

Modelling the bioenergy potential of municipal wastewater treatment plants

Kerstin Schopf, Johannes Judex, Bernhard Schmid
and Thomas Kienberger

ABSTRACT

A municipal wastewater treatment plant accounts for a large portion of the total energy consumption of a municipality. Besides their high energy demand, the plants also display a significant bioenergy potential. This is due to the utilisation of the energy content of digester gas and sewage sludge if there exist suitable units. To maximise the energy recovery efficiency of wastewater treatment systems (WWTS), it is important to analyse the amount of digester gas and sludge produced in different types of plants. Therefore, the present paper deals with designing a tool to answer the following research questions: Which bioenergy potentials occur in different plant types? Which mass and energy flows are related to the specific potentials? Which utilisation processes for the potentials can lead to a high energy recovery efficiency of WWTS? Preliminary analyses with the designed tool were focused on estimating the level of electric and thermal energy self-sufficiency of different plant configuration scenarios including or excluding digester gas and/or sludge utilisation units. First results based on the level of self-sufficiency and associated energy and disposal costs show that a digester gas and sewage sludge utilisation should be considered when designing future WWTS.

Key words | energy balance, energy recovery, mass balance, wastewater treatment plants

Kerstin Schopf (corresponding author)
Bernhard Schmid
Thomas Kienberger
Chair of Energy Network Technology,
University of Leoben,
Franz-Josef-Straße 18, 8700 Leoben,
Austria
E-mail: kerstin.schopf@unileoben.ac.at

Johannes Judex
Kopf SynGas GmbH & Co KG,
Stützenstraße 6,
72172 Sulz am Neckar,
Germany

INTRODUCTION

Due to the increasing worldwide energy demand, efficient regional systems which include energy recovery are gaining importance, even at a municipal level. When analysing the energy consumption of a municipality, it is revealed that the wastewater treatment is an energy-intensive process. A municipal wastewater treatment plant (WWTP) is responsible for up to 20% of the total energy consumption of a municipality (Fricke 2009). Despite the high energy consumption, the treatment process also leaves behind energy-rich residues, like digester gas and sewage sludge, which represent significant bioenergy potentials. Digester gas is already a widely-used energy source to cover parts of the internal power and heat requirement of a sewage plant. Sewage sludge refers to the semi-solid residual material occurring during the wastewater purification processes and offers a potential input for thermal utilisation units due to the specific energy content. To reach a high energy recovery

efficiency, it is important to design an optimal utilisation path for the bioenergy potentials, especially for sewage sludge.

To identify the bioenergy potentials of different wastewater treatment processes, mass and energy balances are needed. Furthermore, it is necessary to strive to an optimal utilisation path of the potentials, to ensure a high energy recovery efficiency. Within the actual study, the municipal wastewater treatment system (WWTS) and its role as decentralised energy provider in the municipal energy systems is analysed. Therefore, it is necessary to identify the potential of decentralised (on-site) utilisation opportunities. The interaction with the superordinate energy grids (power, heat and gas grid), can then be analysed on the base of the balances. Therefore, a modular tool to model optimal energy networks for WWTS is designed. This tool is based on the calculation of static mass and energy balances.

METHOD OF MODELLING THE BIOENERGY POTENTIAL OF WASTEWATER TREATMENT PLANTS

Based on the static mass and energy balances generated with the developed tool, the goal is to answer the following questions by analysing different types of WWTP: Which bioenergy potentials, specifically which types of sewage sludge, occur in different types of WWTP? Which mass and energy flows are related to the specific potentials? How can the potentials be integrated on-site? Which utilisation processes for the bioenergy potentials can lead to a high energy recovery efficiency of WWTS?

Determination of the bioenergy potentials

The bioenergy potentials – the mass and energy flows of digester gas and sewage sludge – depends on numerous factors like: the chemical components of the wastewater, the plant size or the applied treatment technology (Metcalf & Eddy 2014). To determine the existing potentials of a specific WWTP, it is necessary to generate mass and energy balances including all important influencing factors. The analyses of single processes without integration in an overall system only provides a limited insight and is not a sufficient base for further analyses. Thus, the goal is to simulate the system ‘wastewater treatment plant’ including all process steps, as well as all relevant mass and energy flows. The developed modular tool enables users to generate mass and energy balances of aerobic and anaerobic WWTP with various sizes and different system configurations. A focus on these technologies is based on the fact that in Austria

and Germany over 95% of wastewater is treated in biological WWTP with aerobic or anaerobic stabilisation (BDEW & DESTATIS 2010; Assmann et al. 2015). Due to a lack of representative data, specific treatment processes like an ultrasonic disintegration or a thermal hydrolysis process, are not considered. But the modular model can be expanded with new modules to determine the influence of these technologies. To roughly estimate the influence of such technologies in the actual modular tool, it is possible to define parameters of the individual modules. For example, to take into account the increased anaerobic biodegradability of the raw sludge, the output flows ‘digester gas’ and ‘digester sludge’ are adaptable. Furthermore, any additional energy consumption can be typed into an entry field. Figure 1 illustrates all the modules included in the model for the example of an anaerobic treatment plant. A model of an aerobic treatment plant will not include the modules ‘primary clarifier’ and ‘digestion tank’, as well as the mass flows ‘primary sludge’ and ‘digester gas’.

Types of sewage sludge

Figure 1 illustrates the three main types of sewage sludge produced in a WWTP: primary, secondary and tertiary sludge.

Primary sludge is produced in the mechanical treatment stage in a settling tank, the primary clarifier. It results from the capture of suspended solids and organics through gravitational sedimentation. In the model, the primary clarifier is considered as a settling tank; the option of physico-chemical primary treatment is not considered currently (Metcalf & Eddy 2014).

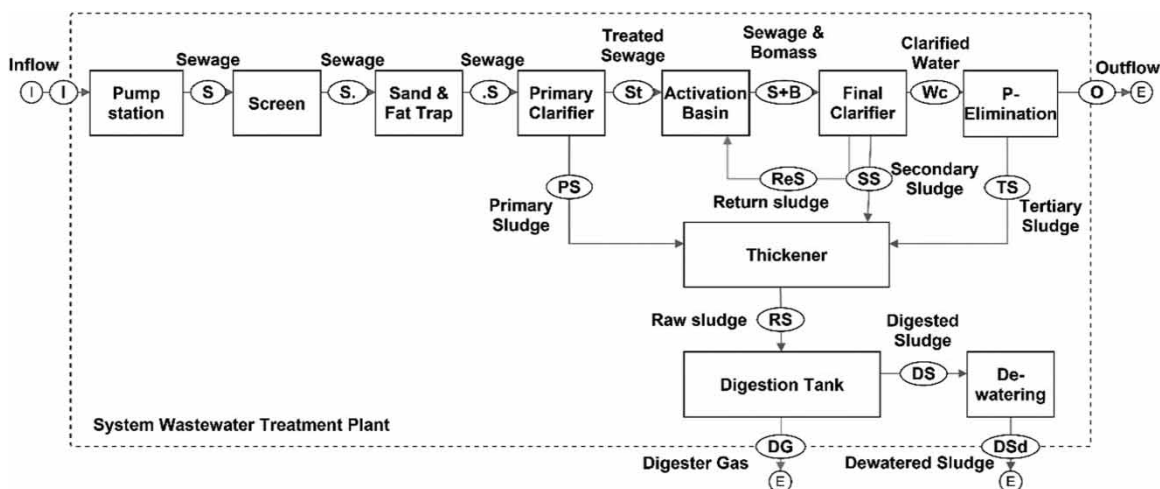


Figure 1 | Structure of the modular model on the system level WWTP.

Secondary sludge is produced in the biological treatment stage, the activation basin and the secondary clarifier. In the activation basin, aerobic microorganisms convert impurities into biomass. This biomass settles in the final clarifier and is removed as secondary sludge. To maintain the biological process, a part of the sludge flow is returned to the activation basin as so-called return sludge or activated sludge (Metcalf & Eddy 2014).

In the model, an often installed additional purification process, the phosphorus elimination which produces tertiary sludge is integrated. In practice, the elimination is either a treatment simultaneous to the biological processes, or a separate treatment unit upstream of the primary clarifier or downstream of the secondary clarifier. In the model, the process is analysed separately downstream of the secondary clarifier to obtain specific results. Through the process, it is possible to remove soluble phosphates through chemical precipitation or biological phosphorus elimination (Metcalf & Eddy 2014).

The other sludge types, the digested and dewatered sludge, are produced through further treatment processes, the digestion and dewatering. In the digestion tank, anaerobic digestion takes place. This is a collection of processes by which microorganisms break down biodegradable matter in the absence of oxygen. The products are a biogas, consisting mainly of methane and carbon dioxide, as well as anaerobically stabilised sludge composed of non-biodegradable organic material, mineral matter like phosphorus, and water. This sludge can be dewatered, dried, and used in energy recovery processes (Bischofsberger et al. 2005).

Mass and energy flows of the bioenergy potentials

Table 1 shows typical mass flows of bioenergy potentials per inhabitant (I) and day (d). Here it is assumed that one inhabitant is responsible for 60 g of biological oxygen demand (BOD₅) and 120 g of chemical oxygen demand (COD) per 24 h. Further details on the assumptions underlying the calculations of the mass flows presented here can be found in the respective literature (Loll et al. 2004).

Energy content of bioenergy potentials

Digester gas consists mainly of methane and carbon dioxide. Assuming a lower heating value of a around 36 MJ/Nm³ methane, an average methane content of about 65% lead to a lower heating value of approximately 23 MJ/Nm³ digester gas (Bischofsberger et al. 2005).

Table 1 | Typical mass flows of bioenergy potentials of municipal wastewater treatment plants

Mass flows	Literature values	Unit
Primary sludge ($t_{PC} = 0.5 \text{ h}$) ^a	30.00	g/(I*d)
Primary sludge ($t_{PC} = 1.0 \text{ h}$) ^a	35.00	g/(I*d)
Primary sludge ($t_{PC} = 2.0 \text{ h}$) ^a	40.00	g/(I*d)
Secondary sludge ($t_{SA} = 5 \text{ d}$, $t_{PC} = 0.5 \text{ h}$) ^{a,b}	46.30	g/(I*d)
Secondary sludge ($t_{SA} = 5 \text{ d}$, $t_{PC} = 1.0 \text{ h}$) ^{a,b}	41.10	g/(I*d)
Secondary sludge ($t_{SA} = 5 \text{ d}$, $t_{PC} = 2.0 \text{ h}$) ^{a,b}	35.80	g/(I*d)
Secondary sludge ($t_{SA} = 10 \text{ d}$, $t_{PC} = 0.5 \text{ h}$) ^{a,b}	42.00	g/(I*d)
Secondary sludge ($t_{SA} = 10 \text{ d}$, $t_{PC} = 1.0 \text{ h}$) ^{a,b}	37.30	g/(I*d)
Secondary sludge ($t_{SA} = 10 \text{ d}$, $t_{PC} = 2.0 \text{ h}$) ^{a,b}	32.40	g/(I*d)
Secondary sludge ($t_{SA} = 15 \text{ d}$, $t_{PC} = 0.5 \text{ h}$) ^{a,b}	39.30	g/(I*d)
Secondary sludge ($t_{SA} = 15 \text{ d}$, $t_{PC} = 1.0 \text{ h}$) ^{a,b}	34.80	g/(I*d)
Secondary sludge ($t_{SA} = 15 \text{ d}$, $t_{PC} = 2.0 \text{ h}$) ^{a,b}	30.20	g/(I*d)
Secondary sludge ($t_{SA} = 25 \text{ d}$) ^b	56.20	g/(I*d)
Tertiary sludge	3.60	g/(I*d)
Digester gas	0.02	m ³ /(I*d)

^aDwell time of the wastewater in the primary clarifier (PC).

^bSludge age (SA) in the activation basin.

The heating value of municipal sewage sludge depends on various factors. One important influence factor is the dry matter (DM) content – the higher the DM content, the higher the heating value. This factor is mainly affected by the sludge treatment processes, dewatering and drying. Furthermore, it is necessary to consider the ash content of the sludge. For example, dried undigested sludge with a DM content of 90% and an ash content of 40% possesses a lower heating value of about 12 MJ/kg, whereas dried digested sludge often has a higher ash content which leads to lower heating values of about 10 to 8 MJ/kg. Typical lower heating values of different sludge types depending on the water-, the dry matter- and the ash content can be found in literature (Spliethoff 2010).

Integration of determined bioenergy potentials into the energy network of a municipal WWTP

After determining the specific mass and energy balances, it is necessary to analyse the energy utilisation opportunities of the bioenergy potentials: digester gas and dewatered sewage sludge. Within the actual study, the municipal WWTS and its role as decentralised energy provider in the municipal energy systems is analysed. Therefore, it is

necessary to identify the energy potential of decentralised utilisation opportunities. Here, decentralised utilisation implies an on-site utilisation. This is an alternative to centralised utilisation possibilities, like co-combustion or large-scale monocombustion plants. It is of importance to know that the technological feasibility and economic efficiency of either a decentralised or a centralised utilisation path depends on many factors and have to be analysed for existing plants individually.

Generally, the digester gas is used in gas-fired combined heat and power (CHP) plants with further utilisation possibilities being gas boilers or micro gas turbines. The decentralised use offers some advantages like a higher level of electric and thermal energy self-sufficiency or low digester gas losses. Furthermore, the units represent state of the art technologies with low personnel, technical and safety effort (Frey 2012).

Dewatered sewage sludge is a bioenergy carrier, which can be converted into recovered energy either through combustion or gasification. For example, in Austria and Germany, 2.1 million tons dry matter (DM) of sludge is produced annually (ÖWAV 2014; DESTATIS 2016). Up to now, sewage sludge have been primarily used as ecological fertiliser in the agricultural sector. However, four factors enhance the attractiveness of a decentralised utilisation of sludge:

1. Due to stricter restrictions and even prohibitions in Europe concerning the disposal of sewage sludge on agricultural fields, a thermal utilisation alternative could be aspired. EU directives and resulting national legal frameworks seek to regulate the use of sludge in agriculture to prevent harmful effects on soil, vegetation, animals and humans (Olivia et al. 2009; ÖWAV 2014; Council of European Communities 1986).
2. Even if a disposal is legally possible, it is due to over fertilisation not always useful (Rehl & Müller 2011). When taking into account transportation costs it shows that the monetary fertiliser value can be exceeded if the transport distance is above 10 km and if the water content is about 70–90% (Döhler & Schliebner 2006).
3. Through the digestion process, only about 50% of the energy content resulting from the organic input can be converted into biogas. The remaining energy content leads to a lower heating value of the digested sludge of about 10 to 8 MJ/kg for 90% dry matter (Bischofsberger et al. 2005). This energy can be used for producing heat and power through thermal combustion or gasification. Furthermore, studies prove that ashes also contain

plant nutrients (Kratzeisen et al. 2010; Neumann et al. 2014).

4. Moreover, a high degree of energy self-sufficiency for municipal WWTP shall be aspired. This is illustrated by deeper analyses of the energy situation of Austrian and German plants. The approximately 12,000 existing plants consume about 4,500 GWh of electric and 1,900 GWh of thermal energy. Therefore, they are responsible for about 20% of the total energy consumption of a municipality (Fricke 2009) and for 1% of the respective total national electricity consumption (Überreiter et al. 2016; Wiechmann et al. 2013).

When considering the disposal restrictions, as well as the necessity for sustainable, decentralised and energy efficient systems, it is important to achieve an optimal integration of the bioenergy potentials into the energy network of municipal WWTP. The developed modular tool enables users to design energy networks and determine their level of self-sufficiency. The energy networks can be generated through the expansion of the system boundaries shown in Figure 1 by the integration of different further treatment units, like gas-fired CHP plants, sludge drying units or thermal sludge utilisation processes. Figure 2 illustrates the expanded system and potential efficient internal energy utilisation paths.

Designing networks with high energy recovery efficiency

To determine an optimum state concerning energy recovery efficiency, various types of plants can be analysed with the developed modular tool. The tool provides an input mask where users can choose their plant configuration by activating the modules seen in Figures 1 and 2. Furthermore, the modules can be specified concerning, for example, the equipment type, rated power, operating hours or efficiencies. Background calculations are based on common equations and assumptions concerning WWTS (DWA 2016; Metcalf & Eddy 2014) and connect the different modules through flows. An error message occurs if technically unfeasible configurations are chosen.

Preliminary analyses based on the average technical configuration of WWTP in Austria and Germany show that the best approach to design a system and analyse the recovery efficiency with the modular tool is a two-step method.

The **first step** is the selection of the type of WWTP, which is possible through the input screen of the developed modular tool. As evident in Figure 1, this includes the choice

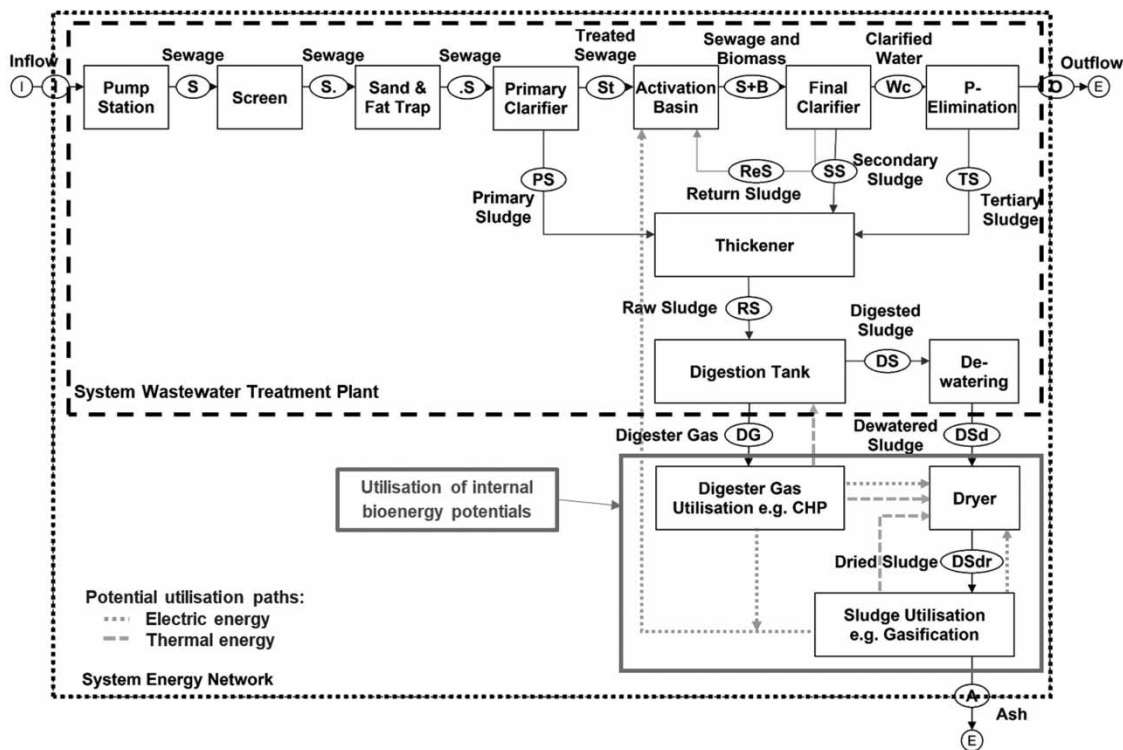


Figure 2 | Structure of the modular model on the system level energy network.

and specification (e.g. equipment type, operating hours, efficiencies) of the units of the modules ‘pump station’, ‘screen’, ‘sand & fat trap’, ‘primary clarifier’ (for anaerobic plants), ‘activation basin’, ‘final clarifier’, ‘p-elimination’, ‘thickener’, and ‘digestion tank’ (for anaerobic plants). Additionally, the unit for the module ‘dewatering’ needs to be defined. Focusing on energy recovery, a low water content (combustion max. 30%, gasification max. 10%) is necessary (Schmid 2015). To reach a DM content of about 30% through dewatering, centrifugation or filter press technology is advisable (DWA 2013). For initial system analyses, an aerobic and an anaerobic model treatment plant is defined to ensure comprehensible results. Some specifications of these plants concerning the included modules are presented in Table 2.

In a **second step**, it is necessary to analyse the possibilities of digester gas and sludge utilisation. As evident in Figure 2, the units and their specifications (e.g. equipment type, operating hours, efficiencies) of the modules ‘digester gas utilisation’, ‘dryer’ and ‘sludge utilisation’ need to be chosen through the input screen of the modular tool. The digester gas is already a widely-used energy source to cover parts of the internal power and heat requirements of a WWTP. Typically installed units are gas-fired CHP plants (Haberker et al. 2008). For the module ‘dryer’,

several drying technologies can be selected. Considering the good system compatibility, the achievable DM content (about 75–98%) and possible heat recovery, low temperature belt dryers represent an attractive option. In Austria and Germany, commonly installed units are disk and drum dryers (Oberberger et al. 2007). For the module ‘sludge utilisation’, two different approaches are available in the tool, a combustion and a gasification unit. It should be mentioned that the gasification provides the opportunity to produce a syngas, which is characterised by a high exergy content and offers the flexibility of producing either electric or thermal energy through gas-fired CHP units, gas turbines or gas boilers. Here, only the energy aspects are considered. Economic, social and ecological aspects must be investigated separately. The model plants (Table 2) for system analyses get expanded with a gas-fired CHP plant for digester gas, a low temperature belt dryer and either a combustion or a gasification unit. The synthesis gas produced by the gasification unit is converted into electricity and heat by a second gas-fired CHP plant.

To optimise the energy recovery efficiency, many factors need to be considered. The modular model offers the possibility to analyse systems individually to determine the specific optimum.

Table 2 | Extract from the plant configuration of the aerobic and anaerobic model plant – activated modules in the designed tool including the module specification

	Unit	Aerobic model treatment plant	Anaerobic model treatment plant
Inflow parameters			
Inhabitants	I	100.000	100.000
Dry weather industrial flow	L/d ^a	0.0	0.0
Dry weather municipal flow	L/(I*d) ^b	210.0	240.0
COD	g/(I*d) ^c	120.0	120.0
BOD ₅	g/(I*d) ^c	60.0	60.0
TSS	g/(I*d) ^c	70.0	70.0
P _{tot}	g/(I*d) ^c	1.8	1.8
N _{tot}	g/(I*d) ^c	11.0	11.0
Pump station			
Unit		Spiral pump	Spiral pump
Screen			
Unit		Fine screen (15 mm)	Fine screen (15 mm)
Sand & fat trap			
Unit		Aeration tank	Aeration tank
Primary clarifier			
Treatment time	h		1.5
Unit			Rectangle basin
Activation basin			
Carbon elimination		Yes	Yes
Nitrification		Yes	Yes
Denitrification		Yes	Yes
Aerobic stabilisation		Yes	No
Sludge age	d	25	15
Ventilation system		Pressure ventilation	Pressure ventilation
Final clarifier			
Unit		Funnel basin	Funnel basin
P-Elimination			
Unit		Chemical	Chemical
Precipitant		Iron salt	Iron salt
Thickener			
Unit for primary sludge			Static thickener
Unit for secondary & tertiary sludge		Drum thickener	Drum thickener
Digestion tank			
Unit			Single-stage, mesophilic
Treatment temperature	°C		38.0
Treatment time	d		25.0
Dewatering			
Unit		Centrifuge	Centrifuge

^aL/d = liters per day.^bL/(I*d) = liters per Inhabitant and day.^cg/(L*d) = gram per Inhabitant and day.

Gasification as one option to gain energy self-sufficiency in wastewater treatment plants

Gasification and combustion are two possible process technologies to convert the energy content of the sewage sludge. Due to the fact that gasification is a less common technology than combustion, a deeper insight is given in this subchapter. Whereas the combustion technology is actually widely used in large centralised plants to treat sludge of surrounded WWTP, gasification is more suitable for a decentralised utilisation, even on small scale plants. This is because gasification is a technology with the ability to deliver high efficiencies even at smaller sizes.

The output of a gasification unit (syngas) is characterised by a high exergy content and offers the flexibility of producing either electric or thermal energy through gas-fired CHP units, gas turbines or gas boilers. Syngas can also be stored and buffered since gas storage elements represent state of the art technologies. To produce a gas with an appropriate quality for combustion units, the sludge must be dried to a minimum DM content of 85%. The electric and thermal energy necessary to run the drying process can be delivered either through a utilisation of the syngas or of digester gas if a digestion tank is included in the energy network (Figure 2).

There already exist wastewater treatment plants with integrated small scale gasification units for the thermal utilisation of sewage sludge in Germany. An example of a plant producing thermal energy for the drier by combusting the syngas is located at Balingen, in southern Germany. A second plant is installed in Koblenz. This plant delivers electrical energy through a gas engine and recovers the sensible energy for the drying process. The gasification units themselves show different process configurations. One of the process configurations is based on a two-step thermal treatment process. In the first step, the dried sludge gets fed into a thermolysis screw. The products of the thermolysis process – gas, carbon and ash – are then subsequently gasified at about 30% of the needed stoichiometric air in a fluidised bed gasification unit. In combination with a gas cleaning process, a good quality syngas can be produced.

Finally, it should be noted that gasification units for sludge as well as small scale combustion units are presently not a state of the art technology. New developments lead to new challenges, like uncertainties concerning reliability, operation safety, compatibility, output quality or economic efficiency. Therefore, it is important to analyse the integration of these units individually based on the specific framework conditions of each site. To analyse the full

potential of these future technologies, the analyses are considered as ‘best case’ analyses. Hence, 8,000 operating hours per year, good compatibility and the best theoretical syngas quality are assumed. The impact of the two thermal sludge utilisation technologies (combustion and gasification) on the recovery efficiency of the energy networks of WWTP are analysed below.

DISCUSSION OF PRELIMINARY RESULTS AND OUTLOOK

Preliminary results based on the defined model plants

Initial analyses with the developed tool are based on the defined model plants (Table 2). As mentioned before, these represent plant configurations established in Austria and Germany. The goal of the analyses is to identify the influence of bioenergy potentials utilisation on the level of energy self-sufficiency of WWTP (Figure 1) and relating energy networks (Figure 2). Therefore, seven configuration scenarios are defined:

1. aerobic plant
2. aerobic plant, *drying and combustion unit*
3. aerobic plant, *drying and gasification unit*
4. anaerobic plant
5. anaerobic plant, digester gas utilisation
6. anaerobic plant, digester gas utilisation, *drying and combustion unit*
7. anaerobic plant, digester gas utilisation, *drying and gasification unit*

Scenarios 1 and 4 represent the first step of designing an optimal system as mentioned above. Therefore, a WWTP including all mechanical and biological treatment processes up to the dewatering unit is analysed (Figure 1). The other scenarios represent the second step of designing. Hence, the scenarios include a digester gas utilisation (for anaerobic plants), a drying unit and either a combustion or a gasification unit (Figure 2). The syngas produced by the gasification unit is converted into electricity and heat by a gas-fired CHP plant.

The results of the preliminary analysis are shown in the following figures. Figure 3 compares the electricity consumption, production and external supply of every scenario.

Figure 4 presents the consumption, production and external supply of thermal energy.

And Figure 5 illustrates the level of electric and thermal self-sufficiency of the seven scenarios. The scenarios are represented by circles with the corresponding number.

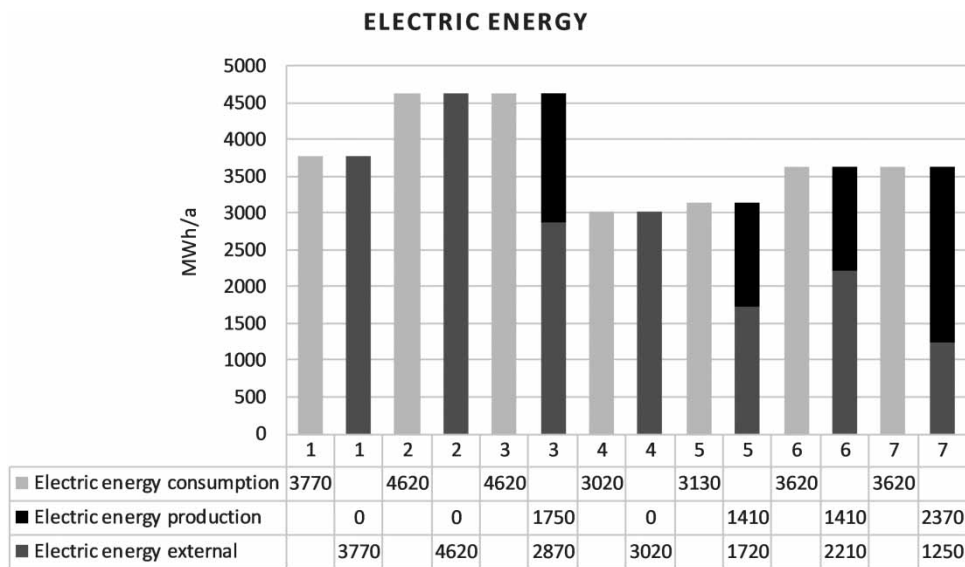


Figure 3 | Consumption, production, and external supply of electric energy of scenarios 1 to 7.

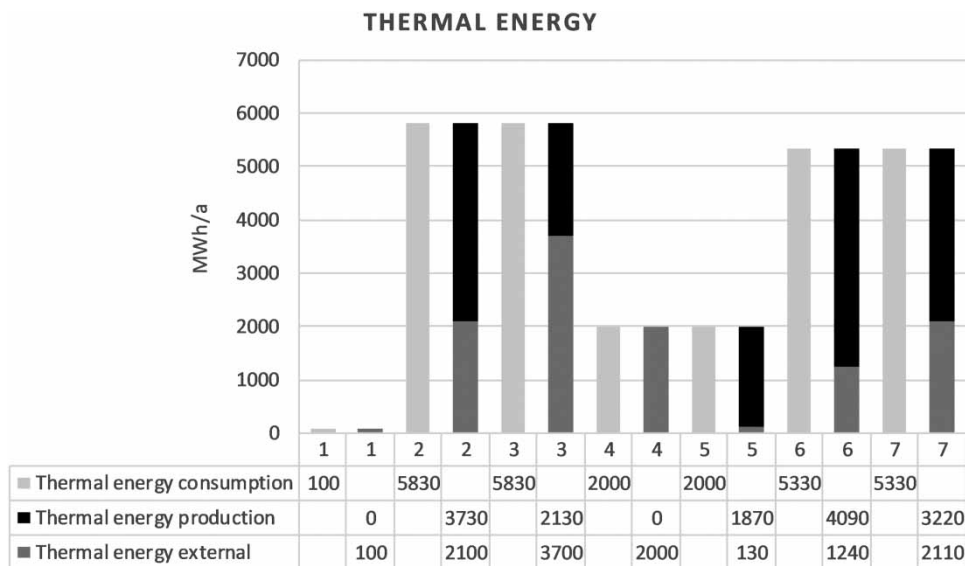


Figure 4 | Consumption, production, and external supply of thermal energy of scenarios 1 to 7.

Figure 6 represents a short monetary assessment of the seven scenarios. The costs for external electric and thermal energy, as well as the costs for sludge and ash disposal are all taken into account. Electric energy costs of 0.20 €/kWh and thermal energy costs of 0.10 €/kWh (DWA 2015) are assumed. Furthermore, disposal costs of about 100 € per ton of sludge or per ton of ash are considered (Oberberger et al. 2007). Due to a lack of representative data, costs related to investments and operating costs are not considered

in these analyses but should be taken into account in plant design decisions.

The initial results show that scenarios 1 and 4 led to a high level of external energy supply, which is accompanied by high energy costs of about 765,000 € and 800,000 € per year. This is due to no energy self-sufficiency. Furthermore, high disposal costs occur for these two scenarios.

When comparing scenarios 2 and 3, the integration of a gasification unit at an aerobic model plant is related with

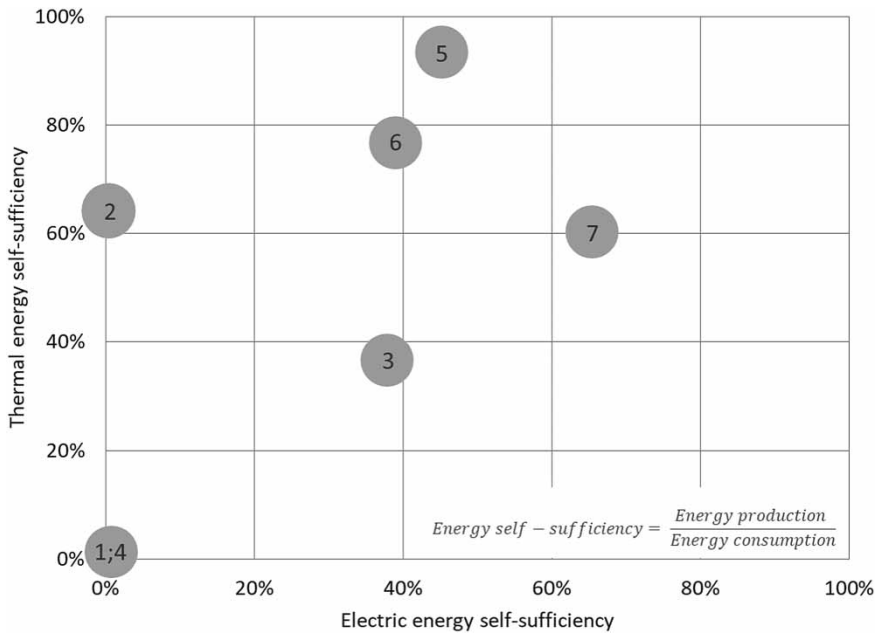


Figure 5 | Electric and thermal energy self-sufficiency of scenarios 1 to 7.

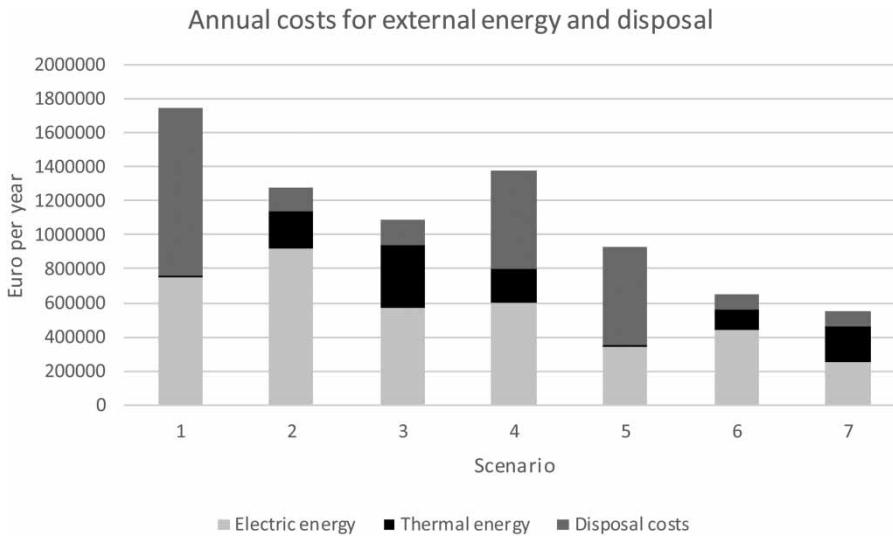


Figure 6 | Costs for external energy and disposal of scenarios 1 to 7.

lower external energy supply as well as lower energy costs. Scenario 2 costs approximately 1,130,000 € per year, while scenario 3 led to annual costs of about 940,000 €. The disposal costs are assumed to be equal for both scenarios. The conversion of synthesis gas produced by the gasification unit induces an increase of the electric energy self-sufficiency.

The scenarios 5 to 7 represent the integration of bio-energy utilisation in anaerobic WWTP. The results illustrate

that scenario 5 generates annual total costs of about 930,000 €, while scenarios 6 and 7 have costs of approximately 650,000 € and 550,000 € per year, respectively. This is due to a higher electric energy self-sufficiency of scenarios 6 and 7. The results demonstrate that scenario 5 represents a good energy network already if no disposal costs for sludge are considered. Future developments should be taken into account for further considerations. The increasing energy and disposal costs, as well as application restrictions will

further increase the attractiveness of decentralised sludge utilisation.

Outlook

Since the results are based on a capacity of 100,000 inhabitants, further analyses for different capacity categories are planned. These results will help answer the following questions:

- Which plant capacity is needed for a reasonable integration of a digestion tank?
- Which kind of digester gas utilisation is suitable for which plant size?
- And is it reasonable from an energy point of view to integrate sewage sludge utilisation even on a small scale WWTP?

This analyses will be performed by using the developed modular tool and are the basis for identifying the role of municipal WWTS as decentralised energy provider in municipal energy systems. After determining the optimal energy networks of municipal WWTP, including the bioenergy potential utilisation, the interaction with the superordinate municipal energy grids (power, heat and gas grid) will be analysed. This will be possible by determining the load and production profiles of the various energy networks. Therefore, the actual modular tool will be improved to generate load and production profiles through a quasi-dynamic simulation via MATLAB.

CONCLUSION

Modelling the bioenergy potentials and their utilisation path reveals the energy recovery potentials and the related influence on the electric and thermal energy self-sufficiency of municipal WWTS. Furthermore, the effect on costs for external energy supply and sludge disposal can be derived. While digester gas is already a widely-used energy source to cover the internal power and head requirement, decentralised sewage sludge utilisation units are not a state of the art technology. But the preliminary scenario based analyses of model plants with a capacity of 100,000 inhabitants concerning the level of energy self-sufficiency show that a digester gas and sewage sludge utilisation should be considered when designing future WWTS. The following results should be pointed out for the aerobic model plant:

- Without a sewage sludge utilisation, annual costs for external energy and disposal of about 1,740,000 € occur.

- The integration of a sludge combustion unit leads to reduced costs of 1,280,000 €/a due to lower disposal costs and a higher thermal energy self-sufficiency.
- Integrating a sludge gasification unit reduces the costs to 1,090,000 €/a. This is based on lower disposal costs and a higher electric energy self-sufficiency.

The following results concerning the anaerobic model plant should be emphasised:

- Without a utilisation of the bioenergy potentials, annual costs for external energy and disposal of about 1,370,000 € are established.
- Taking into account digester gas utilisation in a CHP-plant reduced annual costs of 930,000 € can be reached through lower disposal cost and higher levels of electric and thermal energy self-sufficiency.
- The additional integration of a sludge combustion or gasification unit reduces the annual costs to 650,000 € or 550,000 €. This is due to lower disposal costs. The further reduction by integrating a gasification unit is due to a higher electric energy self-sufficiency of the system.

REFERENCES

- Assmann, M., Dürr, K., Haberfellner-Veit, E., Laber, J., Lindtner, S. & Tschiesche, U. 2015 *Branchenbild der österreichischen Abwasserwirtschaft 2016 (Overview of the Austrian Wastewater Management 2016)*. https://www.umweltfoerderung.at/fileadmin/user_upload/media/umweltfoerderung/Dokumente_Betriebe/Wasser_Betriebe/Studien_Wasserwirtschaft/Branchenbild_2016.pdf (accessed 18 November 2016).
- BDEW and DESTATIS 2010 Zahlen und Fakten der Abwasserentsorgung (Facts and Numbers of Wastewater Management). [https://www.bdew.de/internet.nsf/id/DE_20100910_PM_BDEW_fordert_Abschaffung_der_Abwasserabgabe/\\$file/Informationsbroschuere_Abwasserdaten.pdf](https://www.bdew.de/internet.nsf/id/DE_20100910_PM_BDEW_fordert_Abschaffung_der_Abwasserabgabe/$file/Informationsbroschuere_Abwasserdaten.pdf) (accessed 18 November 2016).
- Bischofsberger, W., Dichtl, N., Rosenwinkel, K. H., Seyfried, C. F. & Böhnke, B. (eds) 2005 *Anaerobtechnik (Anaerobic Technology)*. Springer, Heidelberg, Germany.
- Council of European Communities 1986 *Directive on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge is Used in Agriculture (86/278/EEC)*. Official Journal L181.
- DESTATIS 2016 *Wasserwirtschaft: Klärschlamm Entsorgung aus der öffentlichen Abwasserbehandlung (Water Management: Sewage Sludge Disposal From the Public Wastewater Treatment)*. <https://www.destatis.de> (accessed 24 January 2017).
- Döhler, H. & Schliebner, P. 2006 Verfahren und Wirtschaftlichkeit der Gärrestauffbereitung (Process and management of digestion treatment). *KTBL-Schrift*:

- Verwertung von Wirtschafts- und Sekundärrohstoffen in der Landwirtschaft – Nutzen und Risiken* **444** (1), 191–199.
- DWA 2013 *Arbeitsblatt DWA-A 216: Energiecheck und Energieanalyse (Worksheet DWA-A 216: Energy Check and Energy Analysis)*. DWA, Hennef, Germany.
- DWA 2015 *Schlammfäulung oder gemeinsame aerobe Stabilisierung bei Kläranlagen kleiner und mittlerer Größe (Sludge Digestion or Combined Aerobic Stabilization in Small- and Medium-Sized Sewage Treatment)*. https://de.dwa.de/tl_files/_media/content/PDFs/Abteilung_VuM/kostenlose_Fallbeispiele_aus_DWA_T1_Schlammfäulung.pdf (accessed 10 February 2017).
- DWA 2016 *Arbeitsblatt DWA-A 131: Bemessung von einstufigen Belebungsanlagen (Worksheet DWA-A 131: Plant Design of one-Stage Aeration Plants)*. DWA, Hennef, Germany.
- Frey, W. 2012 *Stand und Trends bei der Faulgasverwertung von Kläranlagen (Status and Trends in the Digester Gas Utilisation of Sewage Plants)*. http://www.aabfrey.com/wp-content/uploads/2012/03/TU_Sem_2012_Text.pdf (accessed 24 January 2017).
- Fricke, K. 2009 *Energieeffizienz kommunaler Kläranlagen (Energy-Efficiency of Municipal Sewage Plants)*. <https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3855.pdf> (accessed 28 March 2017).
- Haberker, B., Maier, W., Schneider, U., Arbeitsgemeinschaft iat, Universität Stuttgart, TU Kaiserslautern and Ryser Ingenieure Bern 2008 *Steigerung der Energieeffizienz auf kommunalen Kläranlagen (Increases in the Energy Efficiency of Municipal Sewage Plants)*. <https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3347.pdf> (accessed 10 March 2016).
- Kratzisen, M., Starcevic, N., Martinov, M., Maurer, C. & Müller, J. 2010 *Applicability of biogas digestate as solid fuel*. *Fuel* **89** (9), 2544–2548.
- Loll, U., Evers, P., Glasenapp, J. & Kassner, W. 2004 *Klärschlammfall und Bemessungsansätze: Neue Erweiterte ‘Schlammliste’ (Sewage Sludge Treatment and Design Approaches: New Expanded Sludge List)*. DWA, Hennef, Germany.
- Metcalf & Eddy I AECOM 2014 *Wastewater Engineering: Treatment and Resource Recovery*, 5th edn. McGraw-Hill, New York, NY, USA.
- Neumann, J., Binder, S., Apfelbacher, A., Gasson, J. R., Ramírez Carcía, P. & Hornung, A. 2014 *Production and characterization of a new quality pyrolysis oil, char and syngas from digestate*. *Journal of Analytical and Applied Pyrolysis* **113** (12), 137–142.
- Obernberger, I., Suspancic, K. & Polzer, A. 2007 *Untersuchung der Stoffflüsse und sinnvollen Verwertung von sowie Reststoffnutzung aus Klärschlamm in der Steiermark (Investigation of Material Flows and Efficient Utilisation of Residual Materials From Sewage Sludge in Styria)*. http://www.abfallwirtschaft.steiermark.at/cms/dokumente/10689314_46576/286682dc/Kl%C3%A4rschlammstudie%20Steiermark.pdf (accessed 15 June 2016).
- Olivia, J., Bernhardt, A., Reisinger, H., Domenig, M. & Krammer, H. J. 2009 *Klärschlamm – Materialien zur Abfallwirtschaft. Report (Sewage Sludge – Materials for Waste Management)*. <http://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0221.pdf> (accessed 6 February 2017).
- ÖWAV 2014 *Klärschlamm als Ressource (Sewage Sludge as a Resource)*. <http://www.oewav.at/Kontext/WebService/SecureFileAccess.aspx?fileguid={b3718331-98a6-4fe1-95bf-69105431395b}> (accessed 26 January 2017).
- Rehl, T. & Müller, J. 2011 *Life cycle assessment of biogas digestate processing technologies*. *Resources Conservation and Recycling* **56** (1), 92–104.
- Schmid, B. 2015 *Exergetisch hochwertige Nutzung von Klärschlamm (High Quality Exergetic Use of Sewage Sludge)*. University of Leoben, Leoben, Austria.
- Splithoff, H. (2010) *Power Generation From Solid Fuels*. Springer-Verlag, Berlin, Germany.
- Überreiter, E., Lenz, K., Zieritz, I., Weber, K. & Eder, I. 2016 *Kommunales Abwasser – Österreichischer Bericht 2016 (Austrian Report – Municipal Wastewater 2016)*. https://www.bmlfuw.gv.at/wasser/wasser-eu-international/europaeische_wasserpolitik/Lagebericht-2016.html (accessed 24 January 2017).
- Wiechmann, B., Dienemann, C., Kabbe, C., Brandt, S., Vogel, I. & Roskosch, A. 2013 *Klärschlamm Entsorgung in der Bundesrepublik Deutschland (Sewage Sludge Disposal in Germany)*. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/klaerschlamm Entsorgung_in_der_bundesrepublik_deutschland.pdf (accessed 24 January 2017).

First received 14 December 2017; accepted in revised form 6 May 2018. Available online 14 May 2018