Energy performance indicators of wastewater treatment: a field study with 17 Portuguese plants

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ABSTRACT

The energy costs usually represent the second largest part of the running costs of a wastewater treatment plant (WWTP). It is therefore crucial to increase the energy efficiency of these infrastructures and to implement energy management systems, where quantitative performance metrics, such as performance indicators (PIs), play a key role. This paper presents energy PIs which cover the unit energy consumption, production, net use from external sources and costs, and the results used to validate them and derive their reference values. The results of a field study with 17 Portuguese WWTPs (5-year period) were consistent with the results obtained through an international literature survey on the two key parcels of the energy balance – consumption and production. The unit energy consumption showed an overall inverse relation with the volume treated, and the reference values reflect this relation for trickling filters and for activated sludge systems (conventional, with coagulation/filtration (C/F) and with nitrification and C/F). The reference values of electrical energy production were derived from the methane generation potential (converted to electrical energy) and literature data, whereas those of energy net use were obtained by the difference between the energy consumption and production.

Key words | activated sludge systems, energy, performance assessment, performance indicators, trickling filters, wastewater treatment plants

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INTRODUCTION

Energy represents one of the higher costs of water and wastewater services, and is usually the second largest part of the running costs of a wastewater treatment plant (WWTP), right after the personnel costs. For example, in the United States, the California Energy Commission and AWWA Research Foundation indicate 28% of WWTP running costs were spent on electrical energy (CEC & AWWARF 2003), the Pacific Gas & Electric Company 25–40% (PG&E 2003) and WERF (2010a) 30–35%; in Southern Europe, Rodriguez-Garcia *et al.* (2011) indicate 26% in Spain and Silva *et al.* (2012) 25% in Portugal. It is therefore crucial to identify the main uses of energy in WWTPs and to develop guidance and strategies to increase the energy efficiency of these infrastructures. On top of operation-related measures, the wastewater utilities should implement energy management systems, as recommended in ISO 50001 (ISO 2011) standards, where quantitative performance metrics, such as performance indicators (PIs), play a key role. According to ISO 50001 (ISO 2011), energy performance is defined by measurable results related to energy efficiency, energy use (manner or kind of application of energy) and energy consumption, the latter expressing the quantity of energy.

Many authors have addressed the WWTP energy performance (as detailed in the third section), but few (e.g. Yang *et al.* 2010; Balmer & Hellström 2012) reported a complete framework of PIs. To assist the continuous improvement of WWTP performance, we have been developing a performance assessment system (PAS) for these infrastructures. Energy PIs are core measures of this system (Silva *et al.* 2012) and were further developed in the current third generation of PAS.

This paper presents the energy PIs and the results obtained in a field study with 17 Portuguese WWTPs. To set the international scene on WWTP energy performance, a literature survey was conducted on the two key parcels of the energy balance – the energy consumption (electrical and all other forms) and the electrical energy production.

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The literature data were then processed according to the proposed PIs and were used with the field data to validate the PIs and derive their reference values.

THE ENERGY PERFORMANCE INDICATORS PROPOSED

The PAS includes a portfolio of PIs in the following eight assessment groups: treated wastewater quality; use of natural resources and raw materials (RU); by-product management (BP); removal efficiency and reliability (ER); economic and financial resources (Fi); safety; personnel; and planning and design (Silva *et al.* 2012).

The energy performance is transversal to four assessment groups, RU, BP, ER and Fi; hence the proposed set of energy PIs includes: (i) the four first level PIs shown in Table 1, one from each of the above-mentioned groups, for assessing the energy consumption, production, net use and costs; and (ii) 11 complementary PIs, related to renewable (wind and solar photovoltaic) energy production and WWTP reliability, e.g. adequacy of plant (hydraulic and mass) capacity, adequacy of pumping capacity, recycling and aeration control.

The developed PIs are defined as ratios between variables; the numerator expresses the PI objective and the denominator represents one dimension of the system. With respect to the system's dimension, although the biochemical oxygen demand (BOD) or chemical oxygen demand (COD) mass removed is as much or even more relevant than the treated wastewater volume for many assessment criteria, namely for the unit consumption of resources, the latter is often preferred for the sake of data accuracy and reliability. The volume of treated wastewater is usually measured on a continuous basis whereas BOD and COD concentrations are determined discontinuously, once or twice a week or a month (or even with lower frequency for small plants), despite their usually significant daily and seasonal variations. PIs are therefore herein defined by default per treated wastewater volume (e.g. wtRU03.1) but they may be expressed per BOD_5 (5-day BOD) (wtRU03.2) or COD (wtRU03.3) mass removed using the explanatory factor wtEF03 for BOD_5 or wtEF04 for COD (Table 1).

The PIs refer to a reference assessment period, usually the calendar year, and require reference values to judge the performance, in this case and for PAS WWTP in general, in three levels: 'good', 'acceptable' and 'unsatisfactory' performance (Silva *et al.* 2014a, b). The reference values hereafter proposed were derived based on literature and field data results, as follows.

Table 1 | First level PIs for assessing WWTP energy performance and associated explanatory factors

PI code, units and processing rule
wtRU03.1 – Energy consumption [kWh/m³]
Energy consumption (kWh)/Treated wastewater (m^3)
wtRU03.2 – Energy consumption [kWh/kg BOD_5 removed]
Energy consumption (kWh)/BOD_5 mass removed (kg)
It may be computed from wtRU03.1 and wtEF03, i.e. wtRU03.2 = wtRU03.1/wtEF03
wtRU03.3 – Energy consumption [kWh/kg COD removed]
Energy consumption (kWh)/COD mass removed (kg)
It may be computed from wtRU03.1 and wtEF04, i.e. wtRU03.2 = wtRU03.1/wtEF04
wtBP18.1 – Production of energy from biogas [kWh/m³]
Electrical energy produced from biogas (kWh)/Treated wastewater (m^3)
wtBP18.2 – Production of energy from biogas [%]
Electrical energy produced from biogas (kWh)/Energy consumption (kWh)*100
wtER08 – Net use of energy from external sources [kWh/m³]
(Energy acquired to external sources – Energy sold to external users (kWh))/Treated wastewater (m^3)
wtFi05 – Electrical energy costs [€/m³]
Electrical energy costs (€)/Treated wastewater (m^3)
Explanatory factor code, units and processing rule
wtEF03 – BOD_5 mass removed/Treated wastewater ratio [kg BOD_5/m^3]
BOD_5 mass removed (kg)/Treated wastewater$_{BOD\ days}$ (m^3)
wtEF04 – COD mass removed/Treated wastewater ratio [kg COD/m³]
COD mass removed (kg)/Treated wastewater$_{COD\ days}$ (m^3)

Note: 'Treated wastewater$_{BOD\ days}$' in wtFE03 and 'Treated wastewater$_{COD\ days}$' in wtFE04 correspond to the sum of the volumes treated during the days with BOD or COD data, whereas 'Treated wastewater' used in the PIs corresponds to the total volume treated during the assessment period.

Energy tariffs vary from region to region and therefore no reference values for international benchmarking of energy costs (wtFi05 PI) were proposed.

UNIT ENERGY CONSUMPTION AND PRODUCTION IN WWTPS WORLDWIDE

The data obtained from a literature survey on energy consumption and energy production in WWTPs were processed to assist the validation of the energy PIs wtRU03.1, wtRU03.2, wtBP18.1 and wtBP18.2 and the derivation of their reference values on an international level.

The unit energy consumption in WWTPs (wtRU03.1, Figure 1; wtRU03.2, Figure 2) varies from country to country and among various authors, but mostly depends on the treatment processes (Burton 1996; Quantum 2001; EPRI 2002; IAMU 2002; SAIC 2006; WEF 2009; Mizuta & Shimada 2010; Yang *et al.* 2010), pumping requirements, and treated wastewater quality requirements (which depend on the influent loads and maximum allowable concentrations of C and N in the effluent), as well as on the operation and maintenance practices and procedures (USEPA 2008; Guimet *et al.* 2010).

Generally, aeration and pumping are the biggest energy consumers (Burton 1996; SAIC 2006; USEPA 2008; Olsson 2011; Hernández-Sancho *et al.* 2011). Depending on the treatment type and season, aeration may be responsible for 25–60% of the total energy consumption (NYSERDA 1995; PG&E 2003; Stoica *et al.* 2009; WEF 2009; Guimet *et al.* 2010; Brandt *et al.* 2011; Shi 2011).

In addition, the unit energy consumption often depends on the plant's size scale in terms of mass removed (Lingsten & Lundkvist 2008; Hernández-Sancho *et al.* 2011) and/or treated wastewater volume (Burton 1996; Quantum 2001; SAIC 2006; ENERGY STAR 2008; Mizuta & Shimada 2010; Yang *et al.* 2010; Shi 2011; Hernández-Sancho *et al.* 2011; WERF 2011; Bodik & Kubaska 2013). Bigger WWTPs and more advanced technology generally consume more energy, but they often use it more efficiently, making the unit energy consumption lower for higher treated wastewater volumes (or mass removed), as illustrated in Figure 3. Moreover, the capacity utilization often affects the energy performance, i.e. the closer the WWTP is to its design capacity the more efficient the operations and processes are, including the unit energy consumption (WERF 2011), as illustrated in Figure 1, 0.15–0.43 kWh/m^3 for 80% capacity vs. 0.32–0.60 kWh/m^3 for 50% capacity.

Although its feasibility is often linked to the plant's size, the energy production may significantly improve the WWTP performance with respect to energy costs and self-sufficiency, defined by production/consumption in percent, as in wtBP18.2 for biogas. Depending on the wastewater characteristics and on the removal efficiencies, 0.074–0.15 kWh/m^3 are reported in the literature (Figure 4), and may ensure or even exceed the plant self-sufficiency, as in the Strass WWTP (108% self-sufficiency) where 8% of the total energy demand of the facility is fed to the public grid (Wett *et al.* 2007).

RESULTS AND DISCUSSION

The field study with 17 Portuguese WWTPs

The data collected within the PASt21 initiative (Silva *et al.* 2012) for 17 Portuguese WWTPs and a 5-year period (2006–2010) were used with the literature data in Figures 1–4 to validate the full set of energy PIs and to derive the reference values proposed for energy consumption (wtRU03), production (wtBP18) and net use (wtER08). The results of the four first level PIs proposed for assessing the plant's overall energy performance, namely wtRU03, wtBP18, wtER08 and wtFi05, are herein presented and discussed (Figures 5–8).

PI results were analysed by WWTP (Figure 5) and further aggregated in box plots defined for percentiles 25 and 75, P25–P75, as detailed in Silva *et al.* (2012). Annual box plots and a 5-year box plot were considered (Figure 6). The percentage of case studies entering the calculation of a given PI is also shown. Whenever relevant and feasible, clusters by treatment type or volume treated were analysed (Figure 7).

Two clusters were considered by treatment type: (i) activated sludge (AS) systems without primary sedimentation, (AS w/o 1sed.), i.e. low-rate and extended aeration systems; and (ii) AS systems with primary sedimentation (AS after 1sed.), i.e. intermediate-rate and conventional aeration systems. The WWTPs with attached growth processes, i.e. with trickling filters (TFs) and with biofilters (Biofor® systems), were analysed separately. In terms of volume treated, the results were aggregated for WWTP clusters below and above 10,000 m^3/d, which is the boundary found between the region where the unit energy consumption significantly decreases with the volume treated and the region where it stabilizes, approaching a plateau (Figure 3).

Figure 5 presents the 'Energy consumption' (wtRU03) and the 'Net use of energy from external sources' (wtER08). For the studied WWTPs, the difference between wtRU03 and wtER08 corresponds to the 'Electrical production of energy from biogas' (wtBP18.1) since there was no other source of energy production (e.g. wind power or solar voltaic energy). Only four WWTPs (13–16, which do not use external organic waste) present a significant energy production, namely 0.12 kWh/m^3 (65% of self-sufficiency, wtBP18.2), 0.25 kWh/m^3 (35%), 0.21 kWh/m^3 (47%) and 0.12 kWh/m^3 (15%) in 2009. Hence, wtER08 and wtRU03.1 are very similar, and they present the same P25–P75, 0.34–1.27 kWh/m^3, for the 5-year period (2006–2010) (Figure 6).

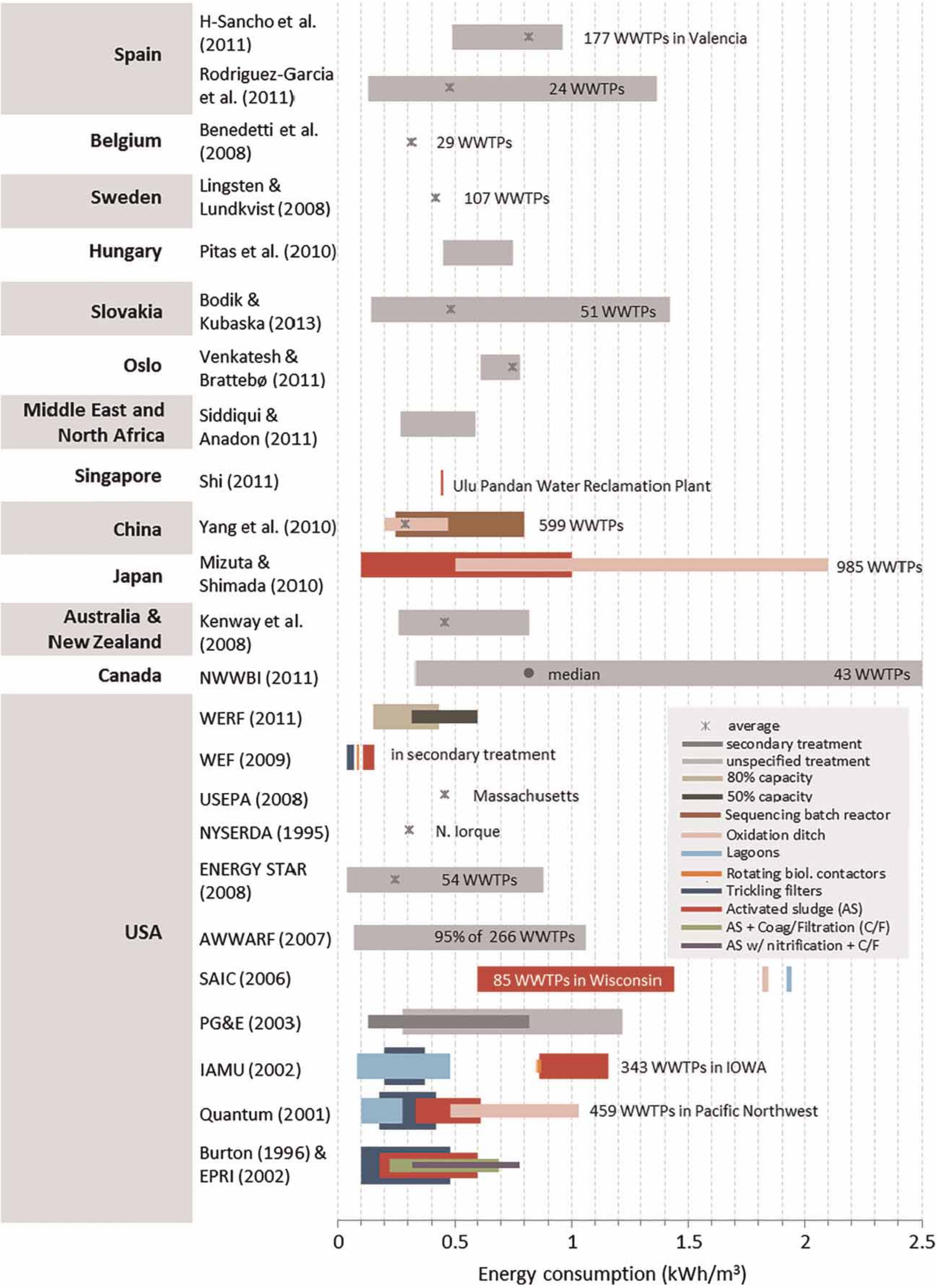

Figure 1 | Energy consumption per treated wastewater volume in different countries.

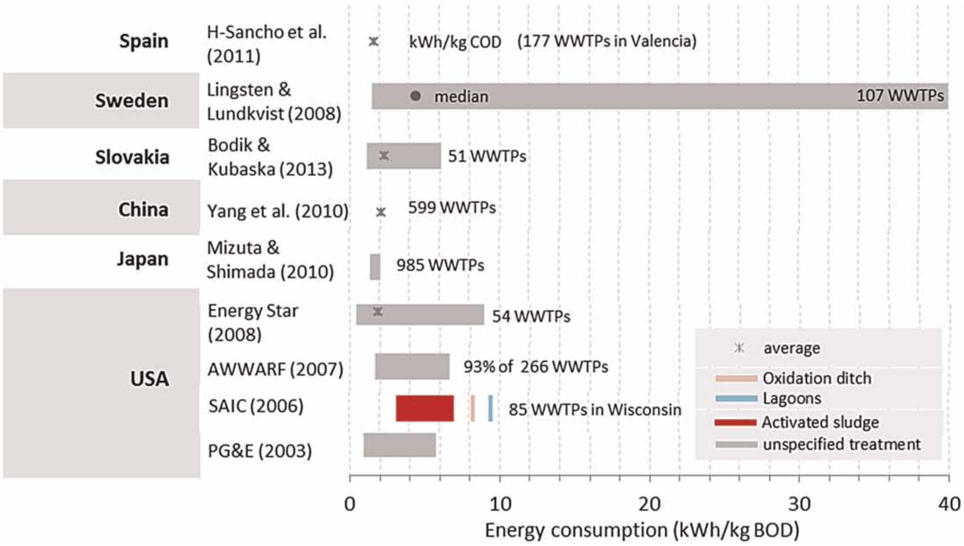

Figure 2 | Energy consumption per BOD_5 mass removed in different countries.

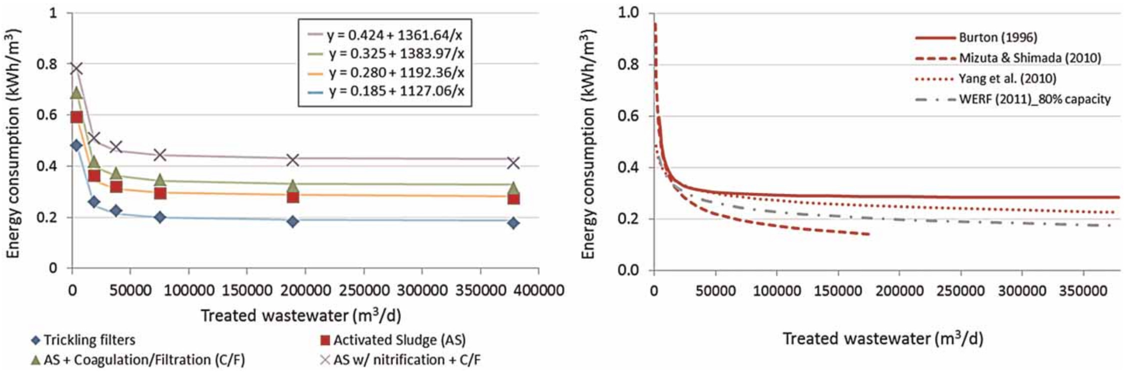

Figure 3 | Energy consumption vs. treated wastewater volume by different treatments (fittings developed from Burton (1996) data) (left) and by AS systems (right).

In terms of BOD_5 or COD mass removed, the average energy consumption for the 5 years studied (2006–2010) is 2.8 kWh/kg BOD_5 and 1.3 kWh/kg COD and the P25–P75 ranges are 0.9–4.2 kWh/kg BOD_5 and 0.5–1.8 kWh/kg COD (Figure 5).

Similarly to energy consumption (wtRU03) and net use from external sources (wtER08), the electrical energy costs (wtFi05, Figure 5) depend on the treatment type, since most WWTPs have no significant energy production. As expected, these PIs are directly related, in this case, by a factor of €0.09/m^3 of treated wastewater (Figure 5). AS (suspended growth) systems without primary sedimentation (AS w/o 1sed.), i.e. low-rate extended aeration processes, show median costs with electrical energy three to four times higher than the conventional rate and aeration AS systems (AS after 1sed.).

The broad range found for wtRU03 requires further analysis as it includes processes of different energy consumption profiles, treated volumes and time trends throughout 2006–2010, the studied period. Regarding the energy consumption profiles, characterized by wtRU03.1, in 2009, AS systems without primary sedimentation present a P25–P75 of 0.72–1.34 kWh/m^3, AS systems with primary sedimentation a P25–P75 of 0.31–0.84 kWh/m^3, biofilters a median of 0.79 kWh/m^3 and the rock trickling filter a value of 0.16 kWh/m^3, which is out of (below) the box plot (Figure 7). The energy consumption therefore shows the expected variation with the type of treatment. For instance, AS systems without primary sedimentation, due to the higher organic loads entering the biological reactor and higher sludge ages (extended aeration), consume almost twice the energy, as given by P25-P75, or three

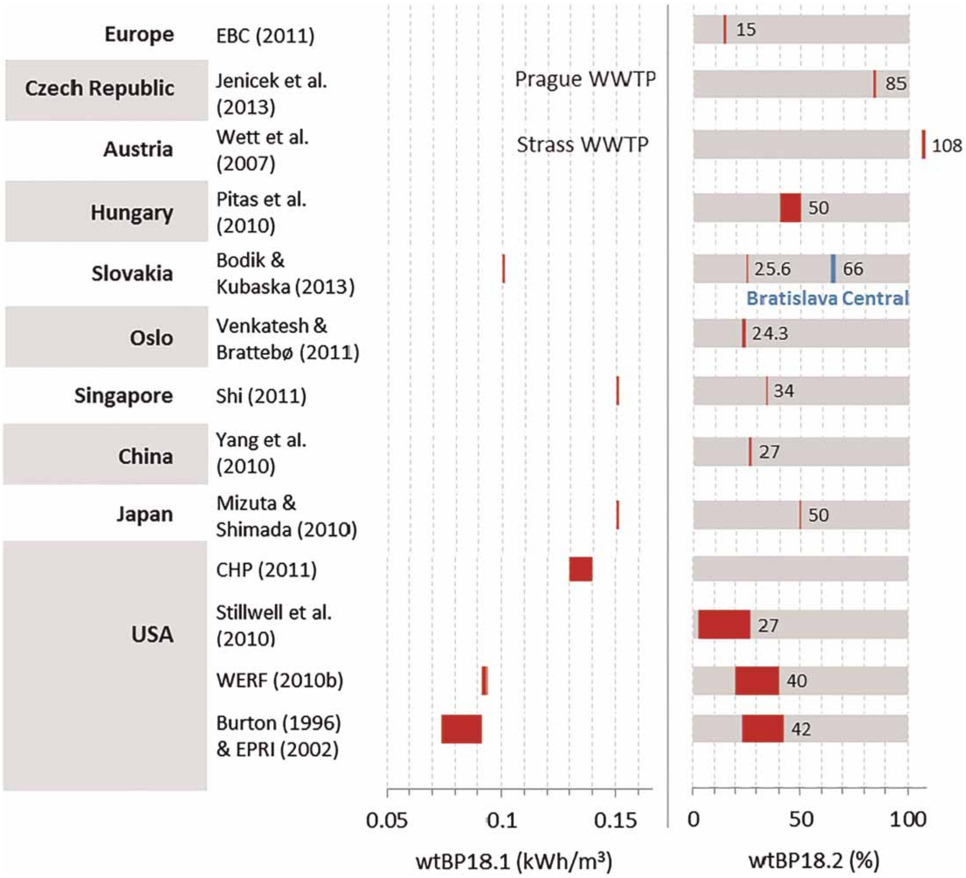

Figure 4 | Unit energy production in different countries.

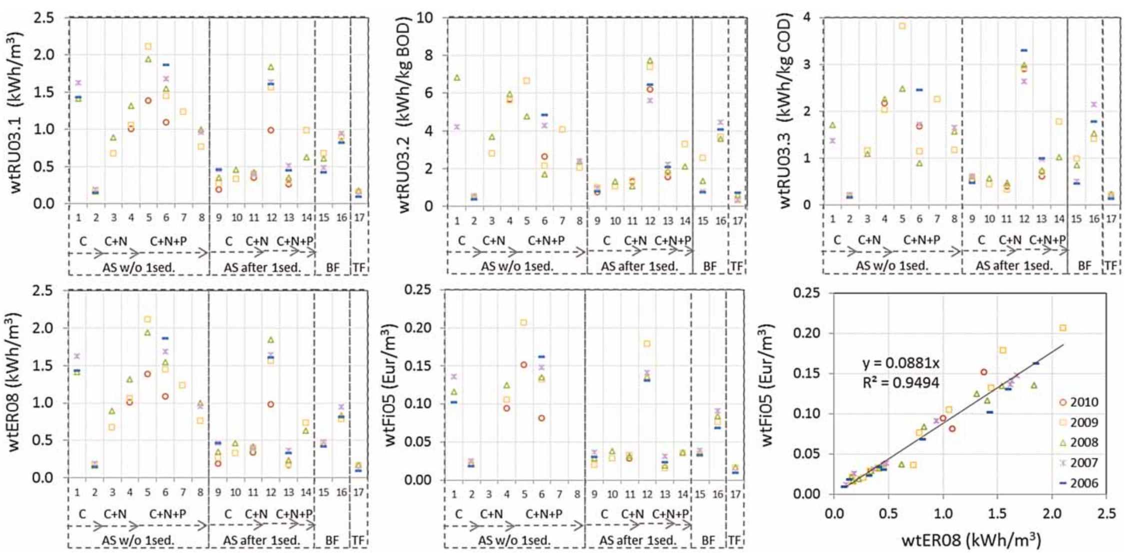

Figure 5 | Energy consumption (wtRU03.1, wtRU03.2, wtRU03.3), net use of energy from external sources (wtER08), electrical energy costs (wtFi05) and wtFi05 vs. wtER08 in 17 WWTPs.

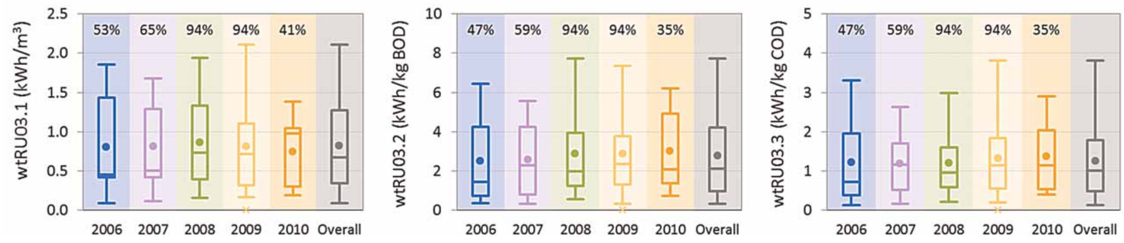

Figure 6 | Box plots for PIs wtRU03.1, wtRU03.2 and wtRU03.3.

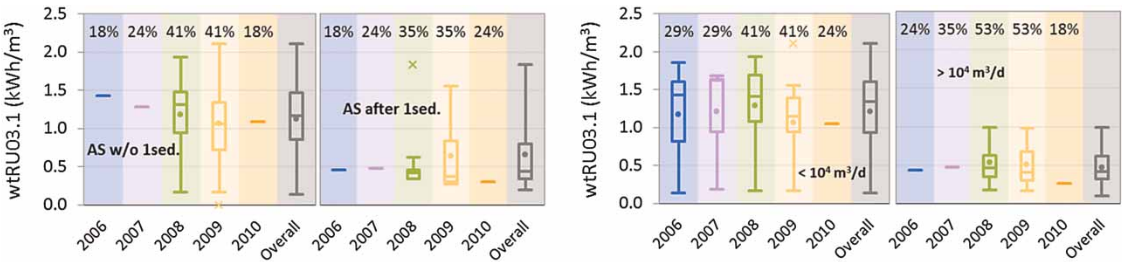

Figure 7 | PI wtRU03.1 box plots for AS clusters and for clusters below and above 10,000 m^3/d.

times the median consumed by AS systems with primary sedimentation (Figure 7).

As far as the volume treated is concerned, for both clusters considered (below or above 10,000 m^3/d) there is a decreasing time trend of the median throughout 2006–2010.

PI reference values proposed

The above results obtained in Portugal are consistent with those from different countries and both data sources were then used to derive the PI reference values.

The unit energy consumption shows an overall inverse relation with the treated wastewater volume, which was further broken down by type of treatment (Figure 8). The relations observed are very similar to those obtained by processing the data of Burton (1996) (Figure 3). Thus, the relations herein derived from Burton's data were used to define the equations from which the reference values of wtRU03.1 are obtained as a function of the volume treated by treatment type (one set of equations for each of the four types considered by Burton (1996)). These equations yield the reference value for good performance, and a 25% tolerance is given for the minimum acceptable performance (Table 2).

The energy consumption per BOD_5 mass removed (wtRU03.2) shows also an increase in energy efficiency with mass removed, ranging from 0.30 to 8.25 kWh/kg BOD_5, with an average of 2.96 kWh/kg BOD_5 (Figure 8). A linear relation was found between wtRU03.2 and wtRU03.1, corresponding, on average, to a 3.4:1 ratio (Figure 8). Higher values above (i.e. higher energy consumption per mass removed) may indicate diluted inflow (e.g. from stormwater) whereas lower values below may act as an alert for industrial (highly charged) inflows. The range covering most of the results (Figures 2 and 8) was used to derive the reference values for good (<2 kWh/kg BOD_5), acceptable (2–10 kWh/kg BOD_5) and unsatisfactory (≥10 kWh/kg BOD_5) performance (Table 2).

The reference values for the unit electrical energy production, wtBP18, are based on the literature data (Figure 4) and on the potential for methane generation (Equation (1)),

$$V_{CH4} = 0.35\left[ES_0 - 1.42\frac{YES_0}{1 + k_d\theta_c}\right] \quad (1)$$

where 0.35 is the theoretical conversion factor for the amount of methane produced from the conversion of BOD_L, the ultimate carbonaceous BOD ($m^3\ CH_4$/kg BOD_L), Y the yield coefficient (typically, 0.04–0.1 mg volatile suspended solids per mg BOD_L); E the waste utilization efficiency (0.6–0.9); S_o the influent BOD_L (kg/d); K_d the endogenous coefficient (0.02–0.04 d^{-1}) and θ_c the mean cell residence time (10–15 d) (Qasim 1999).

Considering these typical ranges, the methane generation was calculated as 0.185–0.304 m^3/kg BOD_L. Considering the theoretical energy content of the methane

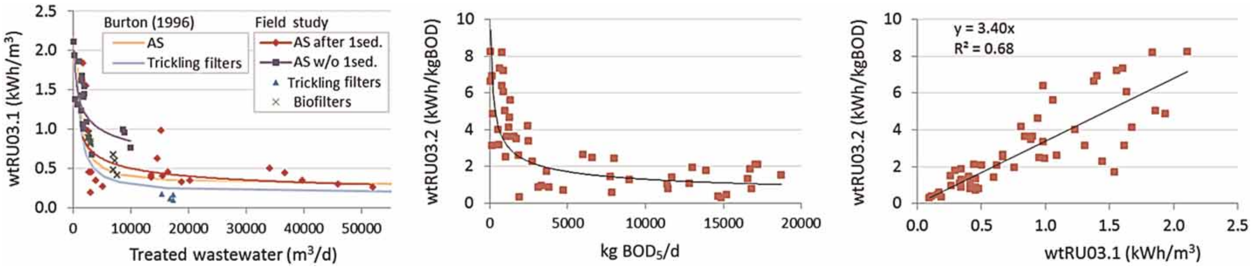

Figure 8 | Energy consumption (wtRU03.1) vs. volume treated and treatment type (left); energy consumption (wtRU03.2) vs. BOD_5 mass removed (centre); wtRU03.1 vs. wtRU03.2 (right) in all WWTPs analysed.

Table 2 | PI reference values proposed for assessing the overall WWTP energy performance

PI reference values

wtRU03.1 – Energy consumption [kWh/m³]			
TF	● $\leq 0.185 + 1127/TW$	● $[0.185 + 1127/TW; 0.231 + 1409/TW]$	● $\geq 0.231 + 1409/TW$
AS	● $\leq 0.280 + 1192/TW$	● $[0.280 + 1192/TW; 0.350 + 1490/TW]$	● $\geq 0.350 + 1490/TW$
AS + coagulation/ filtration (C/F)	● $\leq 0.325 + 1384/TW$	● $[0.325 + 1384/TW; 0.406 + 1730/TW]$	● $\geq 0.406 + 1730/TW$
AS w/ nitrification + C/F	● $\leq 0.424 + 1362/TW$	● $[0.424 + 1362/TW; 0.530 + 1703/TW]$	● $\geq 0.530 + 1703/TW$
wtRU03.2 – Energy consumption [kWh/kg BOD_5]			
	● ≤ 2	● $[2; 10]$	● ≥ 10
wtBP18.1 – Electrical production of energy from biogas [kWh/m³]			
	● $\geq 0.0009\ BOD_5$	● $[0.0007\ BOD_5; 0.0009\ BOD_5]$	● $< 0.0007\ BOD_5$
wtER08 – Net use of energy from external sources [kWh/m³]			
TF	● $\leq 0.185 + 1127/TW - 0.0009\ BOD_5$	● $[0.185 + 1127/TW - 0.0009\ BOD_5; 0.231 + 1409/TW - 0.0007\ BOD_5]$	● $\geq 0.231 + 1409/TW - 0.0007\ BOD_5$
AS	● $\leq 0.280 + 1192/TW - 0.0009\ BOD_5$	● $[0.280 + 1192/TW - 0.0009\ BOD_5; 0.350 + 1490/TW - 0.0007\ BOD_5]$	● $\geq 0.350 + 1490/TW - 0.0007\ BOD_5$
AS + C/F	● $\leq 0.325 + 1384/TW - 0.0009\ BOD_5$	● $[0.325 + 1384/TW - 0.0009\ BOD_5; 0.406 + 1730/TW - 0.0007\ BOD_5]$	● $\geq 0.406 + 1730/TW - 0.0007\ BOD_5$
AS w/ nitrification + C/F	● $\leq 0.424 + 1362/TW - 0.0009\ BOD_5$	● $[0.424 + 1362/TW - 0.0009\ BOD_5; 0.530 + 1703/TW - 0.0007\ BOD_5]$	● $\geq 0.530 + 1703/TW - 0.0007\ BOD_5$

TW = treated wastewater (m^3/d); BOD_5 = influent BOD_5 (mg/L); 'good' (●), 'acceptable' (●) and 'unsatisfactory' (●) performance.

gas (9.944 kWh/m³ CH_4), 25% conversion to electricity, and the BOD_5/BOD_L ratio of 0.68, the unit electrical energy production (per cubic metre) is a function of influent BOD_5 and varies between 0.0007 BOD_5 and 0.0011 BOD_5 (BOD_5 in mg/L). For BOD_5 110–350 mg/L, this relation yields an electrical energy production of 0.074–0.389 kWh/m³, a range covering the literature data (0.07–0.15 kWh/m³) and the field study results (0.12–0.25 kWh/m³). Thus, 0.0007 BOD_5 (the minimum) was used as the reference for the minimum acceptable performance, and 0.0009 BOD_5 (in the middle of the range, corresponding to, for example, 0.20 kWh/m³ for 220 mg/L BOD_5) was considered the reference for the good performance (Table 2).

The reference values for the net use of energy from external sources, wtER08, were defined as the difference between those of energy consumption and electrical energy production (Table 2).

CONCLUSIONS

Energy represents one of the higher costs of wastewater treatment and the energy PIs are thus core measures of the PAS developed for WWTPs. The energy PIs cover the unit energy consumption, the electrical energy production, the net use of energy from external sources and costs.

The results of a field study with 17 Portuguese WWTPs in a 5-year period were consistent with the results obtained for different countries through a literature survey on the two key parcels of the energy balance – the energy consumption and the electrical energy production. The reference values proposed for the unit energy consumption reflect the overall inverse relations observed with the volume treated and are specific for AS systems (conventional, with coagulation/filtration (C/F) and with nitrification and C/F) and TF. The reference values for electrical energy production were derived based on the methane generation potential (converted to electrical energy) and literature data; those of net use of energy from external sources were considered the difference between the references for energy consumption and energy production.

The energy PIs and their reference values, derived on an international level, ultimately constitute an effective tool for each WWTP to improve its energy performance and reduce the energy costs, and for designers to calibrate models between designing and actual performance.

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