended that operators of a plant should regularly evaluate its processes and include the results in an annual report. Improvements and deterioration in performance in comparison to past years should be highlighted. While this brochure focusses on sewage sludge treatment and AD, but it is recommended to integrate the results into an analysis of the entire WWTP.

3.2 Operational and environmental parameters

A number of operational and environmental parameters have been selected in this brochure (non-exhaustive list) in order to assess a plant's sustainability. The situation in any particular plant can be compared to the indicated ranges, which allows one to get an overall idea of the plant's performance and to establish any potentials for improvements. A relatively simple LCA-based tool for evaluation of sustainability performance can be found at: http://va-tekniksodra.se/wp-content/uploads/2015/02/Calculation-Tool-Carbon-Footprint-Wastewater-Treatment-Plants-to-EurEau-members.xls (up-dated link also provided on the IEA Bioenergy Task 37 website). The tool was developed in Sweden in order to allow treatment plants to calculate their Carbon

Footprint and effects of potential process changes and modifications.

3.2.1 Operational parameters: typical values

The values indicated in this chapter refer to a mesophilic digester of a municipal WWTP with primary settler and biological treatment. They suppose the digestion of mixed sludge and without co-substrates. Good quality and complete data are necessary to determine these parameters.

Hydraulic retention time (HRT)

HRT is an operation parameter that describes the theoretical period that the sludge stays in the AD reactor and in which the microorganisms can transform the organic matter into biogas. Too short retention times lead to incomplete degradation and lower biogas yields, and in extreme cases, washout of the microorganisms may occur, leading to a complete biological breakdown of the process. Sediments inside the digester may reduce the net digester volume and thus the HRT; a good reason why they should be removed.

Determination:	$HRT\,[days] = \frac{\text{Net digester volume }[m^3]}{\text{Feedstock input }[m^3/\text{day}]}$	
Typical range:	16 – 25 days	(based on Kind et al., 2012, VSA, 2010)

Temperature

Most AD reactors in WWTPs operate at mesophilic temperatures. As sewage sludge has high water content, a better ratio between energy supply for heating and energy gain is thus achieved. For the same reason, the optimal temperature is lower than in other mesophilic AD plants (typically between 37 and 43°C).

Typical range:	35 – 39 °C	(Lindtner, 2008, VSA, 2010)

Gross gas production and degradation of ODM

As biogas results from the microbial degradation of the ODM (organic dry matter), gross gas production and degradation of ODM are in direct relationship. The proportion of ODM in the sludge and its degradation rate depend on various factors, such as sludge types, sludge age, process characteristics of the water cleaning process and HRT. In consequence, a rather wide range for those parameters is indicated.

Gross gas production:	450 – 500 L/kg ODM or 18 – 26 L/PE/day	(based on Bachmann, 2009, VSA, 2010) (based on Haberkern et al., 2008, Lindtner, 2008, VSA, 2010)
Degradation of ODM:	45 – 55%	(based on Bachmann, 2009, Tietze, 2006, VSA, 2010)

(PE = population equivalent – see Glossary for definition)

Methane content in biogas

Biogas from sewage sludge has a high methane content compared to biogas from other feedstock. Lower values may indicate microbiological problems with the process (e.g. due to temperature variations, overload, etc.).

Typical range:	63 – 67% CH_4	(based on Bachmann, 2009, Kind et al., 2012, Kolisch, 2010)

Utilisation of the biogas produced

Efficient biogas production only makes sense if the biogas is actually used. The parameter "utilisation of the produced biogas" indicates how much of the produced biogas is used for power, heat or biofuel production. The residual part is flared.

Optimal range:	95 – 99%	(VSA, 2010)

Efficiency of biogas conversion by CHP

CHP technology has been improving in the past years and efficiency has been increased significantly. The priority is focussed on the electric efficiency, because heat is usually available in sufficient quantities in plants with CHP. Replacement of old, low efficiency equipment is strongly recommended and also beneficial from a long term economic point of view. Regular maintenance of CHP units is important; deposits (e.g. from siloxanes) deteriorate their efficiency, which can lead to large energy losses.

Electrical efficiency :	< 100 kW: 25 – 35 % 100 – 500 kW: 5 – 40 % > 500 : 38 – 45 %	(based on ASUE, 2011, Schnatmann, 2011)

Energy autonomy of the WWTP (in case of CHP use)

Electricity and heat autonomy indicate the ratio of energy generated to energy used in the WWTP. Larger plants achieve higher levels of autonomy due to more efficient processes (higher production, lower losses). Complete heat autonomy is already being achieved by many plants, while complete energy autonomy today is achieved only by very advanced and sophisticated plants.

Electricity autonomy:	< 10,000 PE: 37% >100,000 PE: 68 – 100%	(Kappeler et al., 2012, Kolisch, 2010, Lindtner, 2008)
Heat autonomy:	90 – 100%	

Further parameters

There is a wide range of further parameters to evaluate a plant. Lindtner, 2008 describes them in a detailed way in the Austrian guideline for setting up an Energy Concept for municipal WWTPs. Some parameters and typical values are given below.

Electric energy generated:	10 – 20 kWh /PE/year
Electric energy for AD	1 – 2.5 kWh/PE/year
Electric energy for sludge dewatering	0.5 – 3.5 kWh/PE/year
Thermal energy for sludge and reactor heating	8 – 16 kWh/PE/year

3.2.2 Qualitative parameters

Qualitative parameters concern the AD concept, namely the handling of the energy generated and digested sludge. Important optimisation potentials may exist in many plants, but they depend on the very specific situation of each plant, as described hereafter.

Biogas conversion technology

Different options for biogas conversion exist, namely conversion to heat, power and biofuel. In function of plant size and energy utilisation, one option may be more beneficial than another.

Heat only production	Not recommended (only adequate in specific situations). Even small plants should assess the option of CHP.
Combined heat and power production	Efficient CHP technology is recommended for all biogas plants, in particular when heat is used in the plant or externally.
Upgrading to biomethane	Larger plants (> 100 Nm^3/h) should assess the option of biogas upgrading. Systems for smaller plants are in a development stages. The biomethane can either be injected into the grid or can be directly sold as biofuel. Biogas upgrading changes considerably the plant's energy management, but today is an often chosen possibility due to economic and environmental advantages.

Exploitation of symbiosis (plant internal and external)

We talk about symbiosis when the by-product of one process is used in another process as a resource. The exploitation and even specific development of symbiosis should be a main objective within the energy concept of a WWTP.

Examples of symbiosis:	• Heat from CHP is used for sludge drying • Residual heat from CHP or from wastewater is recovered and injected into a district heating system • Heat from surrounding industries (for example municipal waste incineration) is used for sludge drying or for heat requirements of the upgrading unit • Separated CO_2 from the upgrading process is used in the food industry or in greenhouses

Recycling or disposal of sewage sludge

The scope for recycling and disposal of sewage sludge is principally limited by legal boundaries. Nevertheless, sustainability criteria should be respected in all pathways.

General criteria:	• If sewage sludge is dried, renewable energy or waste heat should be used • Transport distances should be kept as short as possible. Local solutions must be preferred.
In case of agricultural utilisation:	• Quality management rules must be • respected (c.f. Quality management of digestate from biogas plants used as fertiliser, Al Seadi et al., 2012)
In case of co-digestion:	• No nutrient-rich feedstock should be co-digested if the sludge is incinerated afterwards (because nutrients should be recycled as fertiliser whenever possible)
In case of sludge incineration:	• Heat should be recovered, e.g. in a district heating system

4. Optimisation

4.1 Approach

A possible approach for the implementation of an optimisation process is described hereafter, divided in three main steps.

Situation analysis

The first step is to understand where and why there are deficient performances. The parameters described in Chapter 3.2 are an important tool in this process; ideally, data are collected regularly in order to track their evolution.

For process steps with deficient performances, the following questions must be asked:

- Is the technical equipment efficient?
- Has it been designed appropriately?
- Is it operated correctly?
- Has there been regular maintenance?

Further, it is important to consider the general concept of the plant. Are synergies within the plant being exploited? Are there synergies with surrounding industries that could be exploited or created?

Optimisation plan

The second step involves optimisation measures based on the results of the situation analysis. A number of key measures are described in Chapter 4.2. An evaluation of costs and benefits helps to decide if a measure should actually be applied and to establish the final optimisation plan.

Implementation and further monitoring

The last step is the planning and realisation of the optimisation measures. It is important to continue the monitoring of operational and environmental parameters after the implementation. A comparison before/after is a good way to appreciate the real effectiveness of the applied measures.

4.2 Frequent optimisation measures

Some of the common optimisation measures for AD in municipal WWTPs are described hereafter. However, they should be integrated in a holistic project with situation analysis and an optimisation plan. Here it is important to define why a measure is applied, what performance is expected and what improvement it should bring in comparison to the previous situation.

4.2.1 Replacement of CHP units

The replacement of outdated CHP units is a frequent and efficient optimisation measure (Kolisch, 2010). Old and obsolete CHP technology is associated with a considerable loss in efficiency, which is illustrated in the example in the box.

When replacing the CHP unit, it is appropriate to reconsider the entire conversion concept. Does it make sense to continue with CHP? Or is biogas upgrading a better option? Can symbioses be created through a new energy conversion concept?

Whichever system is chosen, an adequate layout and design are crucial for an optimised operation. Development of future gas production and quality has to be taken into account over the entire lifetime of the planned system.

Example:
A wastewater treatment plant (100,000 PE) with an old CHP unit, having an electric efficiency of 30%, can increase its power production by over 25% by getting a more efficient system, as illustrated below:

WWTP 100,000 PE	Annual production
Gross gas:	876,000 Nm^3 (at 6.5 kWh/Nm^3)
Gross energy:	5,694 MWh
Electric energy:	CHP with $\eta_{el} = 30\ \%$: 1,708 MWh_{el} CHP with $\eta_{el} = 38\ \%$: 2,163 MWh_{el}

4.2.2 Pretreatments for sewage sludge

The aim of sewage sludge pretreatment is destruction of solid structures and the cell walls of the biomass to enhance the rate and volume of gas production. Its main aims are a faster digestion process, higher energy production and a reduction of the sludge volume. Further effects are better dewaterability and a possible reduction of the reactor volume resulting from higher throughput of sewage sludge (and shorter HRT).

A large number of mechanical, thermal, chemical and biochemical pretreatment technologies are available on the market (for sewage sludge also called disintegration technologies). Taking a closer look at different pretreatments, many have not shown themselves to be beneficial from a sustainability point of view (Warthmann et al., 2012), a reason why any purchase must be studied carefully case by case. This chapter gives a very brief overview of the most used technologies; more detailed information is available in the Task 37 technical brochure *Pretreatment of feedstock for enhanced biogas production* (Montgomery et al., 2014).

Mechanical

Mechanical pretreatment involves the use of force for disrupting the microorganisms or sludge cells by shear stress resulting in tension and deformation (Phothilangka, 2008). In consequence, agglomerates and cellular structures are broken down, increasing the contact surface and making cell content available for anaerobic digestion. The most used technologies are ultrasound and high pressure processes such as extruders.

Thermal

Thermal pretreatment uses heat, typically at temperatures from 60 to 200°C, and pressure of around 10 bars in order to destroy cell walls and to release proteins that are then accessible for biodegradation. This accelerates the hydrolysis rate of digestion (Phothilangka, 2008) and also enhances the dewaterability of the sludge. Additionally, foam formation may be reduced and, depending on the temperature, pathogens as well (Abwassertechnische Vereinigung, 2001).

During thermal pretreatment, it is also possible that inhibitory substances for the digestion process are produced (Montgomery et al., 2014). A test phase is therefore recommended.

Biochemical

Biochemical pretreatment is also known as pre-acidification or two stage digestion, wherein the acidogenic stage of AD is physically separated from the rest of the process and the conditions for the growth of acidogenic organisms can thus be optimised.

This pretreatment is often used for high strength industrial wastewaters, but is also efficient for secondary sludge in municipal WWTPs. The effluent from the pre-acidification step can further be used as a carbon source in the denitrification step.

Pretreament of sewage sludge is mainly beneficial if the actual gas yield is not achieving expected levels, for example in case of insufficient reactor volumes, respectively insufficient retention times. It is generally recommended to apply pretreatments on secondary sludge, as the effect is greater than on primary sludge.

Pretreatments may improve the gas production by up to 30% (only possible if the actual gas yield is low), but the pretreatment process is also a significant energy consumer. The implementation of pretreatment technology must be studied carefully case by case, eventually by means of a test phase over several months.

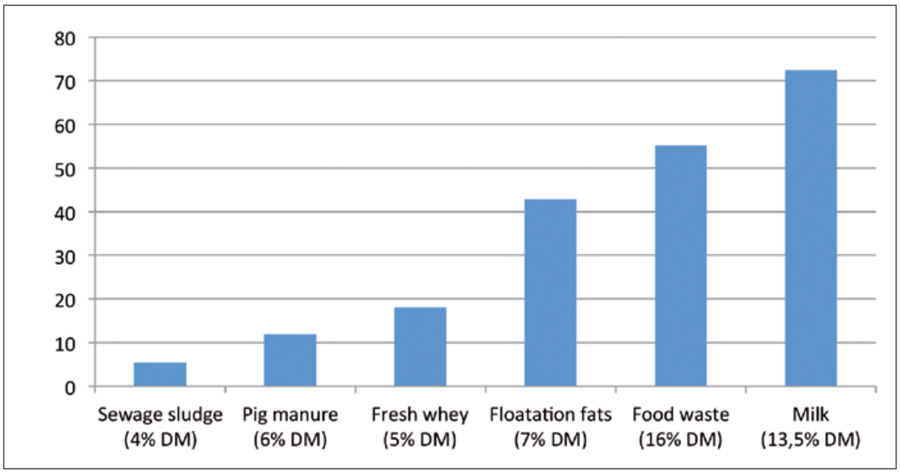

Figure 3: Examples of methane potential of different substrates

4.2.3 Co-digestion

In addition to sewage sludge, some WWTPs include other organic feedstock in the anaerobic reactor. This is referred to as co-digestion. This can lead to a significant increase of the gas production because most co-substrates have a considerably higher methane production per tonne of fresh matter than sewage sludge (Figure 3). This is due to lower water content and high contents of energy-rich substances such as proteins, carbohydrates and fats in co-substrates.

As co-digestion in WWTPs is subject to strict regulations in most countries, the legal situation has to be studied carefully before planning to proceed in the direction of co-digestion.

Co-digestion is an interesting option to optimise the biogas production, but it also involves additional work and infrastructures at the WWTP. Various devices are required for registration (balance, automatic or manual registration system), reception pit (Figure 4), suction device, pretreatment, storage, etc. The additional substrates also induce an increase of the nitrogen load in the process water.

Adequate feedstock is required for sustainable co-digestion, in accordance with the national regulation (sometimes including a “positive list” defining accepted feedstocks). The following elements must be considered:

- **Feedstock with high fertilizing values** (high contents of phosphorus, nitrogen and organic matter) are only of benefit if the digested sludge is used as fertiliser. Examples are dairy by-products or food wastes.
- **Fibre-rich solid feedstock** is not appropriate for CSTR digesters (as used in WWTPs), as they cause clogging and abrasion of pipework, pumps, valves, etc. Examples are garden wastes or wastes from landscape management.
- **Feedstock containing inhibitors**, such as high ammonia or hydrogen sulphide concentration, certain heavy metals, disinfectants, antibiotics, etc., must be handled with care and quantities must be limited. More details on inhibitors can be found in the Technical Brochure of Task 37: Process monitoring in biogas plants (Drosg, 2013).
- **Feedstock containing impurities**, such as plastics, stones, metals, glass, etc., must undergo a pretreatment. Otherwise, it will damage pumps, pipes, stirring systems, etc.
- **Grease trap wastes** are very well adapted for co-digestion in WWTPs. They present low fertilising value and very significant biogas yields. However, specific handling is needed in order to prevent technical and biological problems like clogging or drastic pH swings.

Figure 4: Reception point for liquid co-substrates with different sized grids

4.2.4 Sludge dewatering

After digestion, sewage sludge is dewatered in order to reduce its volume and increase the proportion of DM (as shown in Figure 5). Three different types of dewatering processes can be used consecutively in order to achieve almost complete dewatering: static thickening (up to 8% DM), mechanical thickening (up to ~35% DM) and thermal drying (up to ~92% DM).

Depending on the further utilisation of the sludge and the available energy sources, the level of dewatering can be adapted. A detailed energy balance with different scenarios should allow the optimal dewatering process to be established. Some key factors are indicated below:

- In case of thermal sludge drying, the process takes the highest share within the total energy consumption for sludge treatment (Kind,

Figure 5: Dewatered sewage sludge

2009). The purchase of a drying facility only makes sense in particular cases, for example when the dried sludge is afterwards used as fuel in the cement industry (where only dried sludge is accepted).

- Thermal drying requires much more energy per % increased DM than mechanical thickening. In consequence, the most efficient mechanical thickeners are used in case of subsequent thermal drying.
- Waste heat and renewable thermal energy should be used for sludge drying. Sludges from different WWTPs should be grouped for drying. In case of sufficient space, the option of a solar drying facility should be considered.
- Transport of sewage sludge requires a relatively low share within the total energy consumption for sludge treatment (Kind, 2009 and Bachmann, 2009). In consequence, reduction of transport distances or transport volumes have a limited optimisation potential.

4.2.5 Nitrogen removal from digester liquids

By reintroducing the liquid fraction of the digester effluent to the head of the WWTP, 15 – 20% of the nitrogen load is again fed into the water treatment system (Fux et al., 2004). Separate treatment of this highly loaded stream can reduce its nitrogen content by 85 – 90% and thus reduce the load in the biological reactors of the wastewater treatment. The most applied technologies are the Anammox (ANaerobic AMMonium OXidation) process and Sequencing Batch Reactors (SBR) with classical nitrification/denitrification.

Anammox was discovered about 20 years ago and represents a major breakthrough in the nitrogen removal process. Major advantages in comparison to classical nitrification/denitrification are the absence of emissions of unfavourable intermediates and significantly lower costs (Fux et al., 2004).

4.2.6 Improved phosphorous recycling

Significant quantities of phosphorus and nitrogen are present in sewage sludge. Those nutrients are of great importance for any life and growth process and are main components in fertilisers. Therefore, improved handling of sewage sludge with regard to nutrients, particularly phosphorus, is becoming increasingly important.

When used in agriculture, the sewage sludge partially substitutes mineral fertilisers and brings nutrients in combination with high levels of organic matter back into the soil in a natural way. A growing consciousness about the potential of sewage sludge is leading to a growing need to recycle nutrients, however this requires strictly respecting today's quality requirements concerning heavy metals, persistent organic pollutants and pathogenic microorganisms.

In case of sludge incineration, it is already technically possible to recover phosphorus from the ashes. However, such recovery systems are extremely expensive and are only applied in very specific cases (see also chapter 5).

4.2.7 Education and experience exchange

Education of employees is an important factor for the optimised operation of a plant. Trained staff that understands the different process steps is much more attentive to irregularities and can act appropriately in case of complications. In the same context, experience exchange between plant operators is often a motivating and an effective experience leading to process optimisation.

5. Trends

Expectations towards WWTP are evolving at a rapid pace. The treatment of micropollutants in wastewater and nutrient recovery from sewage sludge are major challenges today which involve new processes and substantial investments. In addition to improvements of water and sludge treatment, WWTPs are confronted with the demand for energy optimisation and nutrient recycling. To meet the series of requirements, the Netherlands has introduced the idea of the NEW Factory (nutrient, energy and water factory), a concept that suggests considering wastewater as a resource of nutrients, energy and clean water, rather than a waste product. A roadmap has been set up on how to achieve the goals of the NEW Factory by 2030 (Roeleveld et al., 2010).

Numerous countries will certainly follow the example of the Netherlands and will focus on integrated management in WWTPs. The coordination of different objectives at nutrient-, energy- and water level will be a key challenge in the future.

So called biorefineries have a very similar concept to the NEW factories. They process biomass into biofuels, power, heat and a range of bio-based products such as chemicals, feed, food, etc. WWTPs, and in particular AD of sewage sludge, may play a key role in biorefineries in the future.

Looking in particular at sewage sludge as an energy and nutrient resource, some interesting trends are listed below.

High-load digestion

High-load digestion consists of an increased concentration of solids and of microorganisms inside the AD reactor, which is achieved by filtering out water. In consequence, the necessary digestion volume is reduced and less heat is required for heating, which lowers investment and operation costs. According to Fraunhofer IGB, developer of such a high-load process, a biogas yield of 23 L/PE/day can be achieved, which is in the same range as in conventional digesters with good gas yields (18-26 L/PE/day). The purchase of a high-load digester is interesting in particular for WWTPs that do not yet have a digestion unit and decide for AD. Also in smaller plants (10,000 PE) AD can become a cost-effective solution (Kempter-Regel, 2010).

Hydrothermal carbonization of sewage sludge

Hydrothermal carbonization (HTC) is a thermochemical process that converts liquid biomass into a so-called biocoal, which can be used as a solid fuel or soil conditioner. In the context of sewage sludge treatment, HTC may be an alternative to anaerobic digestion or a complement. In the latter case, digested sludge serves as feedstock for HTC. The advantage of HTC is nearly complete conversion of the organic matter, very good dewaterability of the resulting sludge and improved energy balance (Jeitz, 2012).

HTC is a recent technology on the market, even though the process has been known for over a hundred years. The first industrial plant was built in 2010 in a WWTP in Germany (Karlsruhe). It is conceivable that HTC will become a standard technology for sludge treatment.

Pyrolysis and gasification

Pyrolysis and gasification are, like HTC, thermochemical processes that can be used to reduce the amount of solids in the residual sewage sludge and generate energy. These processes use dry biomass as feedstock and operate over different temperature and pressure ranges. While pyrolysis and gasification technologies have been used at industrial scale since the 1980s, no commercial breakthrough has as yet been achieved due to frequent technical and economic problems. (Based on Gleis, 2011)

Fuel cells for biogas conversion

Fuel cells (typically solid oxide fuel cells – SOFC) generate electricity directly from the chemical energy contained in the biogas, with an electric efficiency of 50 to 55 %. This process is in theory more efficient than CHP, which generates first thermal-, then mechanical- and only then electric energy. Compared to CHP, fuel cells release lower emissions in terms of CO, NO_x and hydrocarbons. The big disadvantage of fuel cells is their sensitivity to poor gas quality, which is a challenge when biogas is used as fuel. Further negative points are energy requirements during the start-up phase and increased security requirements because of the presence of hydrogen (Kind, 2012). Today, there are individual examples of fuel cells for biogas conversion in WWTPs, but the disadvantages of the system still get in the way of a breakthrough.

Phosphorus recovery from sewage sludge

The recovery of phosphorus from sewage sludge is a great challenge for countries where sewage sludge is incinerated, respectively, where nutrients are not being recycled. Various recovery processes exist today, but they are not (yet) cost-effective and are therefore not yet applied on large scale plants.

A European research and demonstration project, P-Rex (supported by the 7th framework program, European Commission), is about to evaluate different recovery processes, and the products that result from them, on their sustainability and costs. It focusses particularly on phosphorus recovery from ash and phosphorus recovery from sludge processes. The objective is to bring recovery systems from prototype to the market and, in the long term, a Europe-wide implementation of phosphorus recovery from sewage sludge. Project reports can be downloaded on the P-REX website: http://p-rex.eu/.

In Switzerland, regulatory changes foresee already that phosphorus recovery from sewage sludge will become mandatory. Some incineration plants already stock the sludge ashes in order to recover the phosphorus once the technology is available.

6. Recommendations

The best way to towards sustainable biogas production at WWTPs is the establishment of a monitoring system. It is recommended that each plant should regularly evaluate its processes and publish the results in an annual report, illustrating good and deficient performances, as well as optimisation possibilities. Good awareness of each stage of the process and the possibilities for improvement is one of the most important steps in the optimisation process. The annual report can also serve as a communication tool in order to attract attention of the local population and politicians when investments are required.

It is further important to remain attentive to developments and regularly investigate new possibilities. It is sometimes beneficial to replace an old system, even though still functional, by a new, more efficient one. Or, as the industrial neighbourhood of a plant changes, new possibilities for synergies should be examined.

However, plant optimisation is a continuous process, which requires a committed, innovative and dynamic operating team. Continuous education and experience exchange is an effective way to keep up with the best practices and the newest technological developments.

Glossary

Anaerobic digestion (AD): Degradation of organic substances by microorganisms under exclusion of oxygen. The process, also called methanisation, delivers biogas that contains typically 50 to 70% methane, 20 to 45% carbon dioxide and trace gases.

Biochemical oxygen demand (BOD): A parameter that is used to indicate the degree of organic pollution of water. It specifies the amount of oxygen needed by aerobic organisms to break down the organic material.

Co-digestion: Simultaneous AD of multiple organic wastes used to increase methane production in low-yielding or difficult to digest materials.

Combined heat and power (CHP): Energy system that produces both electricity and heat from a single fuel source.

Composting: Biological process where solid organic matter is aerobically processed at thermophilic temperatures to a stabilized and hygienic product rich in humic substances, the compost.

Continuously stirred tank reactor (CSTR): In the case of AD, this is an anaerobic digester with mixers or impellers where material is continuously fed in and removed so as to maintain a steady-state breakdown reaction inside the tank.

Denitrification: In wastewater treatment, biological nitrogen removal consisting of an initial oxidation of ammonium to nitrate followed by the reduction of nitrate to nitrogen gas.

Digested sludge: Sludge after being processed in anaerobic digestion.

Dry matter (DM): Residual substance after complete elimination of water (drying), usually given in weight percentage of fresh material. Also known as total solids.

Heating value: Amount of heat produced by combustion of a unit quantity of fuel [J/Kg].

Hydraulic retention time (HRT): Average time during which the feedstock remains in the AD reactor.

Micropollutants: Organic trace contaminants caused by plant protection products, biocides, pharmaceuticals, body care products, cleaning agents, etc.

Municipal waste incineration (MWI): Thermal waste treatment that involves the combustion of substances contained in municipal waste materials. The heat generated can be used to produce electric power.

Organic dry matter (ODM): Organic fraction of the DM, also known as volatile solids.

Population equivalent (PE): Ratio of the pollution load [BOD/day] arriving at the WWTP from domestic and industrial users and services to the individual pollution load in household sewage produced by one person.

Primary sludge: Concentrated suspension of solids separated by gravitational sedimentation from wastewater in the primary settler in a WWTP.

Secondary sludge: Concentrated suspension of solids separated by gravitational sedimentation after the biological treatment of wastewater in a WWTP.

Wastewater treatment plant (WWTP): Facility where wastewater is processed in a combination of physical, chemical and biological processes and operations to remove solids, organic matter and nutrients before its discharge to the environment.

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Task 37 – Energy from Biogas

IEA Bioenergy

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