Opportunities to improve energy use in urban wastewater treatment: a European scale analysis

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis

To cite this article: Daniele Ganora *et al* 2019 *Environ. Res. Lett.* **14** 044028

IOP Publishing Environ. Res. Lett. 14 (2019) 044028 https://doi.org/10.1088/1748-9326/ab0b54

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
10 October 2018

REVISED
1 February 2019

ACCEPTED FOR PUBLICATION
28 February 2019

PUBLISHED
12 April 2019

LETTER

Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis

Daniele Ganora[1,2,12], **Almudena Hospido**[3], **Jovana Husemann**[4], **Joerg Krampe**[5], **Christian Loderer**[6], **Stefano Longo**[3], **Lucas Moragas Bouyat**[7], **Nathan Obermaier**[8], **Enrico Piraccini**[9], **Stanislav Stanev**[10], **László Váci**[11] and **Alberto Pistocchi**[1,12]

[1] European Commission, Joint Research Centre, Dir. D—Sustainable Resources, Marine and Water Resources Unit. Via E.Fermi, 2749, I-21027, Ispra (VA) Italy
[2] Currently at the Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy
[3] Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, Santiago de Compostela, Spain
[4] Veolia Umweltservice West, Germany
[5] Institute for Water Quality and Resource Management, TU Wien, Vienna, Austria
[6] Kompetenzzentrum Wasser Berlin gGmbH, Germany
[7] Catalan Water Agency, Barcelona, Spain
[8] German Environment Agency, Berlin, Germany
[9] Gruppo Hera s.p.a., Italy
[10] Veolia Bulgaria, Bulgaria
[11] Budapest Waterworks, Hungary
[12] Authors to whom any correspondence should be addressed.

E-mail: daniele.ganora@polito.it **and** alberto.pistocchi@ec.europa.eu

Keywords: Water-Energy Nexus, European-scale analysis, energy saving scenarios, energy-for-wastewater

Supplementary material for this article is available online

Abstract

Wastewater treatment is an essential public service that has a major impact on energy use in the urban water cycle, thus receiving increasing attention in context of the Water-Energy Nexus. Understanding the current energy use for wastewater is an essential step to design reliable policies promoting a more efficient use of resources. This paper develops a pan European estimation of electricity use for the treatment of wastewater, based on a dataset of wastewater treatment plants (WWTPs) across the continent. Prediction of electricity use has been performed using a statistical model that accounts for economies of scale. Different scenarios of improvements of energy use efficiency have been investigated to understand the possible reductions in electricity consumption at the continental scale. The overall WWTP electricity use in Europe (only plants with no less than 2000 population equivalent (PE) have been considered) was estimated at 24 747 GWh yr^{-1}, about the 0.8% of the electricity consumption in the EU-28. Small plants (less than 50 000 PE) represent almost 90% of the total number of plants, but process only 31% of the PE and require 42% of electricity use. Plants from mid to very large size (more than 50 000 PE), being only 10% of the plants, process about 70% of the PE with 58% of the total electricity use. If all plants that use more than the current average were shifted to the average value, the saving would be slightly more than 5500 GWh yr^{-1}. With highly stringent targets of efficiency improvement, saving of about 13 500 GWh yr^{-1} could be expected. Further considerations on the emerging role of WWTPs as energy and material producer are finally discussed.

Introduction

Wastewater treatment (WWT) is an essential environmental and social service that needs to be secured through sound, efficient and economically sustainable operations. Its importance is receiving increasing attention in the context of Water-Energy Nexus (e.g. Venkatesh *et al* 2014, Gude 2015, Liu *et al* 2016, Schopf *et al* 2018) as WWT is a major energy user in the urban water cycle, although the use of energy in WWT may be small compared to industrial uses (it is estimated about 1%–2% of the overall energy use of a country; IEA 2016). Energy makes a significant contribution to the operational costs of WWT (Panepinto *et al* 2016, Castellet-Viciano *et al* 2018), but it is also the cost share that can be most easily reduced. Ensuring cost- and resource-efficiency of WWT is strategically important in order to ensure the reliability and financial sustainability of the service and will likely gain more importance in the future due to different factors such as more stringent water quality standards, increasingly urbanized population worldwide, higher expected standards of living, and more stringent energy efficiency requirements to mitigate climate change. Many of these needs are already acknowledged by European legislation, in particular within the Water Framework Directive 2000/60/EU and Energy Efficiency Directive 2012/27/EU.

As a short-term strategy, energy use can be reduced through more efficient equipment. For instance, the aeration of the biological stage may be made more efficient by investing in upgraded blowers, with pay-back periods as low as two or three years (e.g. Pittoors *et al* 2014). But a careful operation of the plant, taking into account the specificity and variability of the processes, may be equally important. For instance, process-level benchmarking is a suitable tool to identify inefficiencies and unusual conditions (Steele *et al* 2013). Examples of implementation are difficult to cite as data from companies are usually not open, but evidence of the importance of energy use reduction is commonly referred to within the experts' community (e.g. Seibert-Erling 2010).

Wastewater treatment plants (WWTPs) may also offer opportunities for energy recovery, often making net energy use near zero and, in some case, even negative (i.e. the plant can become a net energy producer; e.g. Nowak *et al* 2011, Gude 2015). The most easily exploitable source of energy in a WWTP is the biogas produced in the anaerobic digestion of sludge, yielding both thermal and electric energy, although this source of energy should be carefully evaluated in terms of greenhouse gas (GHG) emissions (Mannina *et al* 2018). Altogether, a growing stock of evidence indicates that wastewater can be valorised as a source of energy as well as materials, although non-technical limitations often hinder its large-scale implementation (e.g. Coats and Wilson 2017).

In this paper we estimate the use of energy in European WWTPs, using a simple but robust statistical model, explicitly accounting for uncertainty. The model is applied to the database of WWTPs built by the European Environment Agency (EEA 2017) on the basis of the information reported by the EU Member States compliant with the Urban Wastewater Treatment Directive (UWWTD) 91/271/EC. The model is also used to quantify the energy use reduction achievable if all plants were adapted to reach at least a given standard of efficiency. We finally discuss the possible policy actions needed to promote effective WWT energy management.

Materials and methods

Energy use in WWTPs includes electricity to power mechanical devices, as well as thermal energy used for the heating of anaerobic digesters. More detailed accounts based on Life Cycle Assessment (e.g. Corominas *et al* 2013, Zang *et al* 2015, Remy *et al* 2017) may include also the energy embedded in chemicals, in the transportation of materials by trucks, in building and decommissioning of equipment and infrastructure, etc. In this work we refer to electric energy only as the main energy input at WWTPs; due to the large data requirements, a more comprehensive energy estimation is not reliable at the continental scale. Electric energy is normalized per population equivalent (PE) and referred to as 'unit energy use' (expressed as kWh/PE/year); this indicator is largely used even if other choices are possible (e.g. Longo *et al* 2016, Maktabifard *et al* 2018, Molinos-Senante *et al* 2018). The choice of PE as reference unit is consistent with the available datasets at the European scale and is justified as its definition is coherent over the whole case study as it is reported according the Wastewater Directive 91/271/EEC.

Collecting energy use data for all European WWTPs proves infeasible at present, at least in a systematic and comprehensive way. A similar issue has been recently raised by Chini and Stillwell (2018) who studied energy use for water and wastewater treatment in the USA by directly requesting data from the operators. On the opposite side, large-scale assessments of energy use have been performed using coarsely aggregated data based on country-wide statistics of wastewater volumes or served population (Liu *et al* 2016). These indicators are multiplied by typical consumption values from the literature, to obtain the overall energy use. This is a pragmatic way to approach the problem and results are particularly useful when the impact of WWT is framed in more general analyses on energy use (IEA 2016). Although simple, this approach cannot reflect the variability of plant characteristics and, more importantly, cannot support the study of policy strategies to improve the use of energy. In this study we build on a database of energy use compiled from data provided by the ENERWATER project (www.enerwater.eu), complemented with additional information obtained from different managing authorities across Europe. Figure 1 shows the data of about 300 plants, highlighting that unit energy use tends to decrease with increasing PE. This aspect is acknowledged as an economy of scale by which larger plants are more efficient (e.g. Longo *et al* 2016, Molinos-Senante *et al* 2018).

This general trend comes with a high residual variability (unit energy use may vary within one order

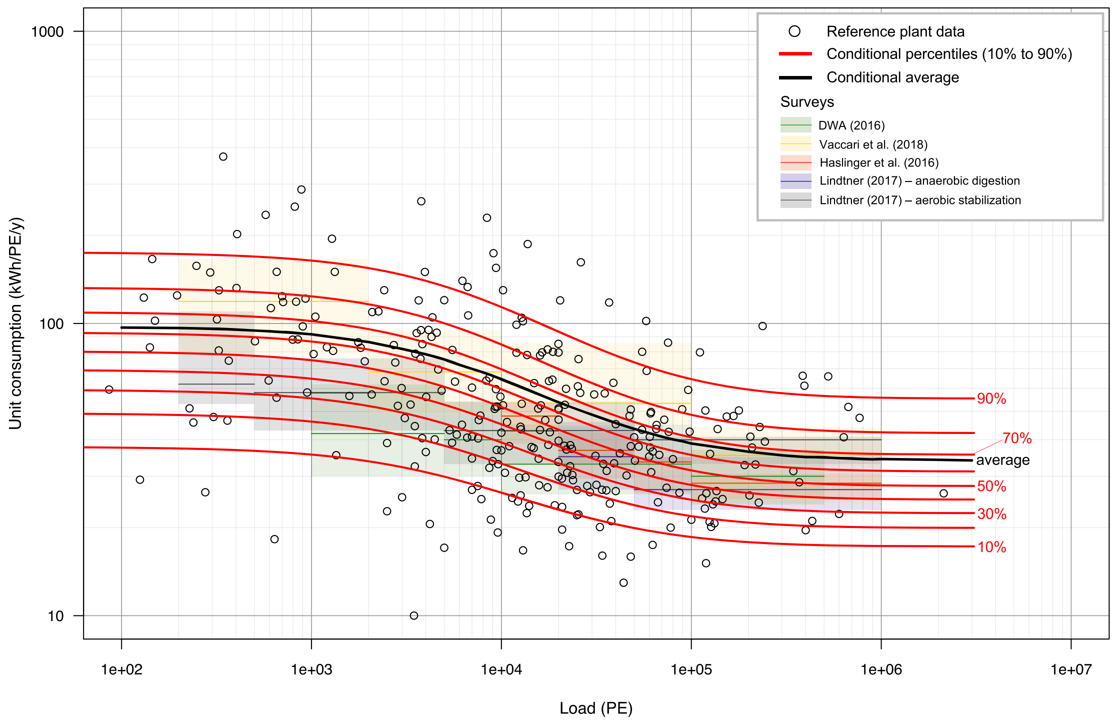

Figure 1. Reference chart of WWTP unit electricity consumption as a function of served PE. Circles represent the single-plant data of the reference dataset while the conditional average (black curve) and the conditional quantiles (from 10% to 90%, red curves) are obtained with the copula regression model of table 1. Coloured boxes represent aggregated data from literature used for comparison (top limit is the 75-percentile, bottom limit is the 25-percentile, solid line is the median).

of magnitude for given PE). Other variables have been used to explain this variability, e.g. level of treatment, climate, inflow dilution, equipment age and efficiency, under/oversize of the plant (Longo *et al* 2018, Molinos-Senante *et al* 2018). However, with the exception of climate, potential explanatory variables are often known only in few cases, hence their use to describe unit energy use across a large region is difficult. Very often, also non-measurable (e.g. the training level of plant operators) or changing variables (e.g. financial constraints) contribute to WWT energy efficiency, leaving *de facto* unexplained the residual variability across the trend.

Once properly acknowledged, the residual variability can be harnessed to infer the probability distribution of the unit energy use conditional to a given load (PE), enabling a quantitative estimate of the overall consumption as a function of the plant's PE, and the associated uncertainty. We represent this probability distribution through quantile curves. This representation is commonly used in other disciplines where the 'natural' variability of a variable is relevant and cannot be ascribed to other predictable factors (for example the children growth charts, WHO 2006). In the present exercise, in order to describe the bivariate distribution of plant load and unit energy use, we adopted a copula regression approach (e.g. Bouyé and Salmon 2009) where the marginal distributions are represented with a 3-parameter log-normal model (Hosking and Wallis 1997) and their correlation structure through a Frank's copula (e.g. Nelsen 2006).

The chart of modelled quantile curves is shown superimposed to the data points of the reference dataset in figure 1; it must be mentioned that the conditional distribution of the unit energy use is positively skewed and its average curve lies between the 60th and 70th percentile. Table 1 reports model equations and parameters that we calibrated (further details can be found in the supplementary material). For a known plant consumption the chart can be used as a diagnostic tool by calculating the corresponding energy-percentile (table 1, column 'a'). Otherwise, the chart can be used like a regression to compute the conditional average value for a given load and its associated uncertainty (table 1, column 'b'); however, as the average value has no analytical form, it needs to be computed numerically.

The model appears consistent with local surveys in Germany (DWA 2016), Austria (Haslinger *et al* 2016, Lindtner 2017) and Italy (Vaccari *et al* 2018) whose ranges are also shown in figure 1 (coloured boxes). Although the three surveys suggest the distribution may not be the same in these three countries, a more general comparison is not possible due to the lack of systematic surveys in many European areas. Indeed, the quantile-lines fit well the overall range of boxplots, thus suggesting the model is suitable for estimation at the European scale where the same level of treatment is taking place.

Table 1. Summary of equations and procedures to manage consumption data according to the model. More details in the supplementary material.

Task	(a) Evaluation of the probability of a given unit energy use (conditioned to the load)	(b) Evaluation of the unit energy use for a given probability level (conditioned to the load)	
Input	$x =$ load in PE	$x =$ load in PE	
	$y =$ unit energy use in kWh/PE/y	P $=$ percentile of interest $\in [0, 1]$	
Calculations	$u = \Phi\left[\frac{\ln(x - \zeta_x) - \mu_x}{\sigma_x}\right]$	$u = \Phi\left[\frac{\ln(x - \zeta_x) - \mu_x}{\sigma_x}\right]$	
	$v = \Phi\left[\frac{\ln(y - \zeta_y) - \mu_y}{\sigma_y}\right]$	$v = -\frac{1}{\alpha}\ln\left\{1 - (1 - \mathrm{e}^{-\alpha})\left[1 + e^{-\alpha\cdot u}\left(\frac{1}{P} - 1\right)\right]^{-1}\right\}$	
Output	$P(y\|x) = e^{-\alpha\cdot u}\left[\frac{1 - e^{-\alpha}}{1 - e^{-\alpha\cdot v}} - (1 - e^{-\alpha\cdot u})\right]^{-1}$	$y(P\|x) = \zeta_y + \exp[\mu_y + \sigma_y \cdot \Phi^{-1}[v]]$	
Parameters	$\Phi =$ frequency of the standard normal distribution	$\zeta_x = -1301.9$	$\zeta_y = 9.1626$
	$\Phi^{-1} =$ quantile of the standard normal distribution	$\mu_x = 9.6521$	$\mu_y = 3.6405$
	$\alpha = -3.4667$	$\sigma_x = 1.6325$	$\sigma_y = 0.819\ 67$

Results

The statistical model of energy use has been applied to a dataset of plants recorded in the last version of the urban WWTPs database issued by the European Environment Agency (EEA 2017; hereafter UWWTD database) and based on mandatory reporting by the Member States. It reports a total of 19 074 plants with actual load equal or greater than 2000 PE and in total capacity of about 569 million PE. This database does not contain any information other than the size (PE and, in some cases, loads and treated volumes) and level of treatment of each individual WWTP.

Thanks to the availability of the probability distribution of energy use for given plant load, we generated in a Monte Carlo framework 10 000 different realizations of the random field of energy use for the whole UWWTD database. Averaging consumption values of each realization, the expected overall WWTP energy use in Europe was estimated at 24 747 GWh yr^{-1} (see table 2). This is about 0.8% of the electricity generation in the EU-28 in 2015 (Eurostat 2017), in line with previous estimations, but derived using information relative to each single plant. Table 2 shows also results grouped by plant size. Plants of small size (less than 50 000 PE) represent almost 90% of the total, but process only 31% of the PE, while they require 42% of electricity use. Plants from mid to very large size, being only the 10% of the plants, process about 70% of the PE with 58% of the total electricity use.

In order to explore scenarios of energy saving, each realization of the random field of energy use was modified assuming that all plants showing an energy use higher than a given benchmark were brought to the benchmark itself. As benchmarks, we considered different percentiles (90%, 80%, 70%, 60%, 50%, 40%, 30%, 20% and 10%) of energy use, and the average value. The 10%-percentile benchmark can be regarded as an 'optimal energy use' scenario. Bringing all higher consumptions to the average may instead represent a 'quick wins' scenario, easier to implement. Statistically-derived benchmark approaches are commonly used in some contexts (e.g. Krampe 2013, Haslinger *et al* 2016) as an alternative to theoretical benchmarks corresponding to the adoption of best practices (e.g. Remy 2016).

The expected energy savings associated to scenarios defined according to statistical benchmarks, are also shown in table 2. Shifting all plants from the current conditions to the benchmark of the 10th percentile enables a saving of about 13 500 GWh yr^{-1} (from 24 747 to 11 237), with an almost linear decreasing trend in energy saving as a function of the percentile taken as a benchmark. If we imagine shifting all plants to no more than the current average, the saving would be slightly more than 5500 GWh yr^{-1} (about one fifth of the current electricity use).

Discussion

We may regard all plants across the EU compliant with the current 10th percentile benchmark as the 'least practically achievable consumption' scenario. A scenario with all plants performing no worse than the current average may be instead regarded as a 'quick win' scenario enabled through easy-to-implement, quick pay-back investments. We can therefore argue that between 5500 and 13 500 GWh could be saved yearly in Europe through appropriate management and targeted investments in UWWTPs. The energy that can be saved with efficient WWT in Europe is relatively little but not negligible, making energy efficiency a reasonable objective for WWTPs.

The impact of energy savings on WW treatment costs is difficult to evaluate as variable energy prices and national subsidies make the rates of wastewater service not everywhere directly linked to the costs, thus requiring further research. However, an approximate estimate of the overall magnitude of the relative economic investments is a valuable information. For an illustrative example, we adopt the average cost of electricity of 110 Euro/MWh (EU-28 average price for non-household consumer reported by EUROSTAT for the year 2017), we can expect to save 0.66 billion Euro per year under the 'quick wins' scenario (average as benchmark), and 1.62 billion Euro per year under the 'optimal energy use' scenario (10th percentile as benchmark). This corresponds to about 0.015–0.03 Euro m^{-3} and 0.03–0.08 Euro m^{-3} for each scenario (with 1 PE to correspond to 0.1–0.2 m^3 d^{-1} of wastewater to treat). Assuming a pay-back of the efficiency measures of 3 years the investments would require 1.8–4.8 billion Euro across Europe.

The reduction of treatment costs associated to energy efficiency can look rather small at a first glance, but is of the same order of the profits (5%–10%) made by certain utilities on. In areas where tariffs are low, and where WWT can hit on affordability constraints of the poorer households, treatment cost reductions of a few cents per cubic meter may relief the water bills and allow margins of flexibility in the design of social tariffs. Nevertheless, how should an effective strategy be ground to improve the energy use in WWTPs? First, it is necessary for the operators to become aware of the energy budget of a plant. A plant's energy auditing can identify the critical sub-systems and quantitatively define the room for improvement under specific plant conditions (load, plant layout, dilution, climate variability, etc). While Directive 2012/27/EU already mandates a regular energy audit for large companies, many plants are managed by smaller companies, hence energy audits remain voluntary. Simple self-diagnostic tools, such as the graph presented in figure 1, may already enable plant operators to look at their specific case in comparison with their peers, and understand in which class of energy efficiency they are. An energy audit, once the plant operator is aware of the energy

Table 2. Expected European electricity consumption under current conditions and based on different target scenarios.

Size class	Served PE	N. plants	Energy use under current conditions GWh yr^{-1} (80% confidence interval)	Energy use under different scenarios GWh/y (targets based on reference chart): Average 'quick wins'	Perc. 10% 'optimal'	Perc. 20%	Perc. 30%	Perc. 40%	Perc. 50%	Perc. 60%	Perc. 70%	Perc. 80%	Perc. 90%
XS (2 k $<$ PE $\leqslant$ 10 k)	51 827 664 (9.1%)	11 046 (57.9%)	3812 (15%) (3775–3849)	2894	1490	1846	2122	2362	2584	2798	3012	3234	3480
S (10 k $<$ PE $\leqslant$ 50 k)	130 862 477 (22.1%)	5824 (30.5%)	6754 (27%) (6664–6846)	5182	2880	3441	3884	4272	4631	4978	5327	5697	6119
M (50 k $<$ PE $\leqslant$ 100 k)	83 228 712 (14.6%)	1180 (6.2%)	3399 (14%) (3304–3494)	2645	1571	1825	2028	2207	2375	2537	2701	2874	3075
L (100 k $<$ PE $\leqslant$ 500 k)	174 421 062 (30.6%)	899 (4.7%)	6358 (26%) (6146–6575)	4999	3091	3538	3895	4212	4509	4799	5092	5403	5762
XL (500 k $<$ PE)	128,847,853 (22.6%)	125 (0.7%)	4424 (18%) (4027–4852)	3495	2205	2505	2745	2958	3159	3355	3554	3765	4009
Total	**569 187 768**	**19 074**	**24 747 (24 267–25 270)**	**19 215**	**11 237**	**13 156**	**14 674**	**16 011**	**17 258**	**18 467**	**19 685**	**20 973**	**22 445**

use of the plant, can better define the investments for energy efficiency.

Examples of good practices can serve as a guide to identify the most appropriate actions. Although data about the financial aspects (investments and paybacks) are hardly available in the literature, it is recognised that simple actions in renewing equipment or tuning processes (for instance air blowers, mixers; Füreder *et al* 2018) have beneficial effects. They impact the energy use reducing the consumption in the order of more than 10% (some examples in Seibert-Erling 2010) and can pay themselves back in 0.5–4 years (Larsson 2011, Pittoors *et al* 2014, Voltz *et al* 2017), therefore representing attractive investments. In some cases, it has been shown that the availability of properly trained personnel, capable of operating a plant in a more careful and competent way, may in itself turn to a significantly reduced energy consumption. Automated control may also help reducing energy use at relatively low costs.

Making WWTPs energy-efficient can be regarded as a no-regret option, because it cuts back on some operational costs with relative quick pay-back investments. Alongside energy use reduction, WWTPs may in principle recover energy from wastewater and sludge in different forms, of which biogas production from anaerobic digestion of sludge is already broadly harnessed. Biogas may be then used for the combined generation of heat and electricity. While, under the most common conditions in many WWTPs, biogas contributes about 50% of the electricity demand, this contribution may be close to 100% (energy neutrality) or even above (energy-positive plants). For example, the Sofiyska Voda WWTP of Sofia, Bulgaria, has notably achieved the 123% energy self-sufficiency in 2017 (unit consumption 21.4 kWh/PE/year) after optimization of aeration processes, improvement of the anaerobic digestion of sludge and utilization of on-site CHP (combined heat and power) cogeneration. The plant's energy production contributes to 91% energy use of the whole water supply system of Sofia municipality. Other full-scale demonstrations of energy-positive plants of different size are reported and discussed within the POWERSTEP project (www.powerstep.eu) that also provides examples of technical solutions for the practical implementation of biogas production.

Although several energy-neutral or energy-positive plants have been demonstrated at full scale of operation, they are not yet the norm. A large-scale transition in this direction requires significant investments, usually possible only for new plants or major overhauls (and primarily for plants larger than 50 000 PE), and should be placed in a broader context. Biogas production for heat and power generation is a great opportunity (Maktabifard *et al* 2018), but may not be always a win-win option, because the GHG footprint of a plant with anaerobic digestion can be larger than a traditional plant (Daelman *et al* 2012, Lorenzo-Toja *et al* 2016, Parravicini *et al* 2016). With the progress of electricity decarbonisation in the EU, especially in certain countries, electricity from WWT may turn to have a higher carbon footprint than grid electricity, and biogas remains attractive only as an alternative to more impacting fossil fuels, while other treatments of sludge (including aerobic stabilization or incineration) may become preferable. Especially in retrofitting of medium-small plants, technologies that are commercially available to implement energy recovery may result in excessive increased complexity of the plant layout and operations so that any change should be carefully evaluated before implementing it (Bertanza *et al* 2018). While a detailed discussion on GHG direct and indirect emissions is out of the scope of the paper, it is worth remarking the distinction between GHG reduction due to increased efficiency of machineries and the GHG impact (positive or negative) that is associated to the whole sludge process chain. General conclusions are difficult due to the paucity and fragmentation of data (Mannina *et al* 2018), but more detailed plant-scale analysis could be encouraged, e.g. through energy audits of plants.

On the other hand, energy recovery can still represent a no-regret option if the plant is considered under a broader perspective. An example is the implementation of co-digestion of the organic fraction of municipal waste (Mattioli *et al* 2017, Maktabifard *et al* 2018) to improve the organic load (and thus gas production) while integrating the waste and WWT chain, which are commonly regarded and managed as separate businesses. Promising options in this direction come from the view of the plant as a material (other than energy) recovery facility (Coats and Wilson 2017, Breach and Simonovic 2018) that look at water reuse, nutrients and chemicals extraction and biosolids reuse. This shift in the perception of the plants is likely to start a competition between alternative 'recovery targets', while should also stimulate the development of detailed analysis of all the energy and mass fluxes within the plants. This is not yet a standard practice in the design and operation of plants but remains essential for the recovery of resources.

Conclusions

We have presented an estimate of the overall electric energy use of European UWWTPs, based on a statistical model calibrated on a reference dataset of almost 300 plants. A dataset based on single-plants information has proven to profitably contribute to the evaluation of current and future scenarios of energy use, while more information is needed to support the assessment of potential energy and materials recovery.

European urban WWTPs account for about 0.8% of total electricity generation in the EU, but energy efficiency in this sector may bring a useful contribution to reducing the tariffs of this essential service, making it economically more sustainable. The existing plants feature a broad variability of electric energy use (without accounting for self-production). Shifting the least efficient plants to an average level of efficiency would enable to save 5500 GWh annually, while a compliance with the standards of the most efficient plants would save 13 500 GWh yr^{-1}. The percentile curves that we propose may be used to raise awareness about the potential for energy savings at very inefficient plants, where 'quick wins' can be identified to bring energy use in line with the average. The curves can also help setting more ambitious benchmarks, which require a systematic review of the plant's energy use in order to optimize it. Energy efficiency is expected to typically require relatively small and quick-payback investments, making it a win-win and no-regret option for UWWTPs in Europe. An effective starter to promote energy efficiency may be a plant's energy audit, anchored to an appropriate energy labelling scheme for UWWTPs, as proposed for instance in the ENERWATER project (ENERWATER methodology 2017) and already being discussed by the WG40 (Wastewater treatment plants >50 PE) of the European Committee for Standardization CEN/TC 165 (Wastewater engineering) as the possible basis for a Technical Report (CEN/TR) on this issue (Longo *et al* 2018b).

Energy efficiency can be in principle accompanied by measures to recover energy, particularly through extraction of biogas for combined heat and power generation. This option is uncontroversial when considering a single plant and the current energy system. However, it may become less clearly a no-regret option with the progress of electricity decarbonisation in Europe.

WWT remains an essential public service, and the users will have to appropriately pay for it in order to keep it sustainable. However, integrated and resource-efficient WWT will be increasingly important in order to keep the service affordable and equitable. Beyond the specific environmental and economic costs and benefits of energy recovery from wastewater, which may require a specific case-by-case assessment, paying attention to the resources potentially available in wastewater and sludge will be unavoidable in the future. It is the first step spearheading the development of an industrial ecology around a WWTP, like for instance the installation of industrial processes or public services requiring low-temperature heat. It can also stimulate a more circular economy, e.g. with co-digestion of urban and other organic waste substrates, the extraction of nutrients and the reuse of treated wastewater.

Acknowledgments

This paper stems from the discussions of a technical workshop held at the Joint Research Centre of the European Commission in Ispra, Italy, in July 2018 with the participation of experts in the field.

This work is part of the project Water-Energy-Food-Ecosystems (WEFE) nexus financed by the Joint Research Centre of the European Commission.

Contributions

DG and AP conceived the work and drafted the paper. DG performed the analysis. All the authors revised the manuscript and contributed with data, examples or personal experiences.

ORCID iDs

Daniele Ganora https://orcid.org/0000-0003-0605-6200

References

Bertanza G, Canato M and Laera G 2018 Towards energy self-sufficiency and integral material recovery in waste water treatment plants: assessment of upgrading options *J. Cleaner Prod.* **170** 1206–18

Bouyé E and Salmon M 2009 Dynamic copula quantile regressions and tail area dynamic dependence in forex markets *Eur. J. Financ.* **15** 721–50

Breach P A and Simonovic S P 2018 Wastewater treatment energy recovery potential for adaptation to global change: an integrated assessment *Environmental Management* **61** 624–36

Castellet-Viciano L, Hernández-Chover V and Hernández-Sancho F 2018 Modelling the energy costs of the wastewater treatment process: the influence of the aging factor *Sci. Total Environ.* **625** 363–72

Chini C M and Stillwell A S 2018 The state of US urban water: data and the energy-water nexus *Water Resour. Res.* **54** 1796–811

Coats E R and Wilson P I 2017 Toward nucleating the concept of the water resource recovery facility (WRRF): perspective from the principal actors *Environ. Sci. Technol.* **51** 4158–64

Corominas L L, Foley J, Guest J S, Hospido A, Larsen H F, Morera S and Shaw A 2013 Life cycle assessment applied to wastewater treatment: state of the art *Water Res.* **47** 5480–92

Daelman M R, van Voorthuizen E M, van Dongen U G, Volcke E I and van Loosdrecht M C 2012 Methane emission during municipal wastewater treatment *Water Res.* **46** 3657–70

DWA 2016 *28. Leistungsvergleich kommunaler Kläranlagen (28th Performance Comparison of Municipal Wastewater Treatment Plants)* (Hennef: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.) (https://bmbf.nawam-erwas.de/sites/default/files/download/leistungsvergleich_2015.pdf)

EEA 2017 European Environment Agency, Waterbase—UWWTD: Urban Waste Water Treatment Directive—reported data (version 6) (https://eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-5) (Accessed: 1 August 2018) (the Microsoft Access version of the database has been used in this analysis)

ENERWATER methodology 2017 Standard method and online tool for assessing and improving the energy efficiency of wastewater treatment plants (https://cordis.europa.eu/project/rcn/194621/factsheet/en) (Accessed: 5 October 2018)

Eurostat 2017 *Energy, transport and environment indicators* Publications Office of the European Union (https://doi.org/10.2785/964100)

Füreder K, Svardal K, Frey W, Kroiss H and Krampe J 2018 Energy consumption of agitators in activated sludge tanks–actual state and optimization potential *Water Sci. Technol.* **77** 800–8

Gude V G 2015 Energy and water autarky of wastewater treatment and power generation systems *Renew. Sustain. Energy Rev.* **45** 52–68
Haslinger J, Lindtner S and Krampe J 2016 Operating costs and energy demand of wastewater treatment plants in Austria: benchmarking results of the last 10 years *Water Sci. Technol.* **74** 2620–6
Hosking J R M and Wallis J R 1997 *Regional Frequency Analysis: An Approach Based on L-Moments* (Cambridge: Cambridge University Press) (https://doi.org/10.1017/cbo9780511529443)
IEA 2016 Water-energy nexus *World Energy Outlook 2016* (Paris: International Energy Agency) (https://doi.org/10.1787/weo-2016-en)
Krampe J 2013 Energy benchmarking of south Australian WWTPs *Water Sci. Technol.* **67** 2059–66
Larsson V 2011 Energy savings with a new aeration and control system in a mid-size Swedish wastewater treatment plant *Master Thesis* Uppsala Universistet (http://diva-portal.org/smash/get/diva2:485284/FULLTEXT01.pdf) (Accessed: 25 January 2019)
Lindtner S 2017 ÖWAV Kläranlagenleistungsvergleich-Betriebsjahr 2016 (ÖWAV treatment plant performance comparison-year of operation 2016) *Conf. of the ÖWAV Canal and Sewage Treatment Plant Neighborhoods (13–14 September 2017 (Hagenberg Austria) (http://kan.at)*
Liu Y, Hejazi M, Kyle P, Kim S H, Davies E, Miralles D G, Teuling A J, He Y and Niyogi D 2016 Global and regional evaluation of energy for water *Environ. Sci. Technol.* **50** 9736–45
Longo S *et al* 2016 Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement *Appl. Energy* **179** 1251–68
Longo S, Hospido A, Lema J M and Mauricio-Iglesias M 2018 A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring data envelopment analysis *Water Res.* **141** 317–28
Longo S, Mauricio-Iglesias M, Soares A, Campo P, Fatone F, Akkersdijk E, Stefani L and Hospido A 2018b ENERWATER-a standard method for assessing and improving the energy efficiency of wastewater treatment plants. Manuscript Unpublished to Applied Energy
Lorenzo-Toja Y, Alfonsín C, Amores M J, Aldea X, Marin D, Moreira M T and Feijoo G 2016 Beyond the conventional life cycle inventory in wastewater treatment plants *Sci. Total Environ.* **553** 71–82
Maktabifard M, Zaborowska E and Makinia J 2018 Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production *Rev. Environ. Sci. Bio/Technol.* **17** 1–35
Mannina G *et al* 2018 Greenhouse gas emissions from integrated urban drainage systems: where do we stand? *J. Hydrol.* **559** 307–14
Mattioli A, Gatti G B, Mattuzzi G P, Cecchi F and Bolzonella D 2017 Co-digestion of the organic fraction of municipal solid waste and sludge improves the energy balance of wastewater treatment plants: rovereto case study *Renew. Energy* **113** 980–8
Molinos-Senante M, Sala-Garrido R and Iftimi A 2018 Energy intensity modeling for wastewater treatment technologies *Sci. Total Environ.* **630** 1565–72
Nelsen R B 2006 *An Introduction to Copulas* 2nd edn (New York: Springer) (https://doi.org/10.1007/0-387-28678-0)
Nowak O, Keil S and Fimml C 2011 Examples of energy self-sufficient municipal nutrient removal plants *Water Sci. Technol.* **64** 1–6
Panepinto D, Fiore S, Zappone M, Genon G and Meucci L 2016 Evaluation of the energy efficiency of a large wastewater treatment plant in Italy *Appl. Energy* **161** 404–11
Parravicini V, Svardal K and Krampe J 2016 Greenhouse gas emissions from wastewater treatment plants *Energy Proc.* **97** 246–53
Pittoors E, Guo Y and Van Hulle S W H 2014 Modeling dissolved oxygen concentration for optimizing aeration systems and reducing oxygen consumption in activated sludge processes: a review *Chem. Eng. Commun.* **201** 983–1002
Remy C 2016 POWERSTEP Deliverable D 5.1: proposition of POWERSTEP process schemes and WWTP reference models (https://cordis.europa.eu/project/rcn/196805/factsheet/de)
Remy C, Corominas L L, Hospido A, Larsen H F and Teodosiu C 2017 Assessing environmental impacts and benefits of wastewater treatment plants *Innovative Wastewater Treatment & Resource Recovery Technologies: Impacts on Energy, Economy and Environment* ed J M Lema and S Suarez (London: IWA Publishing) (https://doi.org/10.2166/9781780407876_0437)
Seibert-Erling G 2010 Praktische Umsetzung von Energiemaßnahmen (Practical implementation of energy measures). Lecture on the occasion of the 11th Cologne Sewer and Sewage Treatment Colloquium, September 2010, Köln (http://setacon.de/images/stories/downloads/Aufsaetze_setacon/2010_koeln_energierecht.pdf) (Accessed: 5 October 2018)
Schopf K, Judex J, Schmid B and Kienberger T 2018 Modelling the bioenergy potential of municipal wastewater treatment plants *Water Sci. Technol.* **77** 2613–23
Steele R, Krampe J and Dinesh N 2013 Process level energy benchmarking as a tool to improve the energy efficiency of wastewater treatment plants *Water J. Aust. Water Assoc.* **40** 129–34 (https://issuu.com/australianwater/docs/water_journal_april_2013)
Vaccari M, Foladori P, Nembrini S and Vitali F 2018 Benchmarking of energy consumption in municipal wastewater treatment plants–a survey of over 200 plants in Italy *Water Sci. Technol.* **77** 2242–52
Venkatesh G, Chan A and Brattebø H 2014 Understanding the water-energy-carbon nexus in urban water utilities: comparison of four city case studies and the relevant influencing factors *Energy* **75** 153–66
Voltz T J, Grischek T and Musche F 2017 Case studies in energy management: experience from Germany *J. Am. Water Works Assoc.* **109** E520–34
WHO Multicentre Growth Reference Study Group 2006 *WHO Child Growth Standards: Length/Height-For-Age, Weight-For-Age, Weight-For-Length, Weight-For-Height and Body Mass Index-for-Age: Methods and Development.* (Geneva: World Health Organization)
Zang Y, Li Y, Wang C, Zhang W and Xiong W 2015 Towards more accurate life cycle assessment of biological wastewater treatment plants: a review *J. Clean. Prod.* **107** 676–92