Energetic flexibility on wastewater treatment plants

M. Schäfer, I. Hobus and T. G. Schmitt

ABSTRACT

In the future, an additional potential of control reserve as well as storage capacities will be required to compensate fluctuating renewable energy availability. The operation of energy systems will change and flexibility in energy generation and consumption will rise to a valuable asset. Wastewater treatment plants (WWTPs) are capable of providing the flexibility needed, not only with their energy generators but also in terms of their energy consuming aggregates on the plant. To meet challenges of the future in regard to energy purchase and to participate in and contribute to such a volatile energy market, WWTPs have to reveal their energetic potential as a flexible service provider. Based on the evaluated literature and a detailed analysis of aggregates on a pilot WWTP an aggregate management has been developed to shift loads and provide a procedure to identify usable aggregates, characteristic values and control parameters to ensure effluent quality. The results show that WWTPs have a significant potential to provide energetic flexibility. Even for vulnerable components such as aeration systems, load-shifting is possible with appropriate control parameters and reasonable time slots without endangering system functionality.

Key words | energetic flexibility, energy management, load-shifting, wastewater treatment plants

M. Schäfer (corresponding author)
T. G. Schmitt
Institute of Urban Water Management,
University of Kaiserslautern,
D-67663 Kaiserslautern,
Germany
E-mail: *michael.schaefer@bauing.uni-kl.de*

I. Hobus
WiW-Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH,
D-42289 Wuppertal,
Germany

INTRODUCTION

Water and energy systems are strongly linked but are mostly managed independently. Energy is needed to pump, purify, distribute and use water – so is water to produce and use energy. The future will differ from the past in terms of technology, efficiency and political decision making, which present important challenges to both sectors (DOE 2014). One of these new challenges will arise due to a high share of fluctuating renewable energy generation leading to an additional need for control reserve as well as storage capacities. This demand is caused by the abandonment of nuclear power and the reduction of fossil-based energy production, which in the past covered a large part of the basic load. In Germany, the demand is more urgent due to the commitment to raise the part of renewable energy to 80% by 2050 (BMWi 2010). In the traditional way, energy is delivered from big base-load power plants to the consumers. In the future a multi-directional flow from small decentralised power plants to consumers who are able to operate as a producer as well is possible. Under these circumstances, the operation of energy grids driven by solar and wind-based energy production won't be sustainable, and the arising energy surpluses and deficits have to be balanced by flexible energy generators and consumers in terms of ancillary and system services. This will face providers with new challenges for system operation (Sterner & Stadler 2014). The flexibility needed is defined as a modification to the energetic consumption pattern in the forms of time and quantity (York & Kushler 2005) and is divided into two effective directions:

- positive flexibility: energy production is increased and energy consumption is reduced;
- negative flexibility: energy production is reduced and energy consumption is increased.

Small decentralised units are able to provide that flexibility (Huneke *et al.* 2016). The integration of widely available wastewater treatment plants (WWTPs) with anaerobic sludge digestion could be a suitable part of the solution with their electrical consumers, energy production via combined heat and power (CHP) units, as well as gas storage units to provide the needed (energetic) flexibility (Schäfer *et al.* 2016). So far, the main focus of attention is on big emergency power generators or CHP units that can meet the needed technical requirements for participation in energy markets by pooling them in a virtual power plant (VPP) by

doi: 10.2166/wst.2017.308

a so called 'pooler' (ASUE 2010). In recent years WWTPs have received more and more focus for pooling their energy production units, leading even to own WWTP-pools with a special focus on their own framework (WVE 2015). Furthermore, innovative approaches with controlled gas production to increase energetic flexibility are shown in Hien & Hansen (2016) and Lensch et al. (2016). However, not only CHP units and emergency power systems are able to provide flexibility. Several other aggregates on WWTPs are capable of providing flexibility as well. Especially aeration systems, which represent more than 65% of the overall energy consumption of WWTPs (Kolisch & Mergelmeyer 2014) are promising for further consideration. Several studies examined aggregates (mostly aerators) for different purposes which are typically demand response in smart grids (Thompson et al. 2008, 2010; Aghajanzadeh et al. 2015) or general potential analysis for load-shifting (Müller et al. 2013; de Bruyn et al. 2014; Nowak et al. 2015). In these studies, aggregates are chosen from practical experience (plant operators) and rough assumptions for a single plant. A 'guideline' for choosing potential aggregates or even including control parameters and the conditions of their usage are not stated or published. Apart from this, technical restrictions and specifications which have to be met to participate in potential flexibility markets are not considered. The focus of this research will be on evaluation of present knowledge and own studies in terms of load-shifting to build a data basis to examine electrical flexibility and verify the procedure at a pilot WWTP to derive assessments for providing flexibility. It should not be considered as a marketing concept to participate in energy markets in general, but to make a contribution for WWTPs to define the position regarding the potential of energetic flexibility, independent from the specific use (e.g. balancing the transmission grid, distribution grids or internal load-shifting). There is a gap of knowledge for a consistent approach to identify aggregates and which requirements they have to meet regarding start-up time, regeneration time, and the borders of existing switch-off times for specific aggregates and their control parameters to guarantee effluent quality.

MATERIAL AND METHODS

Basic data

Description of the pilot plant

The pilot WWTP is designed as an activated sludge plant with anaerobic sludge digestion and an influent load of about 58,000 population equivalents (PE) in 2014 (related to 120 g COD/PE).

The first stage of treatment consists of a screen, an aerated grit chamber and a primary sedimentation tank with solids retention time of 60 min. The second stage consists of two activated sludge aeration tanks with a total volume of 19,536 m^3 (13,536 m^3 + 6,000 m^3). The first basin is a two stage cascade with pre-denitrification. The ratio of denitrification volume to overall volume of the aeration tank (V_D/V_{BB}) can be adjusted via variable usable chambers. The second four-line aeration tank is operated through intermittent aeration without agitators. The aeration is controlled by means of an on-line ammonia (NH_4) and nitrate (NO_3) analyser located at the effluent from the first and second aeration basin to ensure full nitrification. Phosphorus removal is assured by simultaneous precipitation in the first aeration tank. In three secondary sedimentation tanks, the effluent is clarified. Surplus sludge is mechanically thickened and, together with thickened primary sludge, is fed into two digestion tanks with 1,440 m^3 each. The digested sludge is thickened and drained by two chamber filter presses. A flow chart of the plant is given in Figure 1.

In the anaerobic sludge digestor around 17.33 l/(PE · d) raw biogas with a methane (CH_4) content of 58% is generated, producing 12.54 kWh/(PE · a) of electric power with two CHP units (2 · 80 kW_{el}). As a result the WWTP covers 42.3% of its total energy demand of 29.6 kWh/(PE · a) with its own digester gas. 13.8 kWh/ (PE · a) are used for aeration and 15.8 kWh/ (PE · a) by the other treatment steps and devices.

Data basis of energy consumption and production

For the pilot, WWTP electric data have been available in high quality for the main aggregates (15-minute increments for the year 2014). Power consumption was directly measured or could be calculated by analysing additionally operating hours and the mode of operation. Using the nominal power of the aggregates as a basis is not conducive because energy consumption is fluctuating on a daily level. The actual consumption differs from the nominal power and would overestimate the available flexibility significantly. On the basis of these data, a representative day (in 15-minute increments) in regard to actual energy consumption is generated for each aggregate and summarised in a time course. Seasonal variations in terms of influent water amount, influent load and heat demand etc. are neglected, but implicitly included by mean values (data covered over the whole year 2014) of the time series. Furthermore, fluctuations and variability of the results of the simulation model

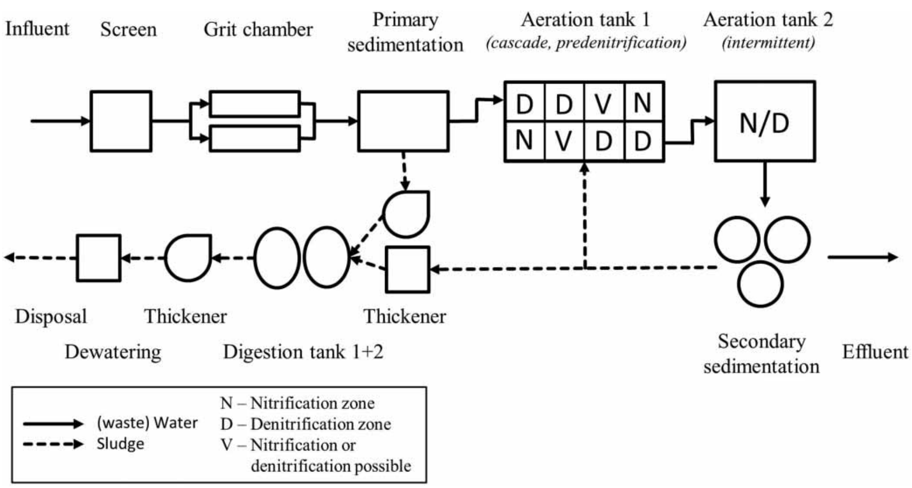

Figure 1 | Flow chart of the pilot WWTP, regarding wastewater and sludge treatment paths.

are better taken into account. Most aggregates are controlled anyway on a daily routine rather than controlled by input parameters. So it is anticipated as a sufficient database for further evaluation.

Evaluation of literature and own studies regarding flexibility

Table 1 shows that there are only few published data referring to load-shifting on WWTPs. As stated before, the selection of criteria of the aggregates is not described in detail, instead it refers to assessments of the operating personnel. Furthermore, the focus of attention is on load-shedding, while powering up aggregates is not considered as feasible. Technical restrictions of the aggregates are unconsidered or generally considered as usable. Several methods in terms of characterisation of the aggregates in fixed time slots for switch-off times (5/15/30/60+ minutes) and/or just textual descriptions of possible obstacles are described, e.g. Müller *et al.* (2013), de Bruyn *et al.* (2014)

Table 1 | Switch-off times for WWTP components used for load-shifting

	Switch-off time					
	Müller *et al.* (2013)		De Bruyn *et al.* (2014)	Nowak *et al.* (2015)	Berger *et al.* (2013)	Own study[a]
	(min)		(min)	(min)	(min)	(min)
Aggregates	**Night**	**Day**				
Inlet pumps	30–60	15–30	5	30	usable *(spiral pumps)*	–
Grit chamber	30	30	5–15 *(scraper)*	usable	–	**60**
Aeration (aeration tank)	60–120	30	15	60–120	15	**60**[b]
Recirculation pumps	–	–	15	usable	–	**60**
Agitator (aeration tank)	30	15	5–15	10–15	–	**30**
Return sludge pumps	120	60	5–15	60–120	–	**120**[b]
Digestion tank	>120[c]	<120[c]	–	120–240[d]	–	**>240**[e]
Dewatering/thickening	not usable	>120 *(decanter)*	240 *(centrifuge)*	usable[f]	–	**120**

The utilisation of inlet pumps, wastewater pumps and centrifuges are confirmed as well in Thompson *et al.* (2010) and Aghajanzadeh *et al.* (2015).
[a]Based on the operational experiences of three different WWTPs.
[b]Load-shedding tested on three different WWTPs.
[c]Including pumps, agitator and heat exchanger.
[d]Including agitator and pumps.
[e]Including pumps and heat exchanger.
[f]Including centrifuge, chamber filter press, screw press and surplus sludge thickening.

and Nowak *et al.* (2015). Verifications for the chosen assumptions are just given in Nowak *et al.* (2015) for the aerators (ASM1-Model) and in field trials for the aerators in Thompson *et al.* (2010). However, there is no unification or standardisation for requirements, procedure of selection or establishing of control parameters for the individual utilisation. Therefore, switch-off times were determined based on the operational experiences of three different WWTPs.

Characteristic values

To shift (electric) loads in a WWTP it is essential to know the technical restrictions of the usable devices (Figure 2) as well as their effects during the purification process. The main parameters originating from the energy sector are power output and how fast the full power-output is available (subsequently called start-up time and shut-down time). The consumption/feed-in gradient is determined by dividing the power output by its corresponding start-up/shutdown time. Furthermore, there are other parameters needed, taking into account limitations of the wastewater treatment. These parameters are regeneration time (required time between two sequences of switching a device on/off) and the duration an aggregate can be switched on or off with regard to the actual operation mode. For the analysis of the needed parameters for further utilisation in terms of flexibility of the aggregates, it is presumed that they still serve the purpose in the plant, e.g. an agitator should at least be active for 15 minutes to stir the tank and should not be activated or deactivated just by technical feasibility. Under these circumstances, the defined values for switching-on/off aggregates are estimated conservatively and could be technically below the stated values.

Procedure for identifying usable aggregates

Identifying possible aggregates is one of the critical steps in the course of developing aggregate management for WWTPs. For the pilot WWTP, basis data have been given in a first step in the form of a full aggregate list, energy consumption data and operating data. These data are usually gathered during energy optimisation studies of WWTPs and is easily available. In a second step, aggregates were chosen by intersecting these data with known literature data in terms of load-shifting studies and technical requirements as well as recommendations and verification of the operating personnel of the plant. This evaluation of primary data of the whole WWTP led to an examination in the form of detailed consideration of the preselected aggregates including their possible integration, emerging restrictions, total power output and the individual characteristic values. A simplified schematic description is given in Figure 3.

RESULTS AND DISCUSSION

Identified aggregates

For the pilot WWTP, 18 aggregates have been identified for load-shifting and to provide flexibility (Table 2). The provided values are the result of the identifying processes shown in Figure 3 and performed field tests as well as simulation results for the different aggregates on the plant. As stated before, continuous processes during the purification processes are more difficult to integrate than discontinuous processes, e.g. sludge treatment. Especially for devices with direct influence on the performance of the plant, control

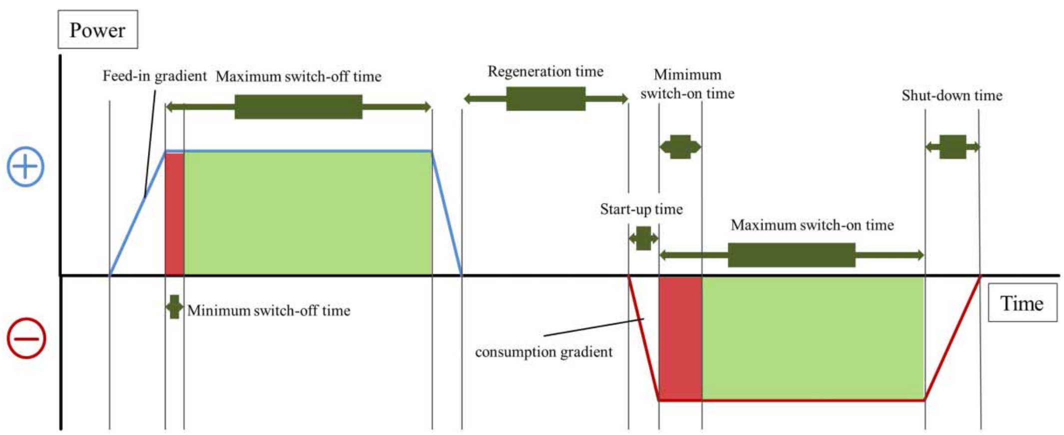

Figure 2 | Schematic representation of characteristic values for positive and negative flexibility of aggregates/consumers.

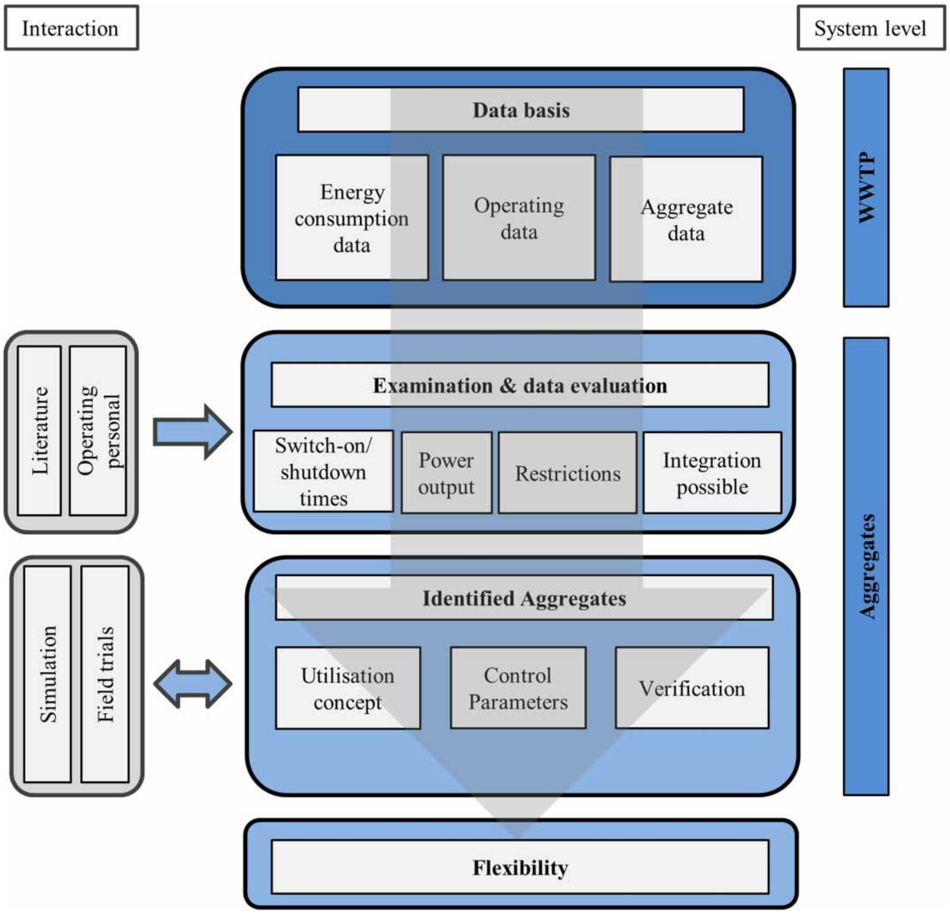

Figure 3 | Simplified schematic procedure to identify and verify aggregates for providing flexibility.

Table 2 | Characteristic values of the pilot WWTP for identified aggregates to provide flexibility (min/max)

Aggregate	Effective power[a] (kW)	Switch-off time [min./max.] (min)	Switch-on time [min./max.] (min)	Regeneration time (min)	Start-up time (s)	Shut-down time (s)
Grit chamber *(aeration, intermittent)*	2.1/2.1	5–60	5–60	30	60	60
Aeration tank 1 + 2 *(aeration, intermittent)*	0.0/61.6–98.9	5–120	–	15	10	5
Aeration tank 1 *(agitator, intermittent)*	7.2/3.6–10.8	15–30	15–40	30	60	60
Return sludge pumps	0.0/16.1–23.6	5–120	–	60	60	5
Recirculation pumps	0.0/4.2	5–1,440	–	30	60	60
Digestion tanks 1 + 2 *(heat sludge pumps)*	6.0/6.0	15–1,440	15–1,440	60	10	5
Digestion tanks 1 + 2 *(raw sludge pumps)*	0.0/2.0	15–360	–	60	120	60
Surplus sludge thickening	9,6/0.0	–	120–1,440	15	60	900
Chamber filter presses 1 + 2	15.0/0.0	–	120	60	120	120
CHP unit 1 + 2	80.0/80.0	5–1,440	5–1,440	5/30[a]	180	300
Emergency generator	0.0/480.0	–	15–240	2.5	60	30

[a]Negative flexibility/positive flexibility.

parameters are inevitable and have to be set with safety factors. Field testing and/or the application of a simulation model is highly recommended. Furthermore, it is shown that even for sensitive aggregates load-shifting is possible and WWTPs have sufficient buffer capacities to compensate and shift processes even for vulnerable sectors in wastewater treatment. Tests on additional WWTPs in addition to the pilot plant have shown that small WWTPs often have a greater flexibility potential due to oversized devices than larger (mostly highly optimised) plants. It has also become evident that the connection to the internal control technology is an important factor, e.g. for a full automated sludge thickening device the full potential of flexibility can be provided without further conditions, but manually operated devices need operating staff, which leads to restriction in time availability, additional effort/costs for personnel and further planning to use the aggregate. Besides that, a fixed limitation for choosing aggregates by their power output is not applicable because smaller aggregates could be internally connected to larger units and would be ignored. For example, the surplus sludge module consists of 8 aggregates below 4 kW_{el} but sum up to 12.7 kW_{el} controlled as a single unit.

In terms of using the devices of the digester tanks, such as heating pumps, switch-off/-on times below 60 minutes are not critical due to the slow response time of the system. Calculations have shown that over a time period of 24 hours the temperature drop is below 1 °C (depending on thermal insulation). The temperature of the digester tank can be controlled very well and it could be probably even used as a 'power-to-heat'-device where energy can be stored in the form of heat during energy surplus, and the energy needed for heating can be shifted. Using aggregates from the digester tank is mostly restricted by local boundary conditions like sludge composition and procedural obstacles rather than technical restrictions. Providing flexibility on energy markets with CHP units and emergency generators is state of the art (ASUE 2010). Many new cogeneration units even include the communication technology for the connection to the VPP or pool operator to bear the incurred costs, resulting in no investment costs for plant operators. Maximum switch-off and switch-on times heavily depend on the size of the gas storage and an optimised timetable for using that flexibility without losses in gas utilisation. Aggregates with nominal power of 2–5 kW_{el} are considered economically unfeasible if it is required to undertake additional investments or if they are difficult to implement in a management system. Furthermore, pool operators will not include devices below 50 kW_{el}. On the basis of that fact a 'pre-pooling' with existing control technology at the plant of most aggregates is recommended and necessary to use the aggregates in connection with energy grids.

Control parameters

An important aspect of shifting loads is to restrict flexibility-calls by establishing control parameters to protect treatment processes if it becomes necessary. As general control parameters for all aggregates, switch on/off times as well as the regeneration time stated in Table 2 are recommended. Furthermore, additional and more individual control parameters for each single aggregate are necessary (Table 3). Especially, wet-weather conditions are pushing the related systems to their limits and narrow buffer capacities for flexibility options of the continuous processes like the grit chamber or return-sludge pumps significantly. Other restrictions are related to their individual operation mode, like non-interruptible sludge dewatering processes. CHP units and emergency generators are mainly limited by their gas/fuel storage and warranty issues (e.g. max. switching cycles, reduced service life). Additional control parameters may be necessary on the basis of individual procedural aspects on the plant.

Review of control parameters

The suitability of the aggregates and their suggested control parameters are verified by a mathematical model (Activated Sludge Model 1) of the pilot WWTP using simba 6.4. Each critical aggregate is individually simulated either for load-shedding or power up energy demand to confirm the usability, to verify the control parameters, detect negative side effects, and ensure effluent quality. A whole year was simulated to consider the variability of the influent load to the WWTPs. Furthermore, some of the identified aggregates (aerators in the aeration tanks, return sludge pumps and recirculation pumps) are tested in real shutdown field trials at three different WWTPs to verify the model and the actual feasibility of the device. The tests are performed for 30, 60 and 120 minutes of shutdown (in dry weather conditions). Figure 4 shows the results of the field trials and the simulation of shutting down the aeration systems of the plant for 60 minutes. It is demonstrated for the pilot WWTP that shutting down the aeration systems is possible without significant loss in effluent quality by releasing 150 kW_{el} electrical energy.

The control parameter on this occasion is the NH_4 effluent of the aeration tank, which should not exceed 3 mg NH_4/l. The NH_4-effluent of the secondary treatment

Table 3 | Suggested additional control parameters for different aggregates in the WWTP

	Control parameter	
Aggregate	**1**	**2**
Inlet pumps	Retention capacity *(upstream sewer system, retention basin)*	–
Grit chamber *(aeration)*	Wastewater inflow[a]	–
Aeration tank *(aeration)*	NH_4 *(aeration tank and effluent secondary sedimentation)*	NH_4-load *(inflow)*
Aeration tank *(agitator)*	Time restriction due operation mode	–
Return sludge pumps	Wastewater inflow[a]	Sludge level
Recirculation pumps	NO_3 *(aeration tank)*	–
Digestion tank *(heat sludge pumps)*	Temperature *(min/max)*	–
Digestion tank *(raw sludge pumps)*	Fill-level raw sludge thickener *(min/max)*	–
Digestion tank *(agitator)*	Foam formation	–
Surplus sludge thickening	Dry matter content[b] *(aeration tank)*	Operation mode/staff working time[c]
Sludge dewatering[d] *(Chamber filter presses/centrifuges/ spiral pumps)*	Fill-level thickener *(min/max)*	Operation mode/staff working time[c]
CHP units	Fill-level gas storage *(min/max)*	Max. switching cycles
Emergency generator	Fill-level fuel storage *(min/max)*	Max. operating hours[e]

[a]Preventing plant overload (stormwater).
[b]Preventing over-extraction of surplus sludge.
[c]Depending on degree of automation.
[d]Sludge dewatering is mostly not interruptible.
[e]Regulated in German law (180 h/a).

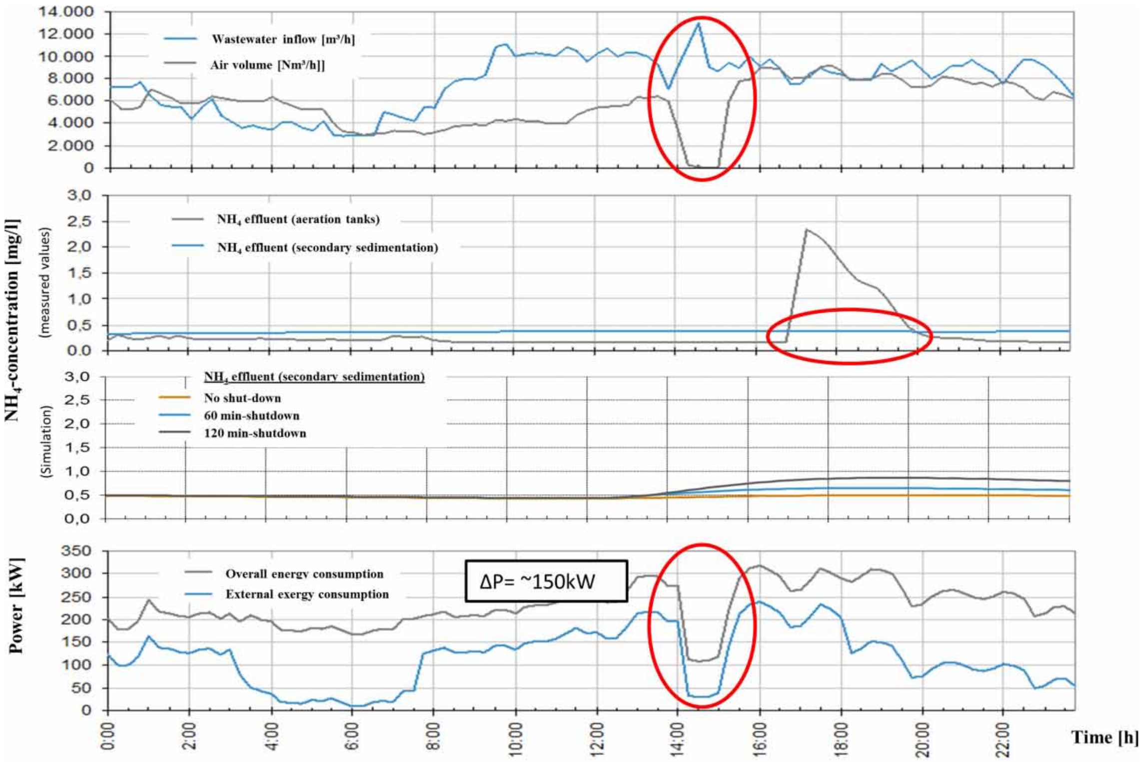

Figure 4 | Impacts of load-shedding of the aerators on NH_4-effluent and power consumption.

shows that there is no notable impact and the characteristic values and restrictions, presumed in a first approach, are confirmed (Figure 4). For other WWTPs, the chosen values can be used as reference points and if necessary, adapted iteratively.

Calculated flexibility and utilisation

The results show that the overall energy consumption of the plant can be decreased with the considered aggregates by 24.4% of the overall energy consumption if no restriction is violated. With regards to powering up the CHP units, no external consumption would be necessary. For positive flexibility, an increase in energy consumption is possible up to 19.9%. By using the gained knowledge in their control system, the pilot WWTP was able to cut peak loads in their energy demand and could optimise their schedules with more flexible operation modes to save money and resources with small effort. Further integration of the aggregate management is planned.

Outlook

Further research is planned to improve the data basis for characteristic values and control parameters for additional aggregates. Based on the results of this study, the behaviour of the WWTP will be tested for calls of the energy market by means of data from the German control energy market in 2014 as well as for predicted market values in 2030. This will show the performance of WWTPs in providing ancillary services and how effluent quality will be affected by participation under present conditions. This information will be important to prove that the shown flexibility is not only important for internal energy management but WWTPs are able to act as both consumer and a producer and flexible player in future energy markets.

CONCLUSIONS

The results presented show that WWTPs have a significant potential to provide energetic flexibility. Even for vulnerable components, load-shifting is, with appropriate control parameters and reasonable time slots, possible without endangering system functionality. Of course, this has to be considered individually taking the local framework of the WWTP into account. Technical restrictions in terms of limiting start-up and shut-down times of the aggregates are not to be expected, but restrictions in terms of maximum switching cycles per day or reduced service life may occur. As a first step, the CHP units offer good opportunities to gain first experiences with energy markets. On the basis of existing experiences in reducing external energy demand and energy self-sufficiency efforts, know-how in adapting CHP schedules is widely spread, which will ease integration. Potentials for providing negative flexibility and ancillary services with CHP units in WWTPs are described in Schäfer *et al.* (2015). However, to identify and establish an aggregate management, it is essential to include the operating staff of the plant from the beginning. A working aggregate management is only feasible with individual and detailed knowledge of the particular WWTP and their cooperative personnel. In terms of approval by the plant operators, there is a lack of knowledge for innovative energy management.

Due to a missing monetary incentive system, participating in energy markets is not yet sufficiently attractive for plant operators. There are just a few research projects and even less published practical implementations on this topic, whilst energy self-sufficiency studies are very common. The stated results may provide assistance to create a basis for future endeavours. High reservations especially regarding effluent quality are widely spread, although an utilisation is possible under controlled conditions for certain plants. Such objections are appropriate and important because the primary task of the WWTP is purifying wastewater and is mandatory. Thus, additional long-term effects due to long shut-down times (e.g. phosphate resolution in aeration tanks or changes in the biocenosis) have to be investigated and require detailed monitoring. Nonetheless, potentials and approaches shouldn't be abandoned due to their innovative character. With a higher share of renewable energies, the demand and value of flexibility will increase and energy purchase will change to more volatile prices during the day and could lead to dynamic power purchasing agreements. Future consumers could have disadvantages due to their inflexibility in a field of flexible participants. This could trigger the needed incitements to deal with complex topics like energy management during day-to-day business. Therefore further research and practical experiences are necessary to implement aggregates of WWTP into smart control systems to provide the needed detailed data for a fast changing energy environment.

ACKNOWLEDGEMENTS

The study was conducted as a part of the research project *arrivee* (www.erwas-arrivee.de). The authors would like to thank the German Federal Ministry for Education, Research and Technologies (BMBF) for the financial support.

REFERENCES

Aghajanzadeh, A., Wray, C. & McKane, A. 2015 Opportunities for Automated Demand Response in California Wastewater Treatment Facilities. August 2015.

ASUE 2010 *Virtuelle Kraftwerke (Virtual Power Plants)*. Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch E.V. (ASUE), Berlin, Germany.

Berger, H., Eisenhut, T., Polak, S. & Hinterberger, R. 2013 *Demand Response Potential of the Austrian Industrial and Commerce Sector*. Bundesministerium für Verkehr, Innovation und Technologie, Vienna, Austria.

BMWi 2010 *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung (Energy Concept for an Environmentally Friendly, Reliable and Affordable Energy Supply)*. Bundesministerium für Wirtschaft und Technologie (BMWi), Berlin, Germany (Ministry for Economy and Technology). September 2010.

De Bruyn, K., Kollmann, A., Moser, S., Schmidthaler, M., Amann, C., Elbe, C., Schmautzer, E., Kraussler, A., Reinhofer-Gubisch, M., Pucker, J. & Frantes, B. 2014 *Projekt LoadShift: Lastverschiebung in Haushalt, Industrie, Gewerbe und kommunaler Infrastruktur Potenzialanalyse für Smart Grids (Load-shifting in Private Households, Industry and Municipal Infrastruktur. Potential Analysis for Smart Grids)*. Bundesministerium für Verkehr, Innovation und Technologie, Linz/Graz, Austria.

DOE 2014 *The Water-Energy Nexus: Challenges and Opportunities*. US Department of Energy (DOE), Full Report. June 2014.

Hien, S. & Hansen, J. 2016 Biogasprognose zur Integration von Kläranlagen in virtuelle Kraftwerke (Biogas forecast for integration of wastewater treatment plants in virtual power plants). In: *Proceedings of 44. Abwassertechnisches Seminar*, Munich, Germany, pp. 61–73.

Huneke, F., Lizzi, P. & Lenck, T. 2016 *Bisherige Auswirkungen des Kernkraftausstiegs auf die Versorgungssicherheit (Past Effects of the Exit From Nuclear Power on Supply Reliability)*. Energy Brainpool, Berlin, Germany. August 2016.

Kolisch, G. & Mergelmeyer, M. 2014 *Optimierung der Klärgasnutzung, Steigerung der Energieausbeute auf kommunalen Kläranlagen (Optimisation of using Digestion Gas, Increasing Energy Yield on Wastewater Treatment Plants)*. Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes NRW (MKUNLV). Final Report. October 2009.

Lensch, D., Schaum, C. & Cornel, P. 2016 Examination of food waste co-digestion to manage the peak in energy demand at wastewater treatment plants. *Water Science and Technology* **73** (3), 588–596.

Müller, E., Graf, E., Kobel, B., Hurni, A., Wenger, R., Frei, U., Christen, C., Moser, R., Fritzsche, C., Mathys, O., Kernen, M. & Fahrni, J. 2013 *Potential der Schweizer Infrastrukturanlagen zur Lastverschiebung (Potential of Swiss Infrastructure Plants for Load Shifting)*. Final Report. Bern, Switzerland. June 2013.

Nowak, O., Enderle, P., Schloffer, M., Lang, E. & Pregartbauer, R. 2015 *Loadshift-ARA – Lastverschiebung in der Abwasserreinigung – Kommunale Kläranlagen als Bestandteil smarter Energiesysteme*. Final Report. Vienna, Austria.

Schäfer, M., Gretzschel, O., Knerr, H. & Schmitt, T. G. 2015 Wastewater treatment plants as system service provider for renewable energy storage and control energy in virtual power plants – a potential analysis. *Energy Procedia* **73**, 87–93.

Schäfer, M., Schmitt, T. G. & Sinß, M. 2016 Die Kläranlage als Regelbaustein im Energienetz (*Wastewater treatment plants as control units in energy grids*). In: *Proceedings 3rd Conference Future energy grids with renewable energy*. Federal Ministry for Economic Affairs and Energy (BMWi). 26–27 January, Berlin, Germany.

Sterner, M. & Stadler, I. 2014 *Energy Storage – Demand, Technologies, Integration*. Springer-Verlag, Berlin Heidelberg, Germany.

Thompson, L., Song, K., Lekov, A. & McKane, A. 2008 *Automated Demand Response Opportunities in Wastewater Treatment Facilities*. Ernest Orlando Lawrence Berkley National Laboratory, Environmental Energy Technologies Division, Berkeley, CA.

Thompson, L., Lekov, A., McKane, A. & Piette, M. A. 2010 *Opportunities for Energy Efficiency and Open Automated Demand Response in Wastewater Treatment Facilities in California – Phase II Report – San Luis Rey Wastewater Treatment Plant Case Study*. Ernest Orlando Lawrence Berkley National Laboratory, Environmental Energy Technologies Division, Berkeley, CA.

WVE 2015 *WVE bündelt Klärgasanlagen zu virtuellem Kraftwerk (WVE is Pooling Wastewater Treatment Plants as a Virtual Power Plant)*. EUWID Wasser und Abwasser. WA43/2015. p. 13.

York, D. & Kushler, M. 2005 *Exploring the Relationship Between Demand Response and Energy Efficiency: A Review of Experience and Discussion of Key Issues*. American Council for an Energy-Efficient Economy. Report Nr. U052. Washington, DC, USA. March 2005.

First received 24 January 2017; accepted in revised form 8 May 2017. Available online 25 May 2017