Short-term flexibility for energy grids provided by wastewater treatment plants with anaerobic sludge digestion

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ABSTRACT

For a sustainable development of the energy sector – in the future – an additional potential of energetic flexibility as well as storage capacities will be required to compensate for fluctuating renewable energy production. The operation of energy systems will change and flexibility in energy generation and consumption will rise to become a valuable asset. Wastewater treatment plants (WWTPs) with anaerobic sludge digestion are capable of providing that needed flexibility, not only with their energy generators but also in terms of their energy consuming aggregates on the plant. Under these circumstances a methodical approach has been developed that can be used to select, evaluate and safely implement typical aggregates on WWTPs for flexible plant operation and the provision of energetic flexibility. Relevant key figures have been developed that reconcile requirements of the purification processes with technical-physical necessities as well as the demands of the energy market. Furthermore, restrictions and control parameters have been established which complement the developed key figures to ensure effluent quality. It was demonstrated that WWTPs are able to adapt their operation mode to external and internal requirements under controlled conditions. The existing flexibility is suitable for a variety of uses, and WWTPs in general are able to participate in today's and in future energy supply products and new business models. The results show that WWTPs have a significant potential to produce renewable energy and to provide energetic flexibility, which is needed to stabilize future renewable-energy-driven energy grids.

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

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INTRODUCTION

In the future, a reorganization of the energy sector and a fundamental transformation of the electrical energy supply system are required. This is caused by abandoning of nuclear power, the reduction of fossil-based energy production and the rising share of renewable energy production. Under these circumstances the operation of energy grids, which is driven by a highly volatile solar and wind based energy production, cannot be maintained as before in the long term. Consequently occurring energy surpluses and deficits have to be balanced by flexible energy generators and consumers (BMWI 2014; DENA 2014; Sterner & Stadler 2016). Especially Germany is forced to find sustainable solutions in the context of its energy transition. Energy and water systems are linked and constantly interact with each other. Energy is needed to pump, purify and distribute water – so is water, to produce energy. The future will differ from the past in terms of technology, efficiency and political decision making, which will present important challenges to both sectors (DOE 2014).

For the aforementioned reasons, there will be a growing demand for energetic flexibility to stabilize electricity grids and guarantee system functionality. The flexibility required is defined as a modification to the energetic consumption pattern in forms of time and quantity and is divided into two effective directions (York & Kushler 2005; Dena 2017):

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doi: 10.2166/wst.2019.365

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

For flexibility, various utilization paths are possible to stabilize energy grids. Short-term flexibility is an important tool to provide control energy and can be additionally used for trading energy in the long term on the energy exchange and to stabilize distribution grids as well. Control energy is divided into three quality levels – primary control reserve (PCR), secondary (SCR) and tertiary control reserve (TCR), which differ in their requirements regarding availability, startup/shutdown time and the nature of provision (DENA 2017).

In this context, wastewater treatment plants (WWTPs) with anaerobic sludge digestion could be a suitable participant in energy markets: on the one side due to their energy production via combined heat and power (CHP) units as well as gas storage units and on the other side, due to their electrical energy consumers (Schloffer *et al.* 2015; Schäfer *et al.* 2016; Seier & Schebek 2017). So far, the main focus has been laid on large emergency power generators or CHP units, which can meet the needed technical requirements of participation in energy markets by pooling them in a virtual power plant (VPP) (ASUE 2010; Müller *et al.* 2017). In recent years, however, WWTPs with anaerobic sludge digestion have received more and more focus for pooling their energy production units, leading even to specific WWTP pools with special focus on their own framework (e.g. Preiß 2015). Furthermore, innovative approaches with focus on CHP units and controlled gas production to increase energetic flexibility can be found in Hien (2017) and Engelhart *et al.* (2018). However, not only CHP units and emergency power systems are able to provide flexibility. Several other aggregates at WWTPs, such as aerators, pumps and agitators, are suspected of providing the needed flexibility as well.

The first theoretical approaches for the identification and use of aggregates at WWTPs to provide flexibility – or rather load-shifting – were investigated in studies carried out in Austria and Switzerland (e.g. Berger *et al.* 2011; Müller *et al.* 2013; Bruyn *et al.* 2014; Schloffer *et al.* 2015) and for demand-response in the USA (Thompson *et al.* 2008; Thompson *et al.* 2010; Aghajanzadeh *et al.* 2015). In summary, it can be stated that (energetic) flexibility at WWTPs is hardly an interesting issue for plant operators in Germany and even less common at an international level due to its challenging practicability and the lack of incentives. This will change and is already changing, particularly in the context of the German energy transition and due to the on-going digitalization of the water sector (Elsner *et al.* 2015; DENA 2017). Previous load-shifting studies conducted in the water sector are of a purely theoretical nature regarding the integration of purification aggregates. The aggregates are mostly chosen based on assessments of plant operators and rough assumptions for single WWTPs. During the last years, practical approaches have been published either with a special focus on the use of CHP units to provide control energy (Müller *et al.* 2017) or with a special focus on modelling and use of aeration systems (Schloffer *et al.* 2015). A guideline with scientific evidence for identifying potential aggregates and especially taking into account possible negative side effects upon system functionality of WWTPs has not been stated, although wastewater treatment is the prior task for WWTPs.

The objective of the present work is to contribute to a better general understanding and knowledge at the interface between the wastewater and the energy sector. Therefore, this study demonstrates the compatibility of flexible plant operation due to individual control parameters and the supply of energetic flexibility without endangering the system's functionality for municipal WWTPs with anaerobic sludge digestion. Furthermore, the flexibility potential of WWTPs is portrayed in the context of its energetic environment. This article summarizes and represents the on-going research based on the initial findings of the project *arrivee* funded by the German Federal Ministry for Education, Research and Technologies (BMBF) in 2014–2017 (Schmitt *et al.* 2017). The following joins and describes the updated findings in the field of short-term flexibility options with special focus on WWTPs with anaerobic sludge digestion, also considering several publications of the author during the last years.

RESEARCH SETTING AND METHODS

Starting from the gap of knowledge stated in the introduction, a methodical approach to identify, evaluate and safely implement typical aggregates on WWTPs for flexible plant operation and the provision of energetic flexibility was developed and applied at a WWTP located in Germany. The application of the method and the results for the pilot plant are stated in Schäfer *et al.* (2017) and are focusing in detail on steps I and II shown in Figure 1. This study describes the results of a preselection of aggregates as well as examination and evaluation of operation data leading to relevant key figures for a flexible plant operation. These key figures have been worked out to reconcile requirements

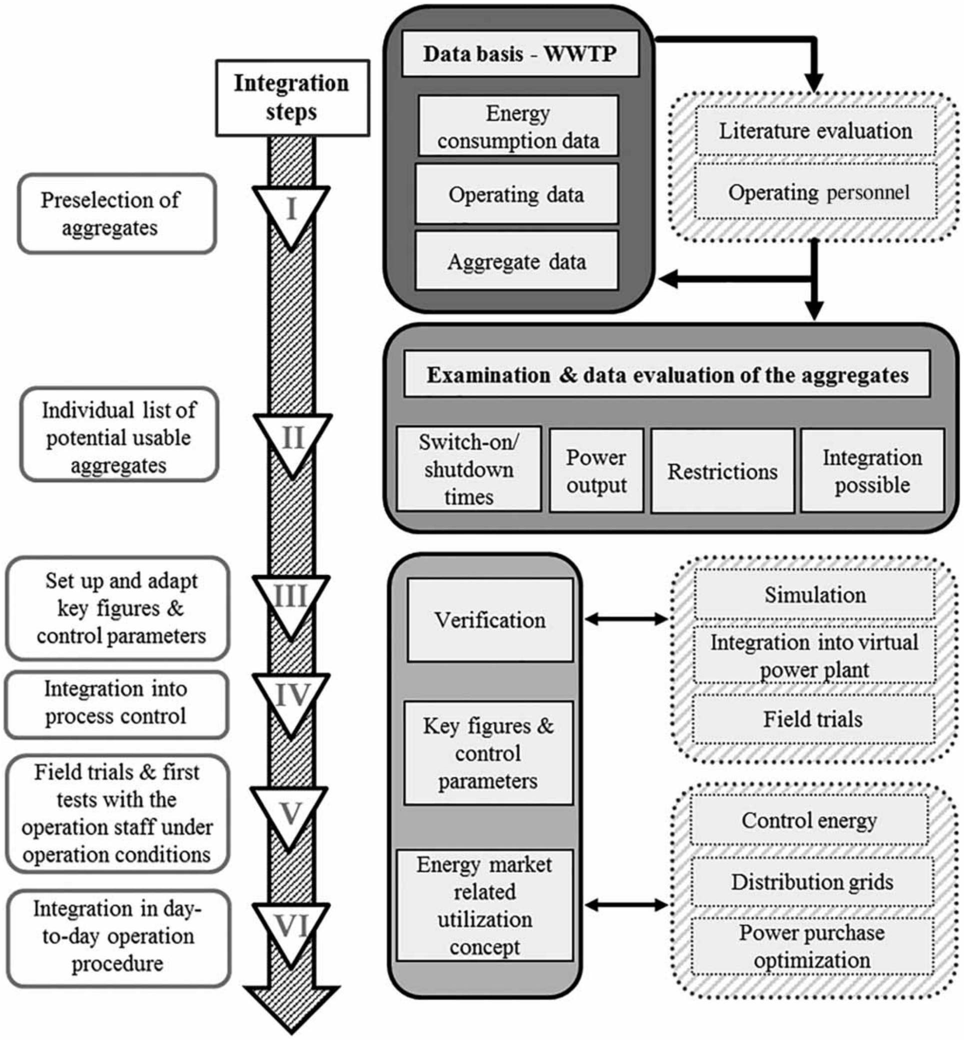

Figure 1 | Simplified schematic procedure for the identification, examination and verification of WWTP aggregates for providing flexibility (adopted from Schäfer *et al.* (2017) and Schäfer (2019)).

of the purification processes with their technical-physical necessities as well as demands of the energy market for a potential utilization (Schäfer *et al.* 2017).

In an in-depth analysis not only for the energetic framework of the whole plant, but also in detail for single aggregates in terms of energy consumption, energy production and procedural layout restrictions, control parameters have been developed and established. These parameters complement the aforementioned key figures to ensure stable operation, processes and effluent quality.

Based on the findings at the pilot plant, the control parameters have been tested with the aid of two simulation models in order to verify and test the control parameters and key figures without compromising plant operation. The first simulation model represents the pilot WWTP (WWTP A). The second one is a fictional standard sample WWTP ('standard WWTP') based on the German set of rules for designing WWTPs (ATV-DVWK 2000) to confirm and enhance the significance of the results based on WWTP A. For the modeling of biological processes, simba 6.4 (Activated Sludge Model 1; Henze *et al.* 2007) and for anaerobic digestion, the model of Siegrist (Siegrist *et al.* 2002) was used. In addition, each implemented aggregate is individually simulated for either load-shedding or powering up energy demand to confirm the usability, to verify the control parameters, detect negative side effects and ensure effluent quality. These examinations were conducted within the project *arrivee* and are stated in detail in Hobus *et al.* (2018), Schmitt *et al.* (2017) and its additional appendix Pyro *et al.* (2017).

Building on the findings of the examination of the pilot plant and the simulation models, real field trials were carried out on WWTP A and two additional WWTPs

(WWTP B and WWTP C). Based on the theoretical results and followed-up verification, the parameters have been adjusted and enhanced to generate a more general and transferable statement for similar plants to reveal and avoid possible negative side effects for using the suggested aggregates as a flexibility option.

An overall schematic procedure for the identification, examination and verification of WWTP aggregates for providing flexibility is given in Figure 1.

Schematic flow charts for all examined WWTPs are shown in the appendix of this article as well as further information regarding the simulation models.

RESULTS AND DISCUSSION

For shifting loads without endangering effluent quality, it is inevitable to restrict an intended utilization by establishing control parameters to protect treatment processes, if it becomes necessary.

This study proposes general control parameters for major aggregates, like switch on/off times as well as a regeneration time after utilization. Furthermore, additional and more individual control parameters are necessary for each single aggregate to picture their specific boundary conditions. Especially wet-weather conditions push the related systems to their limits and narrow buffer capacities for flexibility of the continuous processes significantly (e.g. grit chamber aeration or return-sludge pumps). Other restrictions are related to their individual operation mode, e.g. 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). Other additional control parameters may be necessary based on individual procedural aspects on the considered plant. Relevant key figures for providing flexibility are stated in Table 1.

Results for the simulation models, field trials and practical implementation

The suitability of the identified aggregates and their developed key figures and control parameters were verified by two mathematical models (WWTP A and 'sample WWTP') described in the research setting section and the appendix.

For the verification results due to simulation, it can be stated that the analysis of the simulated ammonium (NH_4-N) concentrations in the effluent of the secondary treatment/clarification in general shows only a slight increase for longer shutdown signals (e.g. TCR). However, due to the specified restrictions, the discharge values are steadily below the monitoring value. In the case of predominantly short request periods (e.g. SCR market), no increase in the ammonia (overall) effluent values has been observed in the performed simulations (Hobus *et al.* 2018).

Furthermore, some of the identified ('critical') aggregates were tested in real shutdown field trials at three different WWTPs to verify the models and the actual feasibility of the proposed devices. In total, 30 tests were conducted in a shut-down time range of 15 minutes up to 120 minutes (Table 2).

Figure 2 shows an exemplary three of the conducted field trials, one for each investigated WWTP (Aggregates used at A and C: aeration systems, B: return sludge pumps). The full documentation of all conducted field trials is shown in the appendix of Schmitt *et al.* (2017). The relevant control parameter on this occasion is the NH_4-N effluent concentration of the aeration tank, which will prevent an increased NH_4-N load to the water body. After the

Table 1 | Key figures and control parameters to provide flexibility on WWTPs (Schäfer 2019)

Parameter	Unit	Description
Effective power	Kilowatt [kW]	Power that is actually available to utilize, depending on the power the aggregate is currently consuming/producing.
Switch-on time *(min./max.)*	Minutes [min]	Minimum and maximum time an aggregate can be switched-on for additional power consumption/generation.
Switch- off time *(min./max.)*	Minutes [min]	Minimum and maximum time an aggregate can be shut-down for a flexibility utilization.
Regeneration time	Minutes [min]	Time needed until the aggregate is usable again after a utilization.
Start-up time	Seconds [sec]	Time needed from idle state to maximum available power.
Shut-down time	Seconds [sec]	Time needed from maximum power to 0%.
Individual control parameter	[–]	Parameters that have to be set up individually for each aggregate based on the monitored process/operation mode *(e.g. wastewater inflow, NH_4-N concentration)*.

Table 2 | Field trials of selected aggregates on three WWTPs (adopted from Schäfer 2019)

	Test duration				
Aggregate	**15 min**	**30 min**	**60 min**	**90 min**	**120 min**
Aeration *(single aerators)*	A	A	A, B, C	B, C	B, C
Aeration *(all aerators)*	A	A	A, C	B	B
Return sludge pumps	–	A	A, B	–	A, B

- WWTP A: 58.000 PE_{120}; 2-stage biological treatment: first basin consists of a two stage cascade with a pre-denitrification and a second basin with intermittent aeration; anaerobic sludge digestion.
- WWTP B: 17.500 PE_{120}; 3 serial intermittent aeration tanks; anaerobic sludge digestion.
- WWTP C: 146.000 PE_{120}; 2-stage biological treatment: first cascade with upstream denitrification and a second stage of intermittent aeration; anaerobic sludge digestion.

shutdown of the aeration system, as expected the NH_4-N concentration is increasing in the respective basin. However, the NH_4-effluent of the secondary treatment shows that there is no critical impact on the overall effluent due to sufficient buffer capacity. Thus, the characteristic values and restrictions are appropriate and could ensure stable processes during the shutdown.

Based on the results of Schäfer *et al.* (2017), the behavior of WWTP A was tested for flexibility 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. Therefore, the pilot plant was integrated in a virtual power plant and tested with data regarding SCR and TCR. To provide positive flexibility the aeration systems of both aeration tanks and the return sludge pumps were used. To provide positive and negative flexibility, the CHP units were integrated. After consistently positive results for the data of 2014, an artificial long-time field trial over 335 minutes was carried out to test the developed aggregate management and its control parameters even further (Figure 3).

During this extraordinary flexibility call, the aeration system has been shut down five times, each followed by the planned regeneration time. After the fourth shutdown, the NH_4-N control value reached the restriction of 8 mg NH_4/l (aeration tank 1) and the control mechanism interfered, so the aeration system was enabled again and the NH_4-N concentration fell again under the defined threshold

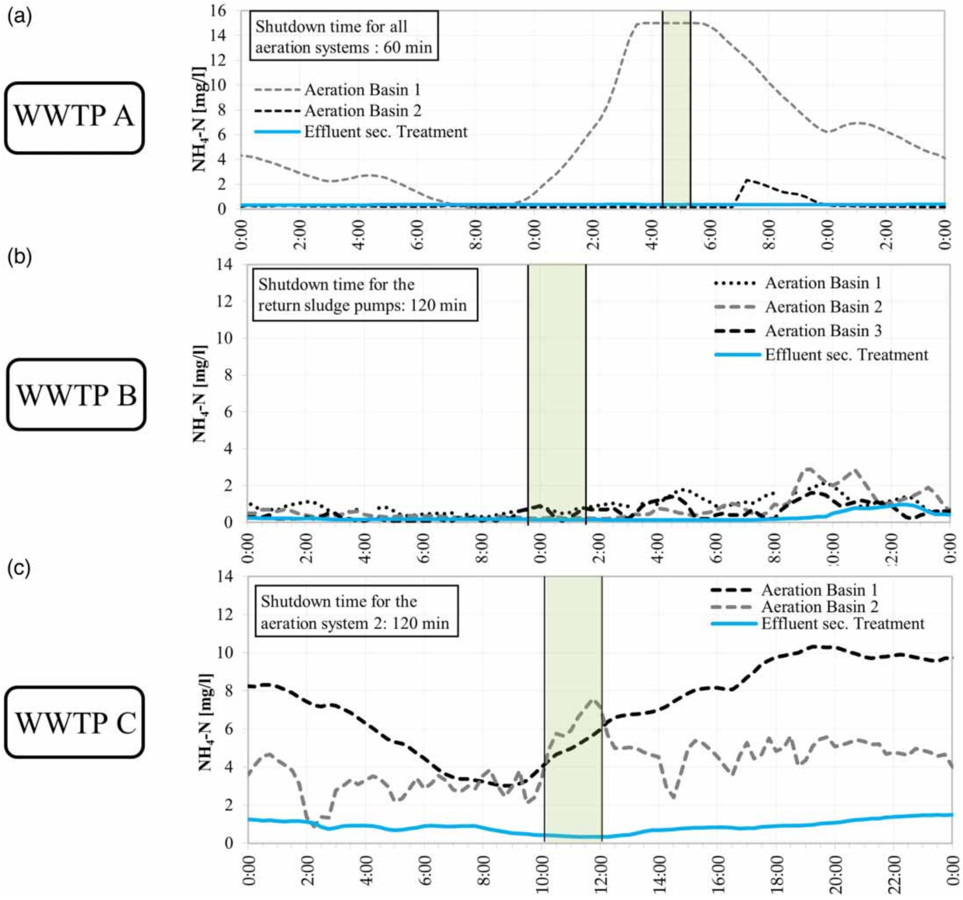

Figure 2 | Field trials of WWTP (a), (b) and (c) (adopted from Schmitt *et al.* 2017).

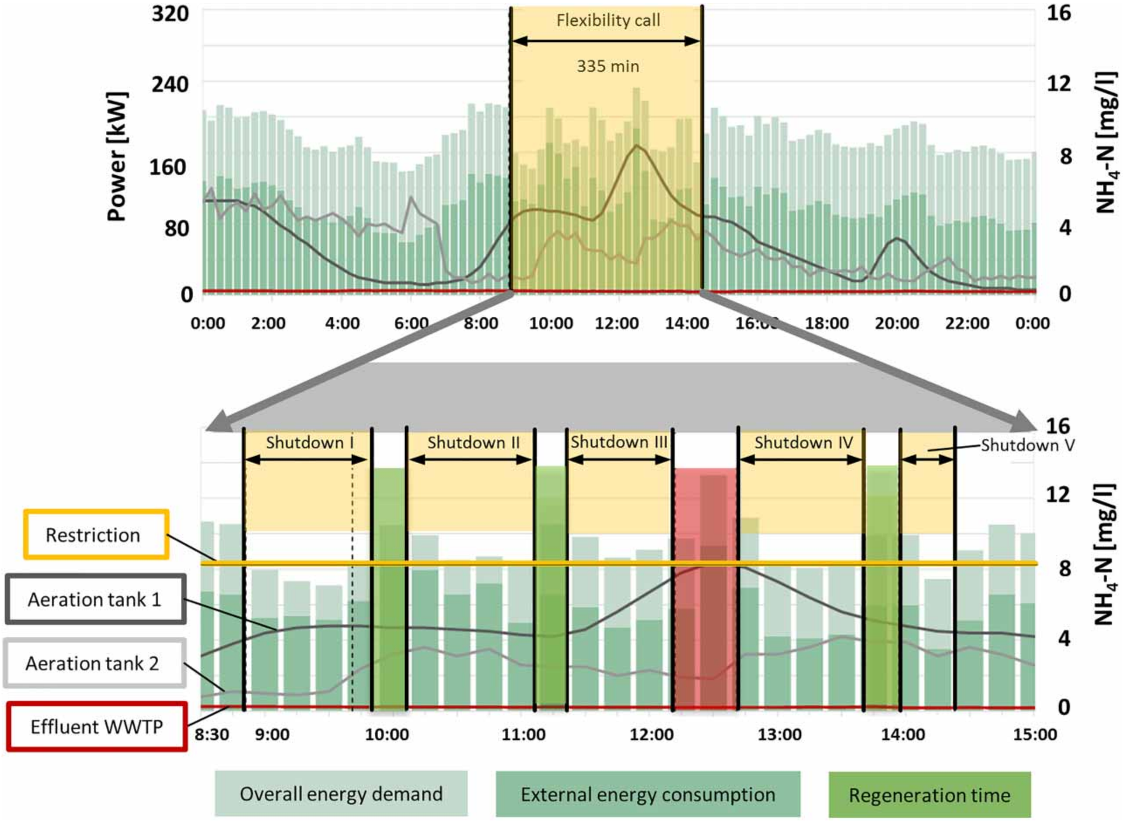

Figure 3 | Long-time flexibility call of 335 min with five shut-downs of the aeration systems and the respective NH_4-N values (adopted and modified from Schmitt *et al.* 2017).

and the aggregate was usable again for a fifth shutdown. During the whole test, the NH_4 effluent of the secondary treatment was stable and remained at an uncritical level. The results show that even for tough conditions stable processes can be maintained with the appropriate control parameters for the monitored WWTP.

Upon confirmation of the characteristic values and control parameters for WWTP A and the experiences and findings of the field trials, simulations and practical application, the parameters have been adapted and safety factors were included for a more general and transferable statement for municipal WWTPs with anaerobic sludge digestion. These updated parameters for typical aggregates on WWTPs are depicted in Table 3.

Potential of short-term flexibility on WWTPs in the framework of the energy market

(*This analysis focuses on the legal and regulatory conditions for the German energy market in 2017 and may differ from other countries.*) The results show that WWTPs are technically capable of providing energetic flexibility under controlled conditions and are able to participate on today's energy markets. However, the different requirements of the energy market have to fit the specific characteristics of the aggregates. A comparison is possible due to the specific requirements of the considered utilization regarding possible switch on/off times, power-up and shut-down times, with the individual key figures of the representive aggregates (Table 3) and the behavior on flexibility calls worked out due to the verification.

Not every aggregate is usable for every utilization path. For instance, some aggregates are better in handling short and more frequent flexibility calls (e.g. return sludge pumps in SCR) and others prefer less but longer calls (e.g. CHP units in TCR). Furthermore, the nature of the call affects the possible effect on treatment processes and has to be tested and assessed for the whole process stage. The control parameters and key figures have to be adjusted individually because WWTPs are highly variable within their specific operation mode, plant configuration and local framework. The established parameters can be used as reference values for implementing flexibility management in WWTPs. Table 4 shows the suitability for different utilization paths for the investigated aggregates on the German energy market (2017).

Table 3 | Characteristic values and control parameters for typical aggregates on WWTPs to provide flexibility (adopted from Schäfer 2019)

	Switch-off time		**Switch-on time**					
Aggregate	**min [min]**	**max [min]**	**min [min]**	**max [min]**	**Regeneration time [min]**	**Start-up time [s]**	**Shut-down time [s]**	**Additional control parameters**
Inlet pumps	5	15	–	–	30	60	60	Retention capacity *(upstream sewer system, retention basin)*
Grit chamber *(aeration, intermittent)*	5	60	–	–	30	60	60	• Wastewater inflow[a] • Sedimentation of organic substances
Aeration *(aeration tank)*	5	60/120*	–	–	15	60	60	• NH_4–N-concentration *(aeration tank & effluent secondary treatment)* • DOC/ NH_4-load *(inflow)*
Agitator *(aeration tank)*	15	30	15	40	30	60	60	• Time restriction due operation mode • Sedimentation processes *(via dry matter content aeration tank)* • Circulation rates *(based on ground shear stress)*
Agitator *(digestion tank)*	15	30	–	–	15	180	60	• Circulation rates • Foam formation and sedimentation processes
Return sludge pumps	5	120	–	–	60	60	60	• Wastewater inflow[a] • Sludge level secondary treatment
Recirculation pumps	5	720	–	–	30	60	60	NO_3–concentration *(aeration tank)*
Heat sludge pumps *(digestion tank)*	15	1.440	15	1.440	60	60	60	Temperature *(min/max)*
Primary/raw sludge pumps *(digestion tank)*	15	30	–	–	15	120	60	Fill-level raw sludge thicken *(min/max)*
Surplus sludge thickening	–	–	120	1.440	15	60	900	• Dry matter content[b] *(aeration tank)* • Operation mode/staff working time[d]
Centrifuge *(dewatering[c])*	–	–	240	420	60	1.200	1.200	• Operation mode/staff working time[d] • Max. switching cycles
Chamber filter presses *(dewatering[c])*	–	–	150	150	60	120	120	• Operation mode/duration • Staff working time[d]
CHP units	5	1.440	60	1.440	5[−]/30[+]	180	300	• Fill-level gas storage *(min/max)* • Max. switching cycles
Emergency generator	–	–	15	900	2,50	60	60	• Fill-level fuel storage *(min/max)* • Max. operating hours[e]

*Aerobic stabilization.

[−] Negative flexibility.

[+] Positive flexibility.

[a] Preventing plant overload (stormwater).

[b] Preventing over-extraction of surplus sludge.

[c] Sludge dewatering is mostly not interruptible.

[d] Depending on degree of automation.

[e] Regulated in German law (180 h/a).

Potentials for providing negative flexibility and ancillary services with CHP units in WWTPs are described in detail in Schäfer *et al.* (2015) and Schäfer (2019). These studies showed that, including the purification aggregates, emergency generators and the CHP units, positive flexibility of 669 MW and 338 MW negative flexibility could be provided via WWTPs in Germany. The potential electrical energy production range lies in between 2.11 and 2.61 TWh per year, respective 25.4–31.4 kWh per inhabitant and year. These results demonstrate that WWTPs have a significant potential

Table 4 | Suitability of the investigated aggregates for different utilization paths (adopted from Schäfer 2019)

Aggregate	Control reserve			Electricity exchange	Internal load shifting	Distribution grids	Application remark
	PCR	SCR	TCR				
Grit chamber *(aeration)*	○	•	•	Medium suitable	Highly suitable	Modest suitable	Strongly influenced by inflow volume
Aeration systems *(aeration tank)*	•	•••	•••				Short and frequent calls preferred
Return sludge pumps	○	•••	••				Short and frequent calls preferred
Recirculation pumps	○	•	••				Strongly influenced by NO_3-control value
Raw sludge pumps	○	••	••				Short and long calls possible
Agitators	○	•	•				Few calls preferred
Surplus sludge thickening	○	○	○				Uninterruptible process
Chamber filter presses	○	○	○				Uninterruptible process
Centrifuge	○	○	•				Few and long calls preferred
CHP units	••	••	•••				Few and long calls preferred
Emergency generator	○	•	•••				Few and long calls preferred

○ not suitable • modest •• medium ••• highly suitable.

to provide energetic flexibility and are able to make a contribution to the German energy transition in terms of power generation, shiftable loads and gas production (Schäfer 2019).

CONCLUSIONS

It was demonstrated that WWTPs are able to adapt their operation mode to external and internal requirements under controlled conditions. The existing flexibility is suitable for a variety of uses and WWTPs are in general able to participate in today's and future energy supply products and new business models. It could also be shown that, with appropriate control parameters and reasonable time slots even for vulnerable aggregates, load shifting is possible without endangering system functionality. The aggregates investigated have different suitabilities depending on their intended use. Nevertheless, the local framework and the individual operation of the WWTP determine significantly the existing flexibility and actual use. Therefore, not every aggregate can be optimally used for every single utilization path. On the basis of existing experiences in reducing external energy demand and energy self-sufficiency efforts, adapting CHP schedules is common know-how among plant operators. Therefore, in a first step, the CHP units offer good opportunities to gain initial experiences with interactions on energy markets without affecting effluent quality. This will ease further steps in integrating aggregates in the considered flexibility markets. The stated results may provide assistance to create a basis and initiate future efforts despite high reservations, especially regarding effluent quality, being widely spread among plant operators. However, a utilization is possible under controlled conditions for certain plants. Such objections are appropriate and important because the primary task of the WWTP is still to treat wastewater. Energy and cost savings should never be carried out at the expense of significantly higher loads to the water body.

Further investigations are required to reveal long-term effects due to long shut-down times (e.g. phosphate resolution in aeration tanks or changes in the biocenosis). Another point of interest is the behavior of the producers and consumers in wet-weather conditions, including the interaction with alternate local renewable energy sources (like photovoltaics) on the plant. Therefore, further research and practical experiences are necessary for the implementation of WWTP aggregates into smart control systems in order to provide and use the needed detailed data in a fast changing energy environment.

There are just a few research projects and even fewer published practical implementations on this topic whereas energy self-sufficiency studies are very common. Unfortunately, participating in energy markets is not yet sufficiently attractive for plant operators, nor is it for grid operators to include WWTPs due to a missing incentive system. The existing legal framework and low economic benefits present high obstacles to dealing with the subject although flexibility will be needed in future from all sectors to ensure system functionality of the energy grid and to support a further integration of renewable energy.

With a higher share of renewable energies in the grids, demand and the value of flexibility will increase and energy purchase will change over to more volatile prices during the day and this could lead to dynamic power purchasing agreements. Future consumers could experience drawbacks due to their inflexibility when competing with participants that are more flexible. This could trigger the needed incitements to deal with complex topics like energy management during day-to-day business at WWTPs. The water sector and the energy sector have been merging, and previous strict borders are blurring. Thus, dealing with the topic is important for a sustainable development of the water and the energy sector by knowing what flexibility is available at WWTPs and to be prepared for future changes in terms of energy purchase, balancing (local) energy grids, reducing energy costs and to make a further contribution to environmental protection in a holistic approach.

ACKNOWLEDGEMENTS

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

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at http://dx.doi.org/10.2166/wst.2019.365.

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First received 28 June 2019; accepted in revised form 28 October 2019. Available online 5 November 2019