Energy consumption of agitators in activated sludge tanks – actual state and optimization potential

K. Füreder, K. Svardal, W. Frey, H. Kroiss and J. Krampe

ABSTRACT

Depending on design capacity, agitators consume about 5 to 20% of the total energy consumption of a wastewater treatment plant. Based on inhabitant-specific energy consumption (kWh $PE_{120}{}^{-1}$ a^{-1}; PE_{120} is population equivalent, assuming 120 g chemical oxygen demand per PE per day), power density (W m^{-3}) and volume-specific energy consumption (Wh m^{-3} d^{-1}) as evaluation indicators, this paper provides a sound contribution to understanding energy consumption and energy optimization potentials of agitators. Basically, there are two ways to optimize agitator operation: the reduction of the power density and the reduction of the daily operating time. Energy saving options range from continuous mixing with low power densities of 1 W m^{-3} to mixing by means of short, intense energy pulses (impulse aeration, impulse stirring). However, the following correlation applies: the shorter the duration of energy input, the higher the power density on the respective volume-specific energy consumption isoline. Under favourable conditions with respect to tank volume, tank geometry, aeration and agitator position, mixing energy can be reduced to 24 Wh m^{-3} d^{-1} and below. Additionally, it could be verified that power density of agitators stands in inverse relation to tank volume.

Key words | agitators, energy optimization, intermittent operation of agitators, mixing power density, municipal wastewater treatment, volume-specific energy consumption

K. Füreder (corresponding author)
K. Svardal
H. Kroiss
J. Krampe
Institute for Water Quality and Resource Management,
TU Wien,
Karlsplatz 13/226-1,
1040 Wien,
Austria
E-mail: *k.fuereder@iwag.tuwien.ac.at*

W. Frey
AAB-Frey,
Hofgartenstraße 4/2,
2100 Korneuburg,
Austria

NOMENCLATURE

P_D	power density of agitator(s) (W m^{-3})
t_d	daily operating time of agitator(s)/mixing system (h d^{-1})
$W_{mix,PE}$	inhabitant-specific energy consumption of agitator(s) (kWh $PE_{120}{}^{-1}$ a^{-1})
$W_{mix,V}$	volume-specific energy consumption of agitator (s) (Wh m^{-3} d^{-1})
COD	chemical oxygen demand
MBWWT	mechanical–biological wastewater treatment
PE_{120}	population equivalent; assuming 120 g COD PE^{-1} d^{-1}
SVI	sludge volume index (mL g^{-1})
TSS	total suspended solids (g L^{-1})
WWTP	wastewater treatment plant

INTRODUCTION

Energy consumption of wastewater treatment plants (WWTPs) amounts to a small part of the overall national energy requirements. In Germany and the USA the share is estimated to about 1% (Goldstein & Smith 2002; Haberkern *et al.* 2008). However, WWTPs are the largest energy consumer at the level of municipalities (Haberkern *et al.* 2008). For this reason and due to increasing energy prices the importance of energy optimization in municipal wastewater treatment has been constantly rising (EPA 2010; Krampe 2013; Marner *et al.* 2016). In this context, it has also become important to optimize agitator operation in activated sludge tanks (Sharma *et al.* 2011).

Mixing and aerating in activated sludge tanks are energy-intensive sub-processes within wastewater treatment. When aerating demands about 50–60% of the total energy consumption of a WWTP (Krampe 2011b), in this paper it is shown that mixing consumes about 5–20%. However, in contrast to aeration systems, agitators have not been standing in the central focus of energy optimization yet. Therefore, the aim of this paper is to fill this gap giving a sound overview regarding the actual state and the optimization potential of energy consumption of agitators (generally: mixing systems) in activated sludge tanks.

doi: 10.2166/wst.2017.596

Data analysis in this paper is based on the evaluation of three different energy indicators: (A) inhabitant-specific energy consumption (kWh PE_{120}^{-1} a^{-1}, where PE_{120} is the population equivalent, assuming 120 g chemical oxygen demand (COD) per PE per day), (B) power density (W m^{-3}) and (C) volume-specific energy consumption (Wh m^{-3} d^{-1}). As only little reference data was available in literature, the first step was to build up a broad and consistent agitator database of operating WWTPs from Austria.

MATERIALS AND METHODS

Database

The database for the study was collected by an Excel-sheet based survey throughout all 942 WWTPs >500 PE_{120} in Austria in the year 2014. Three hundred and ninety-three questionnaires were sent back. Ten per cent of the Excel-sheets had to be excluded because of missing or obviously wrong data. Nine different indicators were built up validating the plausibility of design capacity, average incoming COD load, tank volumes, nominal power and energy consumption of agitators, etc. Only questionnaires that passed the outlier tests of all nine criteria were approved for the study. Finally, the data of 220 treatment plants, ranging from 520 to 950,000 PE_{120} design capacity, could be used for evaluation. The study covers 30% of all Austrian WWTPs with a design capacity ≥ 2,000 PE_{120} and 9% of all plants between 500 and 1,999 PE_{120}. However, the 220 evaluated WWTPs are corresponding to a design capacity of about 6 million PE_{120}, which is 28% of the total design capacity of Austria (Table 1). The scope of the database is comparable to Krampe (2011a).

The Excel-questionnaire was split into two parts. The first consisted of 13 questions (A–M) regarding the treatment plant as a whole, asking for design capacity, average incoming COD load, total volume of all activated sludge tanks, etc. (see appendix, available with the online version of this paper). The second part consisted of 23 questions (Bx-1 to Bx-23) regarding activated sludge tanks (see appendix). Tanks with the same volume, geometry, aeration type and mixing power were grouped and queried as one tank. So, many small treatment plants filled out the questionnaire for just one tank, whereas bigger plants in most cases filled out for two to four different tanks. Altogether 286 different activated sludge tanks were evaluated, consisting of 228 aerated and 58 unaerated tanks between 52 m³ and 15,000 m³ (Table 2).

Table 1 | Austrian WWTPs ≥ 500 PE_{120} vs. evaluated WWTPs

Design capacity class (PE_{120})	WWTPs in Austria*		WWTPs evaluated			
	Number of plants (n)	Design capacity (PE_{120})	Number of plants (n)	%	Design capacity (PE_{120})	(%)
500–1,999	309	305,360	28	9	37,870	12
≥2,000	633	21,309,060	192	30	5,967,570	28
TOTAL	942	21,614,420	220	23	6,005,440	28

*BMLFUW (2016); ÖWAV (2015).

Apart from a few impulse mixing systems, the evaluation concentrated on the four following agitator types as categorized in DWA (2013):

- horizontal drive shaft: fast-running propeller (100–600 rpm, diameter (D) = 0.5–1 m)
- horizontal drive shaft: slow-running propeller (<100 rpm, D = 1–3 m)
- vertical drive shaft: hyperboloid-shaped mixer (<100 rpm, D = 1–2 m)
- vertical drive shaft: slow-running propeller (<100 rpm, D = 1–3 m).

Further, detailed investigations of two WWTPs with low mixing energy consumption (WWTP Wartberg/Krems, WWTP Bad Aussee) were carried out. This included the verification of tank volume, agitator power consumption and energy indicators, measurements of near-ground velocity and tank deposits, recording of exact tank geometry and agitator positions, measurements of sludge volume index (SVI) and total suspended solids (TSS), etc. In addition, the low mixing energy data of WWTP Amperverband (Kopmann 2015: impulse aeration/impulse mixing) was evaluated for the study.

Table 2 | Number of aerated and unaerated tanks evaluated in this paper; sorted by tank volume

Tank volume (m³)	Number aerated (n)	Number unaerated (n)	Total number (n)
<200	8	12	20
200–500	31	23	54
500–1,000	76	12	88
1,000–2,000	62	7	69
>2,000	51	4	55
TOTAL	228	58	286

Energy indicators

Data evaluation in this paper is based on three different energy indicators.

Indicator (A), inhabitant-specific energy consumption of agitators ($W_{mix,PE}$), refers to the incoming COD load to the treatment plant. It is independent of the design capacity of a WWTP. Lindtner (2008) reports values between 1.5 and 4.5 kWh $PE_{120}{}^{-1}$ a^{-1}. $W_{mix,PE}$ is defined as the ratio of annual energy consumption of agitators in activated sludge tanks of a WWTP to the yearly average of the incoming COD load to the plant:

$$W_{mix,PE} = \frac{W_{mix}}{F_{COD}} \tag{1}$$

$W_{mix,PE}$ = kWh $PE_{120}{}^{-1}$ a^{-1} inhabitant-specific energy consumption of agitators
W_{mix} = kWh a^{-1} annual energy consumption for mixing in activated sludge tanks of a WWTP
F_{COD} = PE_{120} yearly average of incoming COD load of the WWTP assuming 120 g COD PE^{-1} d^{-1}

Indicator (B), power density (P_D), refers to activated sludge tanks. Baumann et al. (2014) show that P_D decreases with increasing tank volume and that target areas of P_D range from 4.0 W m^{-3} at small tank volumes of 200 m^3 to 1.5 W m^{-3} at tank volumes >2,000 m^3. It is defined as the quotient of mixing power consumption of agitator(s) and tank volume:

$$P_D = \frac{P}{V} \tag{2}$$

P_D = W m^{-3} power density
P = W power consumption of agitator(s)
V = m^{-3} tank volume

Indicator (C), volume-specific energy consumption ($W_{mix,V}$), again refers to activated sludge tanks. Based on $W_{mix,V}$, the actual energy consumption of agitators can be calculated and compared. $W_{mix,V}$ is defined as the product of P_D and the daily operating time of the agitator (t_d). It can also be calculated for impulse aeration and impulse mixing systems, multiplying P_D and t_d of the impulse mixing system.

$$W_{mix,V} = P_D \cdot t_d \tag{3}$$

$W_{mix,V}$ = Wh m^{-3} d^{-1} volume-specific energy consumption
P_D = W m^{-3} power density
t_d = h d^{-1} daily operating time of the mixing system

Target value and tolerance value

Due to the large number of specific local process configurations and conditions, it is not reasonable to establish energy benchmarks for mixing only. Nevertheless, as an approximation to benchmarks, so called ‘target values’ and ‘tolerance values’ can be derived from the frequency distributions of the energy indicators. In reference to Haberkern et al. (2008), in this paper they are defined as follows:

- target value = 25%-quantile
- tolerance value = median

Influence of tank geometry and aeration

If P_D of agitators strongly differs from target values, this may only be due to the agitator (efficiency, dimensioning). Yet in many cases, it is necessary to look more closely at the overall operating and constructional concept of the tank. In this regard, the interaction between tank geometry and P_D, mixing and aeration, as well as the optimal positioning of agitators, plays a key role (Frey 2007; Frey 2011a, 2011b; DWA 2013). For example, in oxidation ditches, the geometric shape of the deflection is a crucial factor regarding the necessary energy input (Figure 1). However, depending on the type of mixer, different reactor shapes can be optimal.

Near-ground velocity, tank deposits and intermittent operation

Depending on SVI and TSS, near-ground velocity in tanks should vary between 0.10 and 0.25 m s^{-1} (DWA 2013). The prevention of sludge deposits though does not depend on the average value of near-ground velocity but on ‘peak values and their frequency’ (Frey 2009). Therefore, agitators can be switched off partially or completely during aeration (Haberkern et al. 2008). Also in unaerated phases and tanks intermittent operation of agitators is an energy saving option (Baumann et al. 2014). However, there are some measures to be taken. Most important is the control of nitrate and sludge volume in the outlet of the tank. Further, it has to be ensured that the intermittent operation of agitators is shut down during N-peaks in the feed (Baumann et al. 2014). Other control parameters for the intermittent operation of agitators are the vertical layering

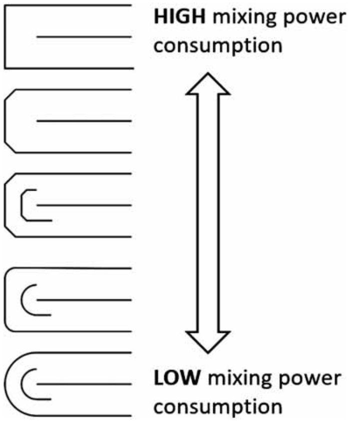


Figure 1 | Oxidation ditches: influence of tank geometry on mixing power consumption.

of TSS and oxygen concentration (Sharma *et al.* 2011; Kopmann 2015).

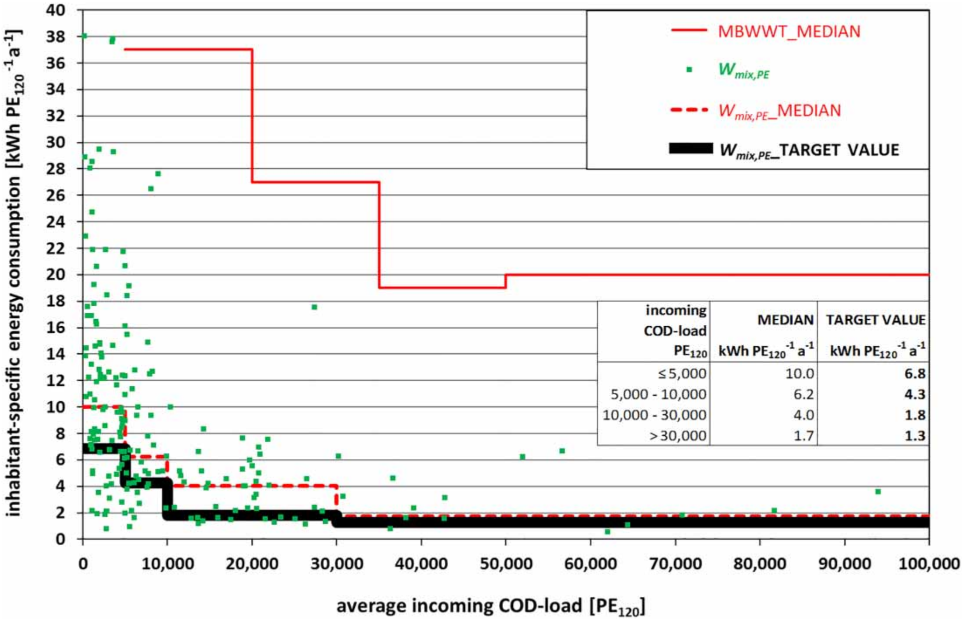
RESULTS AND DISCUSSION

Actual state of energy consumption

Indicator (A), inhabitant-specific energy consumption $W_{mix,PE}$, was calculated for all 220 WWTPs. It showed that it is indirectly proportional to the average incoming COD load (expressed as PE_{120} in Figure 2). So the larger the COD load, the smaller $W_{mix,PE}$. In accordance with Lindtner (2008) the target value ranges from 6.8 kWh $PE_{120}{}^{-1}$ a^{-1} (<5,000 PE_{120}) to 1.3 kWh $PE_{120}{}^{-1}$ a^{-1} (>30,000 PE_{120}) (Figure 2).

Further, the share of mixing energy within the total energy consumption was of interest. Therefore, the medians of $W_{mix,PE}$ are compared to the medians of inhabitant-specific energy consumption of mechanical–biological wastewater treatment (MBWWT). MBWWT, a benchmarking term introduced by Lindtner *et al.* (2004), includes mixing, aeration, return sludge pumping, primary sedimentation tanks and final clarifiers (ÖWAV 2013). It is by far the most energy-intensive sub-process within wastewater treatment (Lindtner 2008; Haslinger *et al.* 2016). Comparing the medians, it can be shown that mixing demands a share of about 10 to 25% of MBWWT (Figure 2). Now taking into account that aeration consumes about 50–60% of the total energy consumption of a WWTP (Krampe 2011b), but about 70% of MBWWT (Lindtner 2008), it can be calculated that mixing demands a share of about 5 to 20% of the total energy consumption of a WWTP.

Finally, it can be shown that the share of mixing energy increases with decreasing COD loads. So, bigger treatment plants – with influent loads ≥35,000 PE_{120} – need a share of about 10% of MBWWT, whereas smaller treatment plants – with influent loads up to 5,000 PE_{120} – need about 25% of MBWWT (Figure 2); again corresponding



incoming COD-load PE_{120}	MEDIAN kWh $PE_{120}{}^{-1}$ a^{-1}	TARGET VALUE kWh $PE_{120}{}^{-1}$ a^{-1}
≤5,000	10.0	**6.8**
5,000 - 10,000	6.2	**4.3**
10,000 - 30,000	4.0	**1.8**
>30,000	1.7	**1.3**

Figure 2 | Inhabitant-specific energy consumption $W_{mix,PE}$ as a function of average incoming COD load (expressed as PE_{120}; $n = 220$ WWTPs) – median of $W_{mix,PE}$ compared to median of inhabitant-specific energy consumption of MBWWT; median of MBWWT according to ÖWAV (2013).

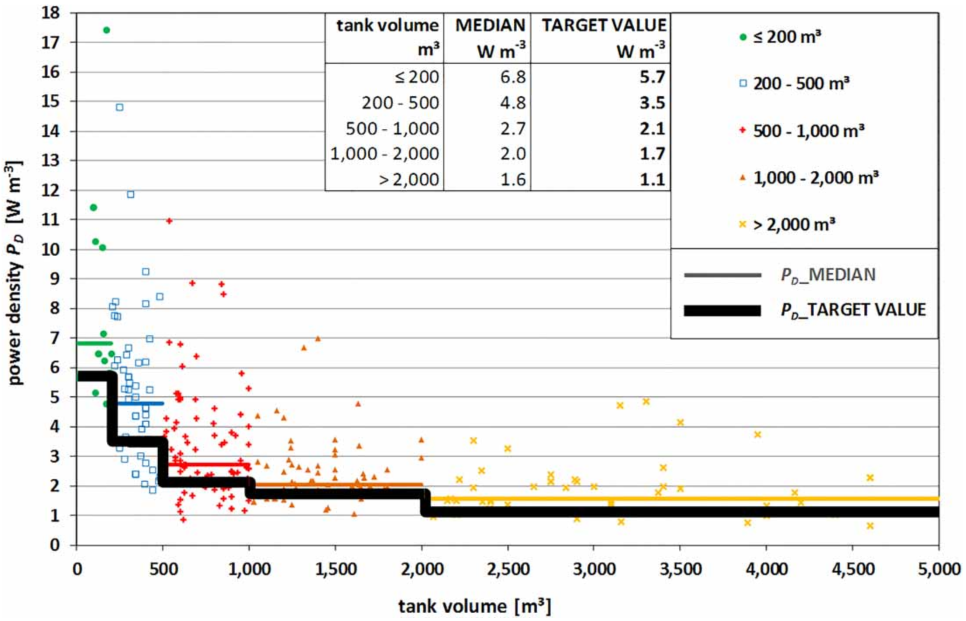


Figure 3 | Power density P_D of aerated and unaerated tanks as a function of tank volume; $n = 286$ tanks.

to about 5–20% of the total energy consumption of a WWTP.

Indicator (B), power density P_D, was calculated for all 286 tanks. Both P_D and its target values and medians prove to be indirectly proportional to tank volume. Target values range from 5.7 W/m³ (≤200 m³) to 1.1 W/m³ (>2,000 m³), medians from 6.8 W/m³ (≤200 m³) to 1.6 W/m³ (>2,000 m³). Target values are within, and medians tend to be at, the upper limit of the target areas indicated by Baumann *et al.* (2014) (Figure 3).

The influence of agitator type (fast-running propeller; slow-running propeller; hyperboloid-shaped mixer) on P_D was examined. Fast-running propellers are only used for tank volumes <1,000 m³ and are operated with higher P_D than other agitator types. The target value for fast-running propellers was assessed to 5.2 W m^{-3}. Between slow-running propellers (horizontal or vertical drive shaft) and hyperboloid-shaped mixers, no difference regarding P_D could be found. P_D target values for tanks <1,000 m³ range around 2.4 W m^{-3} each.

Tank deposits are an important control parameter regarding low mixing power densities. Data evaluation showed that P_D below the target values does not lead to more deposits than P_D above the target values (Table 3). This proves that the P_D target values elaborated in this paper can be put into praxis without harming sludge suspension.

Indicator (C), volume-specific energy consumption $W_{mix,V}$, has more than one main influencing parameter. Therefore, it cannot be evaluated like P_D and $W_{mix,PE}$. $W_{mix,V}$ is mainly dependent on P_D and t_d. Due to the influence of P_D, there is also a slight dependency on tank volume (Figure 4). However, of bigger importance is the aeration. On average, $W_{mix,V}$ in aerated tanks is twice as low as in unaerated tanks. In aerated tanks the average $W_{mix,V}$ is about 50 Wh m^{-3} d^{-1} (Figure 4(a)), in unaerated tanks about 100 Wh m^{-3} d^{-1} (Figure 4(b)). This is mainly due to the mixing energy contribution of aeration. Consequently, t_d in most aerated tanks can be lower than in unaerated tanks, as there is energy input from aeration (see Table 5). In aerated tanks the spectrum of $W_{mix,V}$ ranges from 14 to 119 Wh m^{-3} d^{-1} (Figure 4(a)), in unaerated tanks from 43 to 242 Wh m^{-3} d^{-1} (Figure 4(b)).

Table 3 | Percentage of no/little/a lot tank deposits (as observed by operators): P_D <target value compared to P_D > target value; calculated with target values according to Figure 3

Tank deposits	**P_D < target value (n = 58 tanks)**	**P_D > target value (n = 166 tanks)**
No	28%	25%
Little	66%	68%
A lot	7%	7%
TOTAL	100%	100%

On-site validation of low mixing energy

Activated sludge tanks $>2{,}000\ m^3$ have a P_D target value of about $1\ W\ m^{-3}$ (Figure 3). At continuously mixed tanks ($\rightarrow t_d = 24\ h\ d^{-1}$) this corresponds to a low $W_{mix,V}$ of $24\ Wh\ m^{-3}\ d^{-1}$. For the continuously mixed oxidation ditches at the WWTP Wartberg/Krems (Figure 4(a)) this could be confirmed by on-site measurements. Although a low $W_{mix,V}$ of $22\ Wh\ m^{-3}\ d^{-1}$, near-ground velocities proved to be sufficiently high. The average values of nine different measurement points inside the oxidation ditch came to be $0.13–0.23\ m\ s^{-1}$; the maximum values came to be $0.16–0.30\ m\ s^{-1}$. In accordance with that, no significant deposits could be detected on the base of the tanks. An important reason for the good mixing performance of the oxidation ditches at WWTP Wartberg/Krems is to be found in the favourable agitator position and deflection geometry that equals the optimal geometry in Figure 1.

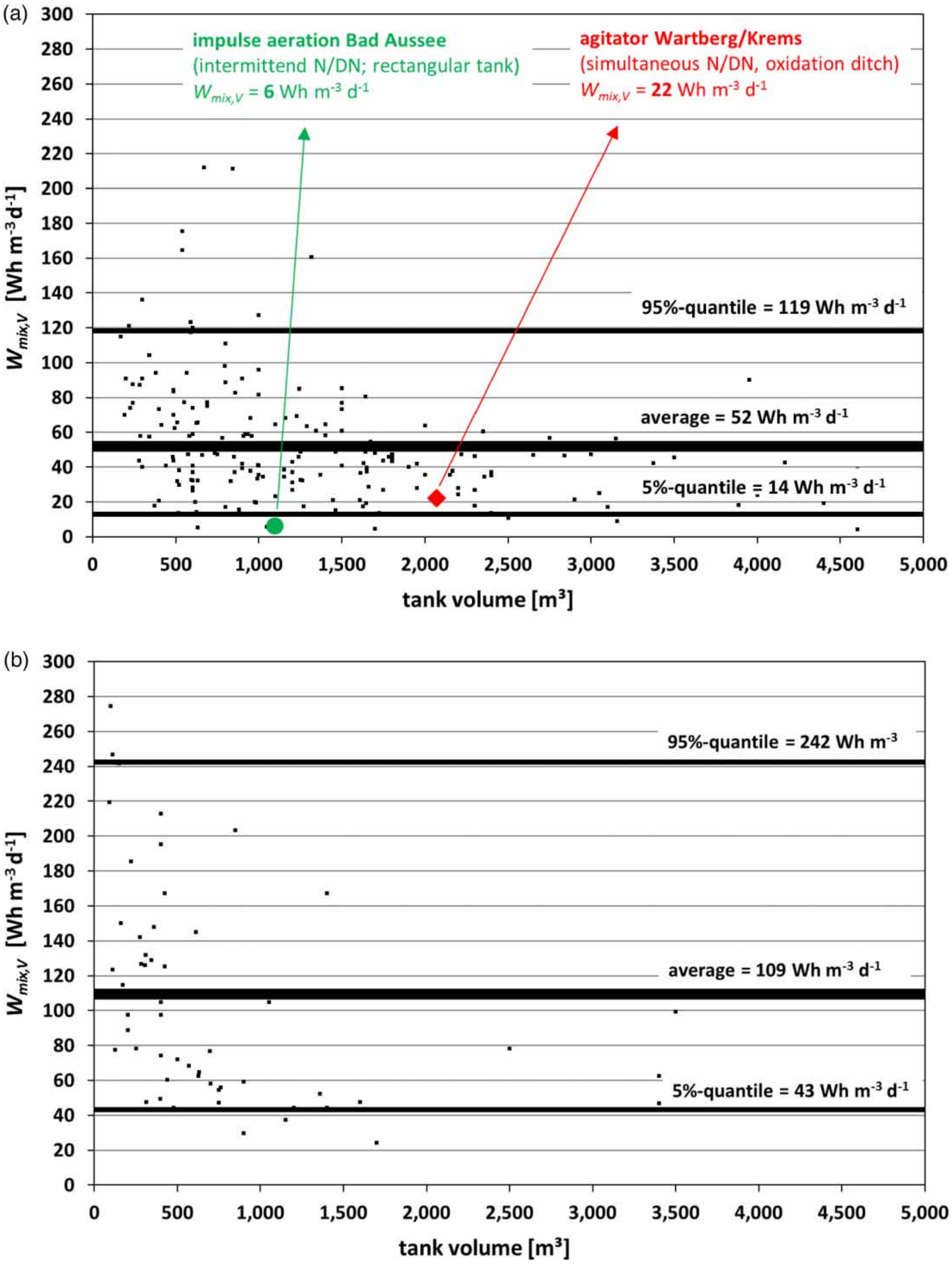


Figure 4 | Volume-specific energy consumption $W_{mix,V}$ as a function of tank volume: (a) aerated ($n = 228$) and (b) unaerated tanks ($n = 58$). N/DN: nitrification/denitrification.

The oxidation ditches of WWTP Wartberg/Krems show that for aerated tanks a low $W_{mix,V}$ of about 24 Wh m^{-3} d^{-1} is feasible in practice under favourable conditions with respect to tank volume, tank geometry and agitator position. However, especially examples of impulse aeration show that $W_{mix,V}$ in aerated tanks can be reduced to even below 24 Wh m^{-3} d^{-1}. This could be confirmed by on-site measurements at the rectangular 1,000 m³ impulse aeration tanks at the WWTP Bad Aussee ($W_{mix,V} = 6$ Wh m^{-3} d^{-1}) (Figure 4(a)). Again, no significant tank deposits could be detected.

As $W_{mix,V}$ of unaerated tanks on average is twice as high as for aerated tanks, for unaerated tanks, an optimization goal of about 48 Wh m³ d^{-1} can be approximated. This is also indicated by similar frequency distributions: 18% of aerated tanks fall below 24 Wh m^{-3} d^{-1}, 17% of unaerated tanks fall below 48 Wh m^{-3} d^{-1}. So both values are in the range of the 25%-quantile (defined as target value).

Energy optimization

The optimization of energy consumption of agitators in activated sludge tanks can be divided into two subareas that can be analyzed separately over a wide range: (1) the reduction of P_D and (2) the reduction of t_d. In the best case, both P_D and t_d are optimized. However, the reduction of P_D, t_d or both P_D and t_d in all cases leads to a reduction of the $W_{mix,V}$ and hence to mixing energy optimization.

The reduction of P_D

Depending on whether the tolerance value (median) or the target value (25%-quantile) is recognized as an optimization goal, it can be assumed that approximately 50 to 75% of the tanks have an energetic optimization potential regarding P_D. Based on this consideration an estimation of the energy saving potential in regard to P_D was carried out for Austrian WWTPs. The 220 WWTPs of the study were taken into account. If P_D in all 286 tanks is reduced to target value about 40% of mixing energy in activated sludge tanks could be saved. With reduction of P_D to tolerance value, about 25% of mixing energy could be saved (Table 4).

The reduction of t_d

The reduction of t_d (→ intermittent operation of agitators) is an energy saving option already being implemented in many pressure-aerated tanks. However, there are differences between different tank types. In oxidation ditches, the share of agitators being operated intermittently is 26%, in circular tanks it is 37%, in rectangular tanks 67%. This can be explained with different operating requirements; e.g. in oxidation ditches, propellers are needed to induce the direction of the water flow during aeration phases, in rectangular tanks not. Anyway, 33% continuously operated agitators also show an optimization potential at rectangular tanks (Table 5).

For unaerated tanks, there is no significant difference between tank types. In the case of oxidation ditches, circular tanks and rectangular tanks, approximately 85% of the agitators are being operated continuously. Nevertheless, about 15% of the tanks show that the continuous operation of agitators is no operating necessity (Table 5). This is consistent with references in DWA (2013) and Baumann et al. (2014).

Energy saving options

It turns out that the range of energy saving options for tank mixing is located between two opposite poles (Figure 5). At one end of the spectrum there are tanks continuously mixed with low P_D (WWTP Wartberg/Krems: $P_D = 0.92$ W m^{-3}).

Table 4 | Energy saving potential by reducing power density to tolerance value or target value – data basis: 220 WWTPs corresponding to 286 tanks with an overall design capacity of ~6 million PE$_{120}$ and an overall volume of ~830,000 m³

Tank volume (m³)	Number of tanks (n)	Energy consumption (kWh a^{-1})	Energy saving potential by reduction to tolerance value (kWh a^{-1})	(%)	Energy saving potential by reduction to target value (kWh a^{-1})	(%)
≤200	20	302,433	104,892	35	147,354	49
200–500	54	902,823	243,509	27	385,893	43
500–1,000	88	3,205,669	895,217	28	1,405,026	44
1,000–2,000	69	3,415,906	739,676	22	1,193,757	35
>2,000	55	5,328,494	1,117,941	21	2,110,003	40
TOTAL	286	13,155,325	3,101,234	24	5,242,033	40

At the other end of the spectrum there are tanks mixed with short high pulses of energy. These energy pulses may either be introduced by air (WWTP Bad Aussee: $P_D = 25\ \mathrm{W\,m^{-3}}$; WWTP Amperverband: $P_D = 15\ \mathrm{W\,m^{-3}}$) or by mixing (WWTP Amperverband: $P_D = 4.5\ \mathrm{W\,m^{-3}}$). The choice of the energy saving option largely depends on the specific operating conditions of the tank. As a consequence, intermittent operation of agitators with $P_D < 1\ \mathrm{W\,m^{-3}}$ is not likely to be reasonable. On the other hand, impulse aerating and impulse mixing can be regarded as 'extreme variants' of intermittent mixing.

In Figure 5 the general relationship between P_D and t_d is demonstrated for a low $W_{mix,V}$ of $24\ \mathrm{Wh\,m^{-3}\,d^{-1}}$: the shorter the duration of energy input t_d, the higher power density P_D on the respective volume-specific energy consumption isoline. The relationship between $W_{mix,V}$, P_D and t_d always follows a power function with the negative exponent $n = -1$ (Equation (4)). Along the respective volume-specific energy consumption isoline, the same mixing energy ($W_{mix,V}$) is consumed. Consequently, different mixing concepts (high P_D, low t_d; low P_D, high t_d) can easily be compared with each other underlying a volume-specific energy consumption isoline.

$$P_D = W_{mix,V} \cdot {t_d}^{-1} \tag{4}$$

Table 5 | Relative number of agitators with different t_d (24 h, 14–22 h, 2–12 h) depending on aeration type (pressure aeration, unaerated tanks) and tank type (oxidation ditch, circular tanks, rectangular tanks)

Daily operating time t_d (h d^{-1})	**Oxidation ditch (%)**	**Circular tanks (%)**	**Rectangular tanks (%)**
Pressure aeration			
24	74	63	33
14–22	14	17	34
2–12	12	20	33
Unaerated tanks			
24	86	86	82
<24	14	14	18

CONCLUSIONS

Agitators consume 5 to 20% of the total energy consumption of a WWTP. Up to 75% of the evaluated tanks have an optimization potential regarding energy consumption. This shows that mixing is an important issue in the energy optimization of WWTPs. The energy consumption indicators applied in this paper ($W_{mix,PE}$, P_D, $W_{mix,V}$) proved to be well applicable to both the calculation of the actual state and of the optimization potential of mixing energy. The first step for operators regarding optimization is thus to compare these indicators with the target values compiled in this paper.

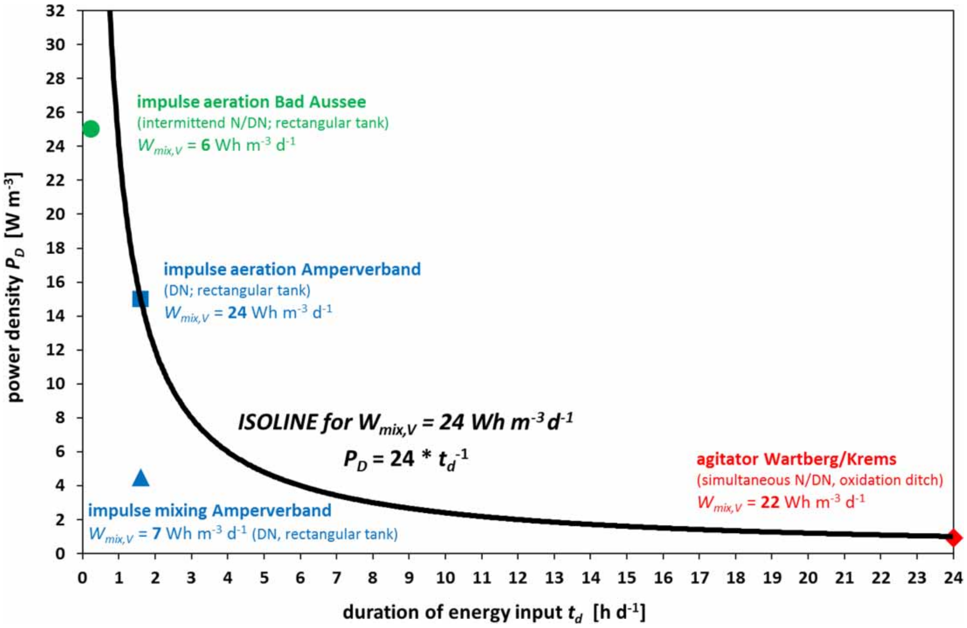


Figure 5 | Volume-specific energy consumption isoline – exemplified with $W_{mix,V} = 24\ \mathrm{Wh\,m^{-3}\,d^{-1}}$; data from Amperverband according to Kopmann (2015). N/DN: nitrification/denitrification.

The optimization itself can be split into two mostly independent strategies: the reduction of power density P_D and the reduction of daily operating time t_d. Ideally, both are optimized. However, this approach is limited by the volume-specific energy consumption $W_{mix,V}$. The following principle applies: the smaller t_d, the higher P_D on the respective volume-specific energy consumption isoline. Along this isoline, the range of energy saving options varies from continuous mixing with power densities as small as $1\,\mathrm{W\,m^{-3}}$ to mixing by short, intense energy impulses (impulse aeration, impulse mixing). When tank geometry, tank volume, agitator position and aeration are favourable, volume-specific mixing energy can be reduced to $24\,\mathrm{Wh\,m^{-3}\,d^{-1}}$ based on available full-scale experiences, and even below.

Aeration shows a major influence on mixing energy consumption $W_{mix,V}$. Concerning the complex interdependencies between the energy consumption of mixing and aeration, further research, based on large-scale experiments and/or CFD simulations, is needed.

REFERENCES

Baumann, P., Maurer, P. & Roth, M. 2014 *Senkung des Stromverbrauchs auf Kläranlagen. Leitfaden für das Betriebspersonal (Reduction of the Energy Consumption of WWTPs – Manual for Operators)*. Heft 4, 3. Aufl., DWA Landesverband Baden-Württemberg, Stuttgart, Germany.

BMLFUW 2016 *Kommunales Abwasser – Österreichischer Bericht 2016 (Municipal Wastewater - Austrian Report 2016)*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Vienna, Austria.

DWA 2013 *Merkblatt DWA-M 229-1. Systeme zur Belüftung und Durchmischung von Belebungsanlagen – Teil 1: Planung, Ausschreibung und Ausführung (Leaflet DWA-M 229-1. Systems for Aeration and Mixing of Activated Sludge Plants – Part 1: Planning, Tendering and Execution)*. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.

EPA 2010 *Evaluation of Energy Conservation Measures for Wastewater Treatment Facilities*. US Environmental Protection Agency Office of Wastewater Management, September 2010.

Frey, W. 2007 The role of diffuser arrangement and mixing for efficiency optimization of fine bubble aeration systems. In: *Large Waste Water Treatment Plant Conference, Vienna, September 2007*.

Frey, W. 2009 *Garantienachweise für die maschinelle Ausrüstung von Kläranlagen – Belüftungssysteme und Rührwerke (Guaranty Values for Mechanical Equipment of WWTPs – Aeration Systems and Agitators)*. Schriftenreihe Kläranlagennachbarschaften, Band 17.

Frey, W. 2011a *Messwerte und Kennzahlen der maschinellen Ausrüstung auf Kläranlagen (Mechanical Equipment of WWTPs: Measured Values and Key Figures)*. Wiener Mitteilungen, Band 224, S. 253-268, 2011.

Frey, W. 2011b Energieeffizientes Mischen und Belüften von Belebungsbecken (Energy-efficient mixing and aerating of activated sludge tanks). *25. Kalsruher Flockungstage, KIT Karlsruhe, 14–15 November 2011*.

Goldstein, R. & Smith, W. 2002 *Water & Sustainability (Volume 4): US Electricity Consumption for Water Supply & Treatment – The Next Half Century*. Electric Power Research Institute (EPRI), Palo Alto, CA, USA.

Haberkern, B., Maier, W. & Schneider, U. 2008 *Steigerung der Energieeffizienz auf Kommunalen Kläranlagen (Increasing the Energy Efficiency of Municipal WWTPs)*. Umweltbundesamt, Dessau-Roßlau, Germany.

Haslinger, J., Lindtner, S. & Krampe, J. 2016 Operating costs and energy demand of wastewater treatment plants in Austria: benchmarking results of the last 10 years. *Water Science and Technology* **74** (11), 2620–2626.

Kopmann, T. 2015 Mischen mit Luft (Impulse aeration). *Seminarband "Belüftung auf Abwasserreinigungsanlagen", Vienna, 19 May 2015*.

Krampe, J. 2011a Assessment of diffuser pressure loss on WWTPs in Baden-Württemberg. *Water Science and Technology* **63** (12), 3027–3033.

Krampe, J. 2011b Full scale evaluation of diffuser ageing with clean water oxygen transfer tests. *Water Science and Technology* **64** (3), 700–707.

Krampe, J. 2013 Energy benchmarking of South Australian WWTPs. *Water Science and Technology* **67** (9), 2059–2066.

Lindtner, S. 2008 *Leitfaden für die Erstellung eines Energiekonzeptes kommunaler Kläranlagen (Guidelines for the Development of an Energy Concept for Municipal WWTPs)*. Ingenieurbüro k2 W.

Lindtner, S., Kroiss, H. & Nowak, O. 2004 Benchmarking of municipal wastewater treatment plants (an Austrian project). *Water Science and Technology* **50** (7), 265–271.

Marner, S. T., Schröter, D. & Jardin, N. 2016 Towards energy neutrality by optimising the activated sludge process of the WWTP Bochum-Ölbachtal. *Water Science and Technology* **73** (12) 3057–3063.

ÖWAV 2013 *Benchmarking für Kläranlagen – Geschäftsjahr 2013. (Benchmarking for WWTP – 2013)*. Österreichischer Wasser- und Abfallwirtschaftsverband, 2013.

ÖWAV 2015 *Branchenbild der österreichischen Abwasserwirtschaft 2016 (Profile of Austrian Wastewater Management 2016)*. Österreichischer Wasser- und Abfallwirtschaftsverband.

Sharma, A. K., Guildal, T., Thomsen, H. R. & Jacobsen, B. N. 2011 Energy savings by reduced mixing in aeration tanks: results from a full scale investigation and long term implementation at Avedoere wastewater treatment plant. *Water Science and Technology* **64** (5) 1089–1095.

First received 27 April 2017; accepted in revised form 13 November 2017. Available online 23 November 2017