

Resource recovery from wastewater in Austria: wastewater treatment plants as regional energy cells

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ABSTRACT

Although the main function of a wastewater treatment plant (WWTP) is to remove various constituents from wastewater it can also serve as a source of energy and other materials. The generated resources can be used either on-site at the WWTP or elsewhere at an adjacent infrastructure. In the course of a current national research project, the possibilities and potentials regarding the integration of WWTPs into local energy supply concepts are being investigated in Austria. Preliminary results show that in particular the amount of thermal energy available exceeds by far the on-site demands of WWTPs. Even on-site electrical energy demands could be self-addressed under certain conditions. This paper describes the estimation of total energy consumption and generation and the related degree of energetic self-sufficiency at certain Austrian WWTPs. Preliminary results regarding the development of a tool for evaluating and optimising on-site and externally supplied use of energy are presented. Finally, the possibilities of energy supply for neighbouring spatial structures are discussed briefly and conclusions drawn about the potential to develop WWTPs as regional energy cells.

Key words | anaerobic sludge treatment, digester gas, heat exchanger, heat pump, material/energy flow, spatial planning

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INTRODUCTION

To strengthen the competitiveness of the European Union and its Member States in a fast changing world, the [European Commission \(n.d.\)](#) defines five strategic targets to be reached by 2020. Regarding the issues of climate change and energy sustainability, the sub-targets are as follows: greenhouse gas emissions must be 20% lower than 1990, 20% of the consumed energy has to come from renewable sources and energy efficiency has to be increased by 20%.

In the search for renewable and climate-friendly energy sources, wastewater has come into view of science and practice. International research is focusing more and more on energy and resource recovery from wastewater ([Rulkens 2008](#); [Verstraete et al. 2009](#); [Stillwell et al. 2010](#); [McCarty](#)

[et al. 2011](#); [Mo & Zhang 2013](#); [Batstone et al. 2015](#); [Gude 2015](#)). Wastewater basically contains two different types of energy ([Frijns et al. 2013](#)): chemical energy in the form of carbon compounds, and thermal energy from urban wastewater discharge. Today the use of chemical energy for biogas generation during anaerobic sludge treatment is implemented at several wastewater treatment plants (WWTPs) where provision of electrical and thermal energy can be achieved by cogenerating the biogas in combined heat and power systems ([Mo & Zhang 2013](#); [Nowak et al. 2015](#)). The application of this technology is obviously limited to WWTPs equipped with digester towers. The use of the thermal heat content of wastewater by means of

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heat exchangers and heat pumps is still not very common, and application is limited to a handful of countries with about 500 estimated applications worldwide (Mo & Zhang 2013), mainly located in Switzerland, Germany and Scandinavia (Hepbasli *et al.* 2014). The use of the thermal energy content of wastewater can take place at different locations in the wastewater infrastructure: in-house (Meggers & Leibundgut 2011), in the sewer systems (Dürrenmatt & Wanner 2014) and in the effluent of a WWTP (Chae & Kang 2013). In contrast, the possible location for the use of chemical energy is restricted to WWTPs as the digestion towers are situated there. Furthermore, WWTPs can also be an adequate location for additional energy generation: mechanical energy from hydro-power installations in the treated effluent and wind power installations within the premises of the WWTP, as well as solar energy from photovoltaic and solar thermic installations on the vacant surfaces of a WWTP (Chae & Kang 2013; Mo & Zhang 2013). These technologies are not connected to the type of sludge stabilisation, and could be implemented at any WWTP. The fact that WWTPs may concentrate different sources of energy on a single location can allow them to play a central role within the wastewater infrastructure from an energetic point of view.

Besides energy generation from wastewater in general, the energetic optimisation of WWTPs towards self-sufficiency (energetic independency) is being addressed in recent international literature (Kind & Levy 2012; Nowak *et al.* 2015). Today, WWTPs (especially those with aerobic sludge treatment) strongly depend on an external energy supply (electricity, natural gas, etc.). According to Lindtner (2008), electricity is needed for the wastewater treatment process (inflow pumping station, mechanical pre-treatment, biological treatment), sludge treatment (mechanical thickening, possibly digestion, dewatering) and for infrastructure (heating, light, etc.). Thermal energy is needed for infrastructure (heating of buildings, hot water production) and sludge treatment (pre-heating of sludge, digester heating, compensation of transmission losses). One possibility to reduce energy demand is to optimise machinery use and operational processes in the WWTPs (Panepinto *et al.* 2016). Another possibility is to intensify on-site energy generation at the WWTPs beyond the common combined heat and power systems (Mo & Zhang 2013). Having a multiplicity

of possibilities for energy generation at hand raises the question of the most appropriate and economical technology. Today, no adequate evaluation tool is available for this purpose. Furthermore, WWTPs are usually just seen as regional energy consumers. Applying multiple technologies for energy recovery from wastewater and energy generation in general might lead to a surplus of energy at WWTPs. In this case, WWTPs could serve as regional energy cells providing adjacent infrastructure with electricity and/or heat. However, an evaluation will be necessary to define the most appropriate and economic way for the integration of WWTPs into regional energy supply concepts. It has to be mentioned that not only technical and operational data concerning the WWTPs have to be considered, but also information on spatial structures in the adjacent area.

In April 2013, a national 3-year research project focusing on the integration of wastewater infrastructure into regional energy supply concepts was launched in Austria. The main goals of the project are the following: estimation of the energetic potential from Austrian wastewater infrastructure, considering aspects of spatial planning; development of a tool for evaluating and optimising on-site and externally supplied material and energy flows of WWTPs to integrate WWTPs into regional energy supply concepts; and practical application of the tool at three different case studies.

The paper will focus on two different aspects. First, a rough estimation of the available electrical and thermal potential at Austrian WWTPs with anaerobic sludge treatment will be carried out. Based on this estimation, the achievable degrees of electrical and thermal self-sufficiency and thus the potential quantities of surplus energy will be described. Second, preliminary results regarding the development of the tool for evaluating and optimising on-site and externally supplied use of energy (optimisation of material and energy flows in WWTPs, respectively) will be presented.

MATERIAL AND METHODS

Energy consumption and generation of WWTPs

In 2010 in Austria there were 1,841 WWTPs larger than 50 population equivalent (PE). Those WWTPs have a total

treatment capacity of about 21.5 million PE. The treated wastewater volume was about 1,061 million m³ per year. Out of the total number of WWTPs, 635 have a capacity of 2,000 PE or more (BMLFUW 2011, 2012). Industrial WWTPs and the related wastewater volumes are not considered.

To get a first impression of the energetic potential with respect to the integration of WWTPs into regional energy supply concepts, the energy consumption (electricity, heat) and generation (electricity, heat) of certain Austrian WWTPs will be estimated. One basis for this estimation will be the standard ranges of energy consumption and generation at Austrian WWTPs from Lindtner (2008) given in Table 1.

Regarding thermal energy, the data in Table 1 consider only the heat generated from digester gas. It does not contain the thermal energy from (treated) wastewater. However, as the total wastewater flow for Austria as well as the specific thermal capacity of (waste-) water is known, estimations can be carried out. For the estimation of energy consumption the following approach has been applied: total electrical, respectively, thermal energy consumption at WWTPs (EC_{el} , EC_{th}) is the product of the current load of the WWTPs in PE and an electrical, respectively, thermal consumption factor (CF_{el} , CF_{th}) derived from the data given in Table 1.

$$EC_{el} = PE \times CF_{el} \quad (1)$$

$$EC_{th} = PE \times CF_{th} \quad (2)$$

The estimation of the total energy generation at WWTPs based on the use of digester gas (EG_{el-DG} , EG_{th-DG}) will be

made analogously:

$$EG_{el-DG} = PE \times GF_{el-DG} \quad (3)$$

$$EG_{th-DG} = PE \times GF_{th-DG} \quad (4)$$

For the estimation of thermal energy potential based on wastewater heat recovery from the effluent of WWTPs, the following approach has been applied: the thermal potential (EG_{HR}) is the product of the total wastewater flow (V_{WW}), the specific thermal capacity of water (c), the cooling of the wastewater (ΔT) and the full-load operating time of the applied heat pump (OT).

$$EG_{HR} = V_{WW} \times c \times \Delta T \times OT \quad (5)$$

Depending on the seasonal performance factor (COP) of the applied heat pump, the thermal potential (EG_{HR-HP}) can even be increased by taking the electrical energy of the heat pump into account:

$$EG_{HR-HP} = EG_{HR} \times COP / (COP - 1) \quad (6)$$

Optimisation of energy flows of WWTPs

As mentioned above, WWTPs may not only serve as consumers, but also as providers of certain types of energy and other resources. In the sense of an efficient (energetic) operation of a WWTP, optimisation at the detailed level of machinery use and operational processes is one important aspect. However, another crucial task is to optimise the different energy flows (and other resources) at superior system level. In this regard, both internal (on-site) as well as external sources and consumers have to be considered.

In the current project, the system will be optimised using process network synthesis (PNS), based on the p-graph method (Friedler et al. 1995). PNS is a method to optimise material and energy flow networks. Its aim is to determine the optimal system of process technologies to transform resources into products (including energy). The approach of process synthesis is already state of the art in process engineering to generate process structures in industries, based on

Table 1 | Standard ranges of energy consumption and generation at Austrian WWTPs (Lindtner 2008)

	Consumption [kWh/PE*a]		Generation* [kWh/PE*a]	
	From	to	from	To
Electric energy	20	50	10	20
Thermal energy	0	30	20	40

*Generated from digester gas.

input–output relations for unit operations. These methods have also been applied to regional material flow networks such as WWTPs (Lam *et al.* 2011; Niemetz *et al.* 2012; Maier & Gemenetzi 2014; Maier & Narodoslowsky 2014).

PNS-Studio (Friedler *et al.* 2011) provides an on-line tool to perform this optimisation. First, a maximum structure of all feasible technology networks will be created. Based on material and energy flows and transport distances, the program then calculates an optimum energy network as a solution (see Figure 1). This optimal technology network is generated from the maximum structure of all feasible networks by a branch and bound optimisation algorithm. The optimum structure represents the ideal use of resources in terms of the highest economic benefit for the region.

As discussed above, the first step in applying PNS for WWTPs optimisation is to define the maximum structure of on-site and externally supplied material and energy flows. In this context, two different types of WWTPs are considered: WWTPs with aerobic and anaerobic sludge stabilisation, respectively. According to Kindermann & Kollmann (2015) the procedure to generate the maximum structure comprises three steps: specification of (raw) materials, specification of operating units (technologies) and specification of products.

Figure 2 gives an overview of the input and output resources of a WWTP (resource consumption and

generation). The corresponding options to further use the generated resources on site and/or externally supplied (ext. sup.) are also displayed.

For the PNS maximum structure set-up, raw materials (input) such as wastewater, electricity and gas supply from public providers as well as bio-waste (cooking oils) were considered.

Regarding the products (output), and depending on the type of WWTP (aerobic or anaerobic sludge stabilisation), the maximum structure of the PNS considers intermediate products (output) such as treated wastewater, stabilised sewage sludge and digester gas. Intermediate products are the basis for generation of (final) products. The possible products are reusable treated wastewater (process water), heating and cooling energy, electric power, processable sewage sludge (nutrient recovery, etc.) and natural gas substitute (gas feed-in).

The PNS maximum structure will not only distinguish between WWTPs with aerobic or anaerobic sludge stabilisation, but will also consider different sub-technologies, for instance heat exchangers and heat pumps, gas burners, combined heat and power systems, etc.

Identifying the optimum structure for a certain WWTP requires information on the prices for all types of raw materials and products. Technologies will be specified by their input and output flows of material and energy, as

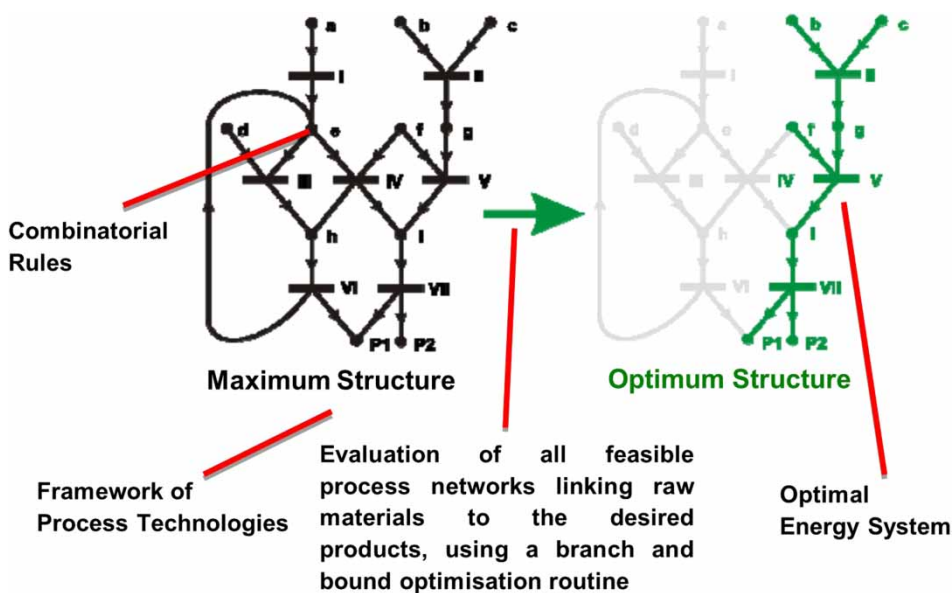


Figure 1 | Maximum and optimum structure of a technology network (Friedler *et al.* 1995, adapted).

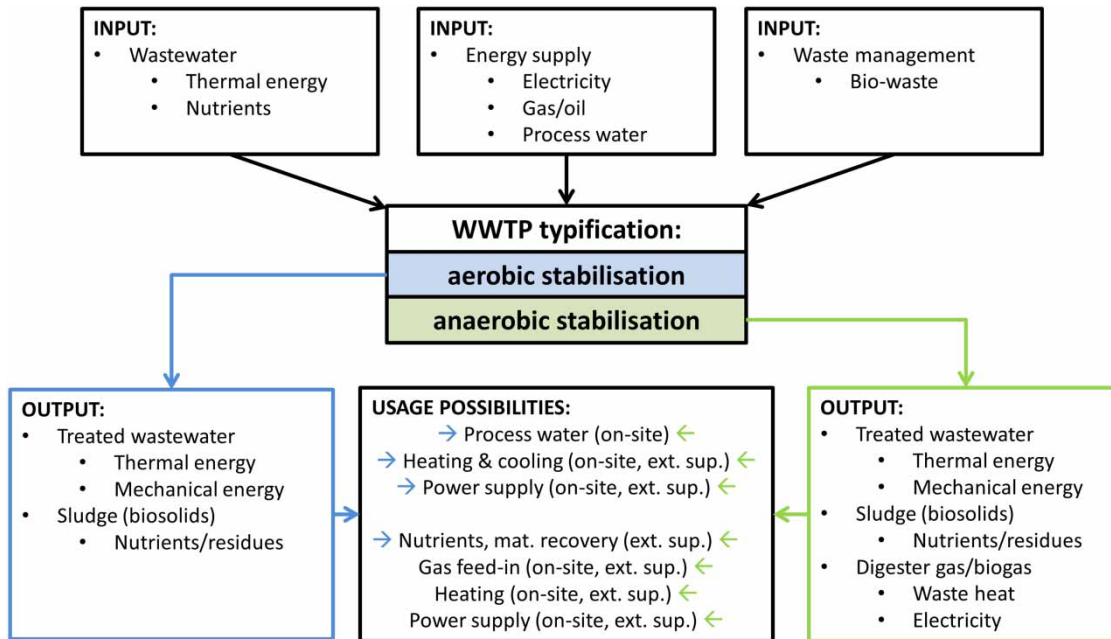


Figure 2 | Resources consumption (input) and generation (output) at WWTPs, and possibilities to further use the generated resources.

well as investment and operating costs. Boundaries can be set to limit the capacity of technologies. Furthermore, additional wastewater-related aspects, such as time-dependent properties due to changing wastewater temperatures, have to be considered as well (Kindermann & Kollmann 2015).

RESULTS AND DISCUSSION

Energy consumption and generation of WWTPs

According to Spatzierer (2012), 159 of the Austrian municipal WWTPs are equipped with digester towers (out of the above-mentioned 635 WWTPs with a design capacity of at least 2,000 PE). These WWTPs represent a treatment capacity of about 11.6 million PE (around 55% of the total

capacity of municipal WWTPs), representing a current load of about 7.9 million PE (EEA 2012). On the one hand, electrical and thermal energy from digester gas processing can be made available at these WWTPs. On the other hand, thermal energy can be retrieved from the wastewater (effluent) by the use of heat exchangers and heat pumps. The latter is also available at WWTPs without digester towers. However, regarding the estimation of energy consumption and generation, the focus in this paper is on digester gas-producing WWTPs.

Table 2 shows estimated energy consumption and generation of WWTPs including digestion towers. For the calculation of energy consumption and generation from digester gas, Equations (1) and (2), respectively, Equations (3) and (4) were applied. The calculated values are based on a current load of about 7.9 million PE and the energy

Table 2 | Estimated energy consumption and generation of WWTPs including digestion towers

	Consumption [GWh/a]		Generation from digester gas [GWh/a]		Generation from wastewater [GWh/a]
	Electric	Thermal	Electric	Thermal	Thermal
Average performance	277	119	119	237	510
Optimised performance	158	119	158	316	681

standard ranges mentioned in Table 1 (CF_{el} and CF_{th} , respectively, GF_{el-DG} and GF_{th-DG}). Average and optimised performance in the first column refer to the performance of the WWTPs. Based on the ranges given in Table 1, average performance represents mean values in energy consumption and generation (for electric and thermal energy from digester gas processing). Optimised performance represents minimum values for energy consumption (as the minimum value regarding thermal energy consumption is zero, the mean value was also used here) and maximum values for energy generation.

The estimation of thermal energy from wastewater (application of Equation (5)) is based on a municipal wastewater flow of about 1,061 million m^3 per year (BMLFUW 2011). The estimated pro rata dry weather flow of the WWTPs with digester towers (V_{WW}) is about 390 million m^3 per year (about 40,000 m^3/h). The specific thermal capacity of water (c) is 1.16 kWh/ $m^3 \cdot K$; this value was adopted for wastewater. Further, it was assumed that the wastewater in the effluent will be cooled down by 5 K (ΔT) and the annual duration of thermal extraction (OT) is 2,200 hours (this value can be higher if the system is not only operated during the winter period). The average value only considers the thermal energy content of wastewater. The optimised value comprises the electric energy use of a heat pump with a seasonal performance factor of 4 (application of Equation (6)).

The ratio between energy consumption and generation gives the degree of self-sufficiency of the considered WWTPs. In Table 3, the different values are given. It seems that self-sufficiency regarding electric energy can be achieved or even exceeded in the case of boundary conditions and WWTPs performing near the optimum. However, the

thermal energy generated during digester gas processing usually exceeds the WWTP demands even under average conditions. If heat extraction from wastewater (effluent) is also considered, the WWTP can certainly be regarded as a significant regional source of thermal energy. This statement also applies to WWTPs without digestion towers.

The figures presented in Tables 2 and 3 should be seen as a rough estimation, because detailed calculations are very site-specific and also depend on the type of WWTP. Nonetheless, it is clear that there is a significant potential for external supply of thermal energy. In contrast to electricity, which can be fed to the power supply grid at almost every point, the supply of thermal energy is a more complicated task (with lower spreading of head supply systems, and infeed temperature constraints). Heat loss in the transportation system is a major issue in thermal energy supply. There are technical solutions to counteract the problem, for instance pipe isolation, cold and warm district heating options and the like. But the distance between the heat generation and heat consumption sites remains of crucial importance for the overall heat loss and economic feasibility. In some cases, the availability of potential energy consumers within certain distances around WWTPs represents the limiting factor rather than the thermal energy capacity (Project Consortium 'Energie aus Abwasser' 2012). Therefore, spatial management and planning are of great importance by interlinking potential present and prospective energy consumers and available excess energy. It can be seen as the key for exploring the currently almost unused thermal surplus of about 600–900 GWh/year.

Optimisation of energy flows of WWTPs

Figure 3 shows the PNS maximum structure for a WWTP with anaerobic sludge stabilisation. The structure comprises different raw materials (raw wastewater, natural gas, electricity and bio-waste), technologies (the WWTP itself, digestion tower, heat exchanger and heat pump, etc.), intermediate products (digester gas, treated sewage sludge, etc.) and final products (electricity, heat, etc.). Additionally, all possible material/energy flows between raw materials, technologies, intermediate products and final products are defined.

This PNS maximum structure is currently being applied in three different case studies at Austrian WWTPs. Based on

Table 3 | Degree of self-sufficiency regarding electrical and thermal energy

	Degree of self-sufficiency [%]		
	Electric energy	Thermal energy	
		Excluding wastewater	Including wastewater
Average performance	43	200	631
Optimised performance	100	267	841

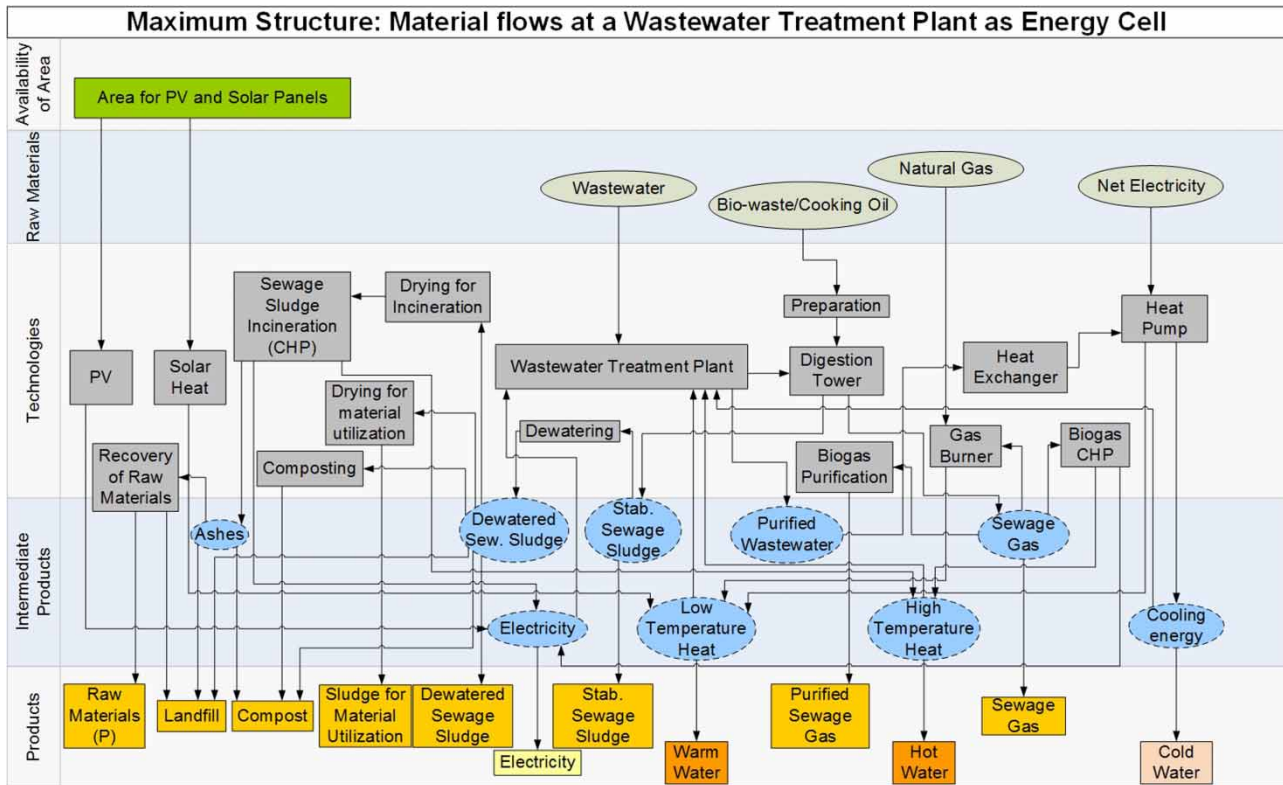


Figure 3 | Current version of the maximum structure regarding material/energy flows at a WWTP with anaerobic sludge stabilisation.

the outcomes of stakeholder workshops, the maximum structure was adapted to the local context (technical features of the WWTP, existing energy supply infrastructure, etc.) at each site. Based on local costs for raw materials, technologies and products, the best (most cost efficient) structure of the examined system will be calculated. Preliminary PNS analysis at one case study site has already confirmed the possibility of energetic self-sufficiency of WWTPs mentioned above: the on-site heat demand of the WWTP can be met easily. Thermal excess energy could be supplied to neighbouring consumers at competitive cost.

PNS application can play a central role in integrating WWTPs into regional energy supply concepts, as it supports the merging of two major aspects from an economic point of view: theoretical excess energy generation at a WWTP with a diversity of different technologies, and the actual energy demand of adjacent consumers. The optimisation of a certain energy generation and supply system (energy flows and applied technologies) can be seen as a rather dynamic process, as it strongly depends on generated energy quantities and

related energy prices. Regional planning can certainly have a greater influence on the former than on the latter. The targeted location of heat-demanding consumers in close vicinity to a WWTP would consolidate its position as a regional energy provider. According to Neugebauer & Stöglehner (2015) the following options for the use of surplus thermal energy can be considered: agricultural and forestry purposes (dewatering of agricultural and forest products, heating of barns, heating of greenhouses, aquaculture) and low temperature heating demands in settlement areas (residential, commercial and industrial needs). Existing energy supply infrastructures may compete with thermal energy provision gained from wastewater, but also offer possible synergies.

CONCLUSIONS

The main function of a WWTP is to remove certain constituents from wastewater. For the treatment processes and the maintenance of the infrastructure, different sorts of energy

and other resources are being consumed. However, WWTPs also generate different kinds of energy and other resources.

In the course of a current research project, the possibilities and potentials regarding the integration of WWTPs into local energy supply concepts are being investigated in Austria. Preliminary results show that, in particular, the amount of thermal energy available from digester gas processing and heat recovery from wastewater exceeds by far the on-site demands of WWTPs. The currently almost unused thermal surplus at WWTPs with anaerobic sludge stabilisation is about 600–900 GWh/year. Also WWTPs could be self-sufficient in on-site electrical energy demands under certain conditions.

For the positioning of WWTPs as regional energy cells, the evaluation and optimisation of material/energy flows of WWTPs in a regional context is an important issue. PNS can be applied to identify optimum flows within a defined system. Currently a wastewater-related PNS maximum structure comprising different raw materials, technologies and products is being set up and applied at three different WWTPs case studies in Austria. The goal of these analyses is to define the most appropriate solution for merging excess energy generation potentials at the considered WWTPs and the actual energy demands in their adjacent infrastructure. Based on the experiences gained in the case studies, a user friendly version of the PNS tool will be developed.

To increase thermal energy demand in the close vicinity of WWTPs, the targeted location of appropriate consumers is of crucial importance. For an optimised integration of WWTPs into regional energy supply systems, it is absolutely necessary to consider local boundary conditions and limitations such as spatial planning at an early planning stage.

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REFERENCES

- Batstone, D. J., Hülsen, T., Metha, C. M. & Keller, J. 2015 *Platforms for energy and nutrient recovery from domestic wastewater: a review*. *Chemosphere* **140**, 2–11.
- BMLFUW 2011 Schmutzfrachteintrag und Abwasserentsorgung (Pollutant Load Discharge and Sewage Disposal). <http://www.lebensministerium.at/wasser/wasserqualitaet/abwasserreinigung/schmutzfrachteintrag.html> (accessed November 2011).
- BMLFUW 2012 *Kommunale Abwasserichtlinie der EU-91/271/ EWG-Oesterreichischer Bericht 2012 (Council Directive 91/271/EEC Concerning Urban Wastewater Treatment: Austrian Report 2012)*. Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management (BMLFUW), Vienna.
- Chae, K.-J. & Kang, J. 2013 *Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources*. *Energy Conversion and Management* **75**, 664–672.
- Dürrenmatt, D. J. & Wanner, O. 2014 *A mathematical model to predict the effect of heat recovery on the wastewater temperature in sewers*. *Water Research* **48**, 548–558.
- European Commission n.d. *Europe 2020 Targets*. <http://ec.europa.eu/europe2020/targets/eu-targets/> (accessed September 2013).
- European Environmental Agency EEA 2012 *Waterbase-UWWTD Urban Waste Water Treatment Directive*. <http://www.eea.europa.eu/data-and-maps> (accessed August 2012).
- Friedler, F., Varga, J. B. & Fan, L. T. 1995 *Decision-mapping: a tool for consistent and complete decisions in process synthesis*. *Chemical Engineering Science* **50**, 1755–1768.
- Friedler, F., Tarjan, K., Huang, Y. W., Fan, L. T., Varga, J. B. & Feher, E. 2011 P-graph, PNS Software Version 3.0.4, 2011. www.p-graph.com (accessed 29 January 2014).
- Frijns, J., Hofman, J. & Nederlof, M. 2013 *The potential of (waste) water as energy carrier*. *Energy Conversion and Management* **65**, 357–363.
- Gude, V. G. 2015 *Energy and water autarky of wastewater treatment and power generation systems*. *Renewable and Sustainable Energy Reviews* **45**, 52–68.
- Hepbasli, A., Biyik, E., Ekren, O., Gunerhan, H. & Araz, M. 2014 *A key review of wastewater source heat pump (WWSHP) systems*. *Energy Conversion and Management* **88**, 700–722.
- Kind, E. & Levy, G. A. 2012 *Energieeffizienz und Energieproduktion auf ARA (Energy Efficiency and Energy Generation at WWTP)*. Swiss Federal Office of the Environment, Bern.
- Kindermann, H. & Kollmann, R. 2015 *Optimisation of regional energy systems centred on wastewater treatment plants*. *Sustainable Sanitation Practice* **22** (1/2015), 10–24.
- Lam, H. L., Varbanov, P. & Klemeš, J. 2011 *Regional renewable energy and resource planning*. *Applied Energy* **88** (2), 545–550.
- Lindtner, S. 2008 *Leitfaden fuer die Erstellung eines Energiekonzeptes kommunaler Kläranlagen (Guideline for*

- the development of an energy concept for municipal wastewater treatment plants*). Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management (BMLFUW), Vienna.
- Maier, S. & Gemenetzi, A. 2014 [Optimal renewable energy systems for industries in rural regions](#). *Energy, Sustainability and Society* **4**, 9.
- Maier, S. & Narodoslowsky, M. 2014 Optimal renewable energy systems for smart cities. In: *Computer Aided Chemical Engineering, 24th European Symposium on Computer Aided Process Engineering*, Vol. 33, Elsevier, pp. 1849–1854.
- McCarty, P. L., Bae, J. & Kim, J. 2011 [Domestic wastewater treatment as a net energy producer: can this be achieved?](#) *Environmental Science & Technology* **45**, 7100–7106.
- Meggers, F. & Leibundgut, H. 2011 [The potential of wastewater heat and exergy: decentralized high-temperature recovery with heat pump](#). *Energy and Buildings* **43**, 879–886.
- Mo, W. & Zhang, Q. 2013 [Energy-nutrients-water nexus: integrated resource recovery in municipal wastewater treatment plants](#). *Journal of Environmental Management* **127**, 255–267.
- Neugebauer, G. & Stöglehner, G. 2015 Realising energy potentials from wastewater by integrating spatial and energy planning. *Sustainable Sanitation Practice* **22** (1/2015), 15–21.
- Niemetz, N., Kettl, K. H., Eder, M. & Narodoslowsky, M. 2012 Regiopt conceptual planner – identifying possible energy network solutions for regions. *Chemical Engineering Transactions* **29**, 517–522.
- Nowak, O., Enderle, P. & Varbanov, P. 2015 [Ways to optimize the energy balance of municipal wastewater systems: lessons learned from Austrian applications](#). *Journal of Cleaner Production* **88**, 125–131.
- Panepinto, D., Fiore, S., Zappone, M., Genon, G. & Meucci, L. 2016 [Evaluation of the energy efficiency of a large wastewater treatment plant in Italy](#). *Applied Energy* **161**, 404–411.
- Project Consortium ‘Energie aus Abwasser’ 2012 Energie aus Abwasser–Abwasserwaerme–und–kaeltenutzung mittels hocheffizienter Grosswaermepumpen (Energy from Wastewater: Heat and Cold Extraction from Wastewater Using High Efficiency Heat Pumps). Vienna.
- Rulkens, W. 2008 [Sewage sludge as a biomass resource for the production of energy: overview and assessment of the various options](#). *Energy and Fuels* **22**, 9–15.
- Spatzierer, G. 2012 OEWA-V-Klaeranlagen-Leistungsvergleich–Berichtsjahr 2011 (*Wastewater Treatment Plant Performance Benchmarking*). Austrian Water and Waste Management Association, Vienna.
- Stillwell, A. S., Hoppcock, D. C. & Webber, M. E. 2010 [Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus](#). *Sustainability* **2**, 945–962.
- Verstraete, W., Van de Caveye, P. & Diamantis, V. 2009 [Maximum use of resources present in domestic ‘used water’](#). *Bioresource Technology* **100**, 5537–5545.

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