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Energy efficiency of wastewater treatment plants. Overview of the literature and critical discussion of energy data

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Abstract: In response to strong growth in energy intensive wastewater treatment, public agencies and industry began to explore and implement measures to ensure achievement of the target indicated in the 2020 Climate and Energy Package. However, in the absence of fundamental and globally recognized approach evaluating wastewater treatment plants (WWTPs) energy performance, these policies could be economically wasteful. This paper gives an overview of the literature of WWTPs energy-use performance. Energy key performance indicators (KPIs) found are presented and critically assessed, pointing out the limits to their validity. Data from more than 430 WWTPs, together with the methods for synthesizing the information is presented. The assessment of a large data sample provided some evidence about the effect of the plant size, dilution factor and flowrate. The technology choice, plant layout and country of location were seen as important elements that contributed to the large variability observed.

Keywords: Wastewater treatment; energy efficiency; KPI

Introduction

As a result of the nexus between water and energy, the consumption of water and energy forms a positive feedback loop: when the use of water increases, the associated energy use caused by water and wastewater services will also increase, which will further increase the water consumed in energy production. The resulting trend is an increasing interest in understanding baseline energy use and opportunities for reducing energy consumption by wastewater agencies.

In order to compare energy efficiency between different WWTPs, the energy consumption has to be expressed based on certain guidelines and equal dimensions, i.e. the volume of wastewater treated, the unit per capita loading as PE or unit of pollutant removed. These partial measures are generally available, and provide the simplest way to perform comparison.

By assessing the literature of WWTPs energy-use performance, this paper represents the first step in the development of a systematic methodology for evaluation and improvement of energy performance in WWTPs operation. Such a methodology is the main objective of the ENERWATER coordinated support action, a three-year activity within the Horizon 2020 program with 9 partners from 4 European countries (www.enerwater.eu).

Material and Methods

A thorough review of the literature on WWTP energy-use performance and related benchmarking methods was carried out using different combinations of the following keywords: ‘wastewater’, ‘WWTP’, ‘energy’, ‘energy consumption’, ‘energy performance’, ‘energy efficiency assessment’, ‘energy benchmarking’, ‘life cycle assessment’, and ‘LCA’, in web search engines. WWTP energy consumption was gathered together with data related to the operation, influent and effluent characteristics.

Dataset was classified according to five different WWTP class sizes: PE < 2 k; 2 k < PE < 10 k; 10 k < PE < 50; 50 k < PE < 100 k; PE > 100 k, where k stands for 1000 PE. In addition, datasets were further classified based on a country scale and secondary treatment technology.

Results and Conclusions

Description of key performance indicators found and critical discussion about their validity. Traditionally, energy consumption in WWTPs has been reported as referred to the volume of treated wastewater (kWh/m^3) or per unit of population equivalent (kWh/PE). As a result, the energy consumed (due to aeration, mixing, pumping, sludge treatment, etc.) was considered to be proportional to the amount of wastewater treated or the amount of pollution load coming into the WWTP. Although these approaches are very simple and can easily provide calculated energy consumption indicators, they have significant limitations: it is assumed that pollutants concentrations in the influent (solids, organic matter, nitrogen and phosphorus) do not vary significantly between WWTPs or that effluent qualities are also similar, hence restricting the application of these approaches. Studies reporting the WWTP energy consumption in kWh/m^3 often result in values that are influenced by the degree of dilution of the wastewater: plants treating wastewater from combined sewer overflows often show higher energy efficiency, which is caused by the higher dilution of the pollutants in the influent.

Therefore, a sensible approach is to report the energy consumption in WWTPs per unit of pollutant removed, i.e. TSS, BOD, COD, N and/or P removed, depending on the object of the study and plant treatment scheme. Several authors have used kWh/kg TSS$_{\text{removed}}$, kWh/kg BOD$_{\text{removed}}$ and kWh/kg COD$_{\text{removed}}$, kWh/kg N$_{\text{removed}}$ in the case of nitrogen removal processes or a combination of these indicators where both organic matter and nutrients (N, P) are merged and converted in terms of a reference unit such as PO_4^{3-} equivalent. However, WWTPs can have different functions, i.e. removing of COD, removing of N and/or P, producing an effluent free of pathogens. Although current legislation in Europe only requires the reduction of N and P for the treated effluents returned to a sensitive area, the objectives of a WWTP are expected to become broader and include, e.g. the removal of micropollutants or the production of reusable water. Even more so, the approach of report energy data based on single KPI (i.e. kWh/m^3 or kWh/kg COD$_{\text{removed}}$) it seems not reliable. Rather, the choice of the correct KPI should be related to the function of the WWTP.

Indeed, WWTPs feature complex processes composed by several subsystems (stages), i.e. preliminary, primary, secondary, tertiary and sludge treatment, each one with different function and as a result partial KPIs seem to be more appropriate to be used for treatment stage(s) with different function. As for instance, kWh/m^3 does not represent necessarily the overall plant performance since, i.e., in the case of mixed sewer system this KPI is affected by dilution of the wastewater (Gallego et al., 2008). However, it could be suitable, as partial KPI for hydraulic-based stages (e.g. preliminary treatment), which are designed using hydraulic loads and typically equipped with pumps, screens, sieving, scrappers, and filters, in which energy depends on the volume of the influent wastewater processed.

Energy consumption respect to scale, type of treatment and country. In order to elucidate the influence of individual variables on the energy performance, Fig. 1 reports the data variability classified by class size (2.A), technology (2.B) and country (2.C).

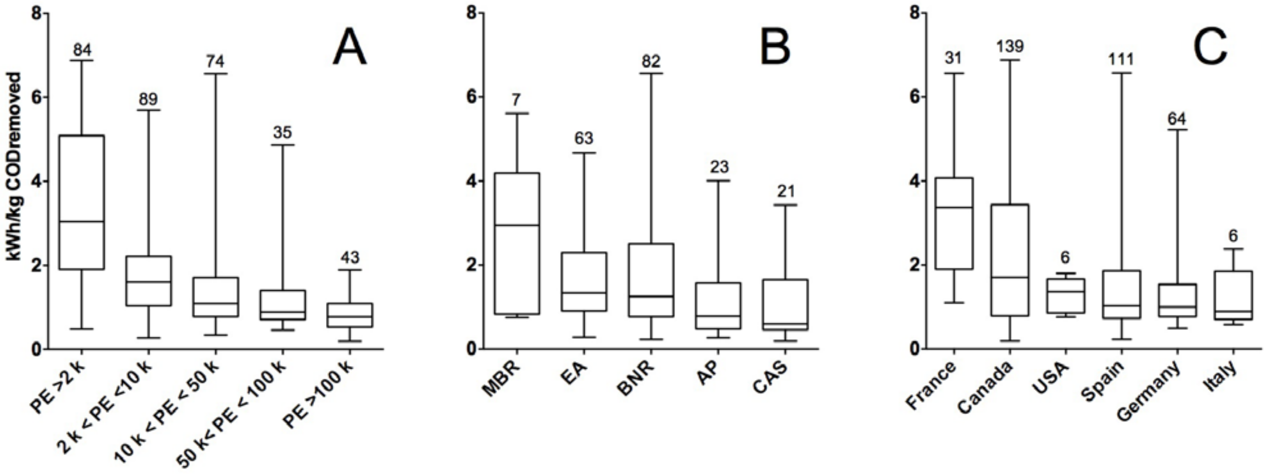

Figure 1. Total WWTPs energy consumption per: (A) class size, (B) type of treatment and (C) country. (Numbers on top of each box plot represents sample population).

According to Fig. 1.A, it can be seen that the energy consumption decreases when increasing the population equivalent. This can be due to: i) exploiting economies of scale, by using large and generally more efficient equipment, in particular larger pumps and compressors; ii) ensuring that the process operates at more stable conditions; iii) providing the automation for the treatment process (for example, regulation of the oxygen levels by controlling the operation of the aeration pumps); iv) more and especially better trained staff operating large plants, which is seldom the case for small WWTPs.

In Fig. 1.B a general overview of the energy consumption is reported for the sample analysed and different technology. According to the box plot graph, plants that carry out CAS and AP process showed the slowest energy consumption, while as expected MBR system are characterized by the highest energy consumption, being 2.3 times that of BNR system. However, reporting energy in term of kg of $COD_{removed}$ does not take into account the additional complexity of BNR systems to remove N and/or P (i.e. higher volume of mixed liquor to be mixed and/or to be recirculated and higher air to be supplied), thus it is plausible expect higher energy consumption compared with AP and CAS system (that are characterized by a lower intensity of treatment.

As seen in the previous section the type of treatment used influences energy consumption. Therefore, it is reasonable to expect differences between different countries, where for economic and/or environmental reasons a particular type of treatment might prevail (Fig. 1.C). Moreover, from the analysis of the data collected it turned out that factors such as influent dilution and plant load factor greatly influence energy efficiency (data not shown).

Fig. 2 summarises energy consumption of WWTPs values, grouped by country and secondary treatment type of technology plotted against plant size (stated in terms of PE).

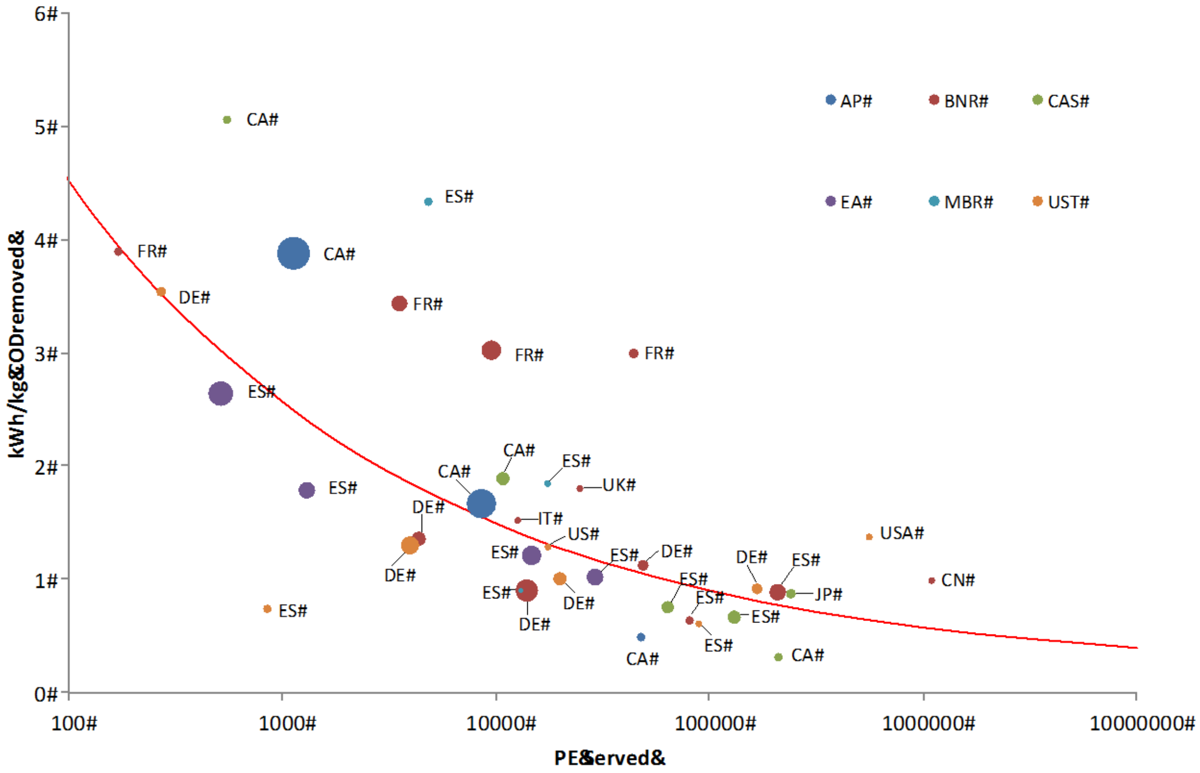

Figure 2. WWTPs energy consumption per country and type of treatment (bubbles size by sample population).

Aside form treatment technology, scale and operational condition, other factors, such as electric energy price, are likely to influence WWTP energy consumption among the various countries. A number of barriers can inhibit proactive energy management to address energy efficiency issues at WWTPs (Liu et al., 2012): politicizing of water and wastewater tariffs, low electricity prices can influence energy efficiency at WWTPs. In addition, the human factor is often neglected when looking at WWTPs performance: the lack of or the existence of misleading incentives for plant stakeholders involved can considerably influence plant performances (Rieger & Olsson, 2012).

Quantitative analysis of the aforementioned variables will be the object of a forthcoming publication.

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