

Benchmarking of energy consumption in municipal wastewater treatment plants – a survey of over 200 plants in Italy

M. Vaccari, P. Foladori, S. Nembrini and F. Vitali

ABSTRACT

One of the largest surveys in Europe about energy consumption in Italian wastewater treatment plants (WWTPs) is presented, based on 241 WWTPs and a total population equivalent (PE) of more than 9,000,000 PE. The study contributes towards standardised resilient data and benchmarking and to identify potentials for energy savings. In the energy benchmark, three indicators were used: specific energy consumption expressed per population equivalents ($\text{kWh PE}^{-1} \text{ year}^{-1}$), per cubic meter (kWh/m^3), and per unit of chemical oxygen demand (COD) removed (kWh/kgCOD). The indicator kWh/m^3 , even though widely applied, resulted in a biased benchmark, because highly influenced by stormwater and infiltrations. Plants with combined networks (often used in Europe) showed an apparent better energy performance. Conversely, the indicator $\text{kWh PE}^{-1} \text{ year}^{-1}$ resulted in a more meaningful definition of a benchmark. High energy efficiency was associated with: (i) large capacity of the plant, (ii) higher COD concentration in wastewater, (iii) separate sewer systems, (iv) capacity utilisation over 80%, and (v) high organic loads, but without overloading. The 25th percentile was proposed as a benchmark for four size classes: 23 $\text{kWh PE}^{-1} \text{ y}^{-1}$ for large plants $> 100,000$ PE; 42 $\text{kWh PE}^{-1} \text{ y}^{-1}$ for capacity $10,000 < \text{PE} < 100,000$, 48 $\text{kWh PE}^{-1} \text{ y}^{-1}$ for capacity $2,000 < \text{PE} < 10,000$ and 76 $\text{kWh PE}^{-1} \text{ y}^{-1}$ for small plants $< 2,000$ PE.

Key words | benchmark, electric energy consumption, energy efficiency, performance indicators, survey, wastewater

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INTRODUCTION

More than 2% of the world's electrical energy is a rough estimation of the energy used for water supply and wastewater treatment worldwide (Olsson 2012; Plappally & Lienhard 2012). Municipal wastewater treatment plants (WWTPs), as a major sub-sector of the water utilities, accounts for a significant amount of the overall energy consumption in this field. A large amount of primary energy, mainly originated from fossil sources, is used in WWTPs to meet stringent targets on effluent water quality, but contributes to environmental problems such as global warming and climate change. In this context, measures simultaneously aimed at maintaining

a good quality of effluents but improving energy efficiency in WWTPs are imperative.

The benchmark of energy consumption in WWTPs represents a powerful management tool which uses specific indicators to find the optimal performance or to evaluate the energy efficiency of a plant in comparison with other plants or a standard value (*inter alia* Lindtner *et al.* 2004; Krampe 2013; Torregrossa *et al.* 2016). The benchmarking analysis helps to identify potentials for energy savings and may help in prioritising optimisation efforts (Krampe 2013). Currently, a universal benchmarking of energy performance in WWTPs does not exist yet at an international level (Belloir *et al.* 2015; Longo *et al.* 2016), and the rare benchmarking studies appear very fragmented and piecemeal because they were carried out locally on the basis of national/regional surveys.

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Up to now, energy benchmarks have been referred to in the literature only for Austria (Lindtner *et al.* 2008; Haslinger *et al.* 2016), Germany (Baumann & Roth 2008; Haberkern *et al.* 2008), Australia (Krampe 2013; de Haas *et al.* 2015), the USA (WEF 2009; WERF 2011), Japan (Mizuta & Shimada 2010), and some plants in North Europe such as in Sweden (Lingsten *et al.* 2011), Denmark, Norway and Finland (Gustavsson & Tumlin 2013).

Among them, the Austrian Benchmarking System was developed in 1999 and regards more than 130 municipal WWTPs with population equivalent (PE) from 2,000 to 1,000,000 PE, and includes various financial costs expressed in Euros PE⁻¹ year⁻¹ (Lindtner *et al.* 2008). More recently, the energy consumption of the 104 Austrian municipal WWTPs in the period 2003–2013 were detailed by Haslinger *et al.* (2016).

The energy benchmark of German plants is based on the 'target values' which indicate the top performance and are comprised in the range 18–38 kWh PE⁻¹ year⁻¹ depending on the size of the plant (Baumann & Roth 2008; Haberkern *et al.* 2008). These values have been adopted as guide values to reflect the best practices in the first benchmarking study on energy use in 142 Australian plants (de Haas *et al.* 2015).

Energy benchmarks for different types of WWTPs in the USA were reported by WEF (2009) and WERF (2011). The ENERGY STAR[®] Score for Wastewater Treatment Plants (USEPA) provides a platform for energy efficiency evaluation.

The benchmark of energy consumption in Japanese municipal WWTPs was produced by Mizuta & Shimada (2010) analysing a large survey of 985 plants with various configurations.

Other field studies were reported in the literature aimed at evaluating good energy performances. In particular, the energy consumption of 17 Portuguese WWTPs was analysed by Silva & Rosa (2015) who proposed some benchmark equations to define plants with good energy performances. The best energy performance derived for Swedish WWTPs (Lingsten *et al.* 2011) was 35–38 kWh PE⁻¹ year⁻¹, which may be considered as a benchmark for this group of plants. Energy consumption of 16 municipal WWTPs in Sweden, Denmark, Norway and Finland was analysed by Gustavsson & Tumlin (2013): plants with electricity usage of 36 and 23 kWh PE⁻¹ year⁻¹ offered the possibility to become almost electricity self-sufficient plants thanks to biogas production.

A broad survey of a total of 298 WWTPs in Austria, Belgium, Switzerland, Germany, Denmark, France, Luxembourg and the Netherlands is referred to by Becker & Hansen (2013).

In China, various studies present the current state of energy consumption in WWTPs: 22 WWTPs in Shenzhen referred to by Li *et al.* (2016), 529 secondary treatment plants with capacity up to 600,000 m³/d referred to by Yang *et al.* (2010) and more than 3,000 WWTPs in urban China presented by Zhang *et al.* (2016).

Currently, no benchmarking of energy consumption is available for Italian WWTPs in the international literature. Although a few case studies have been reported in the literature about energy efficiency improvements in certain Italian WWTPs (recently Foladori *et al.* 2015; Panepinto *et al.* 2016), no reference data are available in Italy to be used as a benchmark.

This paper presents the outcomes derived from the largest survey conducted in Italy (also one of the largest surveys in Europe) about energy consumption in WWTPs. A total of 289 municipal WWTPs were included in the survey, for a total PE of more than 9,000,000 PE (approximately 10% of the total Italian equivalent population). Detailed data about PE, chemical oxygen demand (COD) concentrations, annual average hydraulic flow rate, configurations and electricity consumption for the whole plants were collected. Reference values for benchmarking were proposed and conclusive remarks on the parameters of influence and on the use of the Italian benchmarking in comparison with other international contexts are provided.

The objective of the paper is to add a new benchmark to the international framework of energy consumption in WWTPs: seven benchmark studies have been already published in the journal *Water Science & Technology*, specifically for Austrian, Scandinavian, Portuguese, Australian and Japanese plants. The present research contributes to improve the knowledge and data in an area which will require further efforts in the near future to respond to the need of energy efficient WWTPs.

MATERIALS AND METHODS

The survey of Italian WWTPs

A number of 289 WWTPs located in Italy were included in a survey. Data were obtained from a questionnaire compiled by the treatment plant managers of 19 large multi-utility bodies. The following information was asked: (1) influent flow rate; (2) influent and effluent COD loads; (3) design capacity; (4) actual capacity expressed in terms of PE served; (5) domestic population served; (6) type of sewer system; (7) flow-sheet of the configuration; and (8) electrical

energy consumption acquired from the electricity bill. PE was calculated referring to a per capita contribution of 120 gCOD PE⁻¹ d⁻¹. Data variable over time were collected as average values on an annual basis. With regard to the configuration, the following options could be chosen: fine screen, coarse screen, grit and oil removal, head pumping (and head pumping position), primary sedimentation, nitrification, phosphorus removal, final sedimentation, disinfection, sludge treatment type, sludge thickening, aerobic sludge digestion, sludge storage, sludge centrifuge, sludge filter press, sludge belt press, etc. In total, 45 variables were considered in the survey. In some cases, additional details not included originally in the questionnaire were asked personally to the plant managers in order to ensure the acquisition of a reliable and accurate database.

Selection of a representative sample

Only WWTPs with an activated sludge configuration (267 plants), which is the most common system in Italy (Collivignarelli *et al.* 2009), were considered in order to compare plants with a similar layout.

Secondly, WWTPs with unusual characteristics or with an insufficient level of information or inconsistent were excluded from the sample. Facilities whose total energy consumption did not fall within the 95th percentile of the sample were analysed in detail with the support of the plant manager, in order to understand anomalous technical factors and to decide whether or not include them in the sample.

Finally, the sample was composed of 241 activated sludge facilities, covering a total amount of 9.1 million PE. This corresponds to 9.5% of the total urban PE according to the Italian National Institute of Statistics ISTAT (2011). The majority of PE (92%) was treated in WWTPs with more than 10,000 PE.

Specific energy consumption indicators

A specific energy consumption indicator (ECI) is commonly defined as the ratio between the energy consumption, posed at the numerator, and one relevant parameter in the plant, posed at the denominator (*inter alia* Silva & Rosa 2015). Three ECIs were calculated for each WWTP, according to the following expressions:

- (1) ECI_{m3} defined as the ratio between the daily energy consumption and the daily volume treated (annual average

is considered):

$$ECI_{m3} [kWh/m^3] = \frac{\text{Energy consumption [kWh/d]}}{\text{Treated wastewater [m}^3\text{/d]}}$$

- (2) ECI_{COD} defined as the ratio between the daily energy consumption and the COD mass daily removed in the plant (annual average is considered):

$$ECI_{COD} [kWh/kgCOD_{rem}] = \frac{\text{Energy consumption [kWh/d]}}{\text{COD mass removed [kgCOD}_{rem}\text{/d]}}$$

- (3) ECI_{PE} defined as the ratio between the annual energy consumption and the PE served in the plant:

$$ECI_{PE} [kWh PE^{-1} year^{-1}] = \frac{\text{Energy consumption [kWh/year]}}{\text{Population Equivalent [PE]}}$$

Statistical analysis

The data analysis was applied after dividing the representative sample into four classes of plant size: (1) class with PE < 2,000, which comprises 57 plants, 23.5% of the dataset; (2) class with 2,000 ≤ PE < 10,000, which comprises 106 plants, 44% of the dataset; (3) class with 10,000 ≤ PE < 100,000, which comprises 60 plants, 25% of the dataset; (4) class with PE ≥ 100,000, which comprises 18 plants, 7.5% of the dataset.

The analysis was performed using the Excel MS, SPSS and R software. The t-test which produces one-sided *p*-values was applied to evaluate the significant difference in energy consumption.

RESULTS AND DISCUSSION

Total energy consumption is a power law of the applied load

The total energy consumption of the Italian WWTPs is presented in a bilogarithmic graph in Figure 1 and expressed as kWh/year for an immediate estimation of the annual bill. The total energy consumption increases for increasing loads in the plants; this behaviour is expected and in agreement

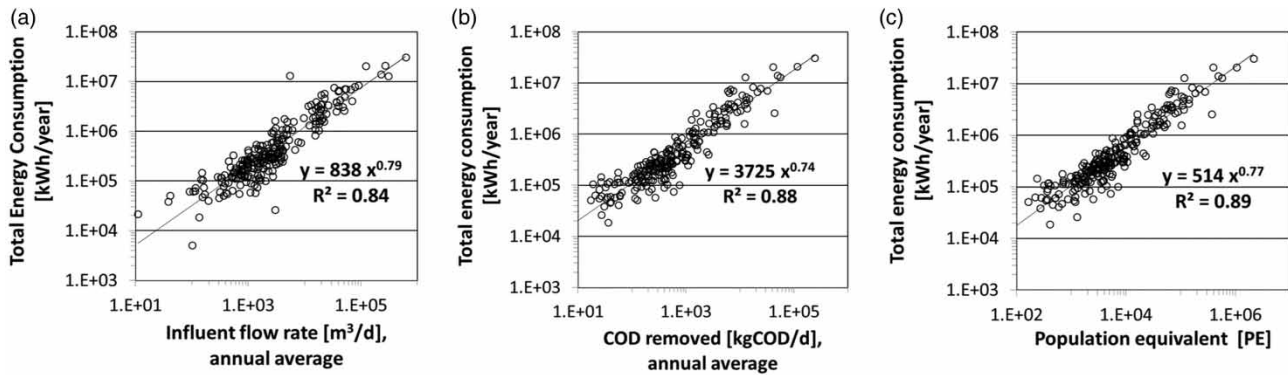


Figure 1 | Total energy consumption as a function of: (a) daily flowrate calculated as annual average; (b) daily COD removed calculated as annual average; (c) PE.

with literature. In the Italian plants, the interpolation with a power law gives a good correlation with the influent flow rate (least square regression $R^2 = 0.84$), the removed COD load ($R^2 = 0.88$) and the PE served ($R^2 = 0.89$).

The specific energy consumption indicator ECI_{m3} (kWh/m³) may lead to incorrect benchmark

The specific energy consumption expressed as ECI_{m3} is summarised in Figure 2 where the statistical parameters of four classes of WWTP capacity is presented, including the arithmetic mean and the box plots of 10th, 25th, 50th, 75th and 90th percentiles. The arithmetic mean may be affected by extreme values, while the median (50th percentile) is considered a more reliable index.

The median value of ECI_{m3} for all the Italian plants is 0.45 kWh/m³. Observing the single classes, the higher median (0.60 kWh/m³) is for small plants in the class <2,000 PE. Other studies confirms the higher specific energy consumption in small plants: Bodík & Kubaská (2013) observed that small WWTPs (influent flow rate <300 m³/d) presented a high average energy demand of 0.91 kWh/m³, very similar to the mean value of 0.86 kWh/m³ found here for Italian plants. Despite the simplified configuration of wastewater and sludge treatments, small plants may suffer from simplified management and less frequent optimisations which remarkably increase the specific energy consumption (Foladori et al. 2015).

The classes from 2,000 to over 100,000 PE have medians in the range 0.28–0.42 kWh/m³, not significantly different

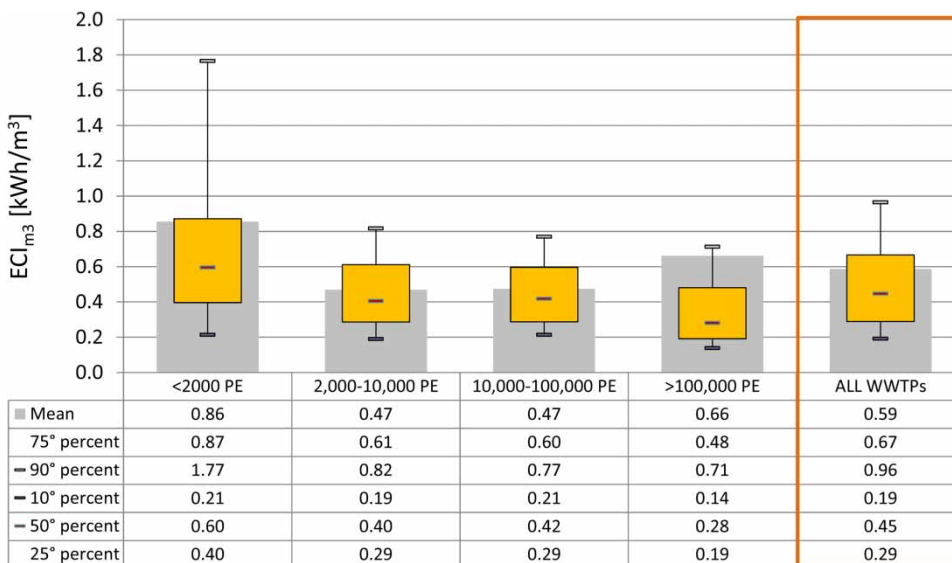


Figure 2 | Specific energy consumption ECI_{m3} (kWh/m³) of Italian WWTPs and statistical parameters of four classes of capacity (the box includes statistical data of all WWTPs).

among the classes. This is in agreement with the survey of Bodík & Kubaská (2013) who observed a relatively steady energy demand of 0.33–0.41 kWh/m³ in the group of medium-large WWTPs (inflow >5,000 m³/d).

From Figure 2 it is evident a large variability in the specific energy consumption in all the classes. Comparing the 10th and 90th extremes in Figure 2, the range of ECI_{m3} for all the Italian plants passes from 0.21–1.77 kWh/m³ in small plants (<2,000 PE) to 0.14–0.71 kWh/m³ in plants >100,000 PE.

The small plants (<2,000 PE) are characterised by a highly variable energy consumption as shown by the large frequency distribution of the indicator ECI_{m3}. Conversely, for plants from 2,000 to over 100,000 PE, the 10th–90th ranges are very similar among classes, suggesting that the indicator ECI_{m3} is affected only marginally by the size of the plants, while other factors influence energy consumption. Mizuta & Shimada (2010), for Japanese plants, indicate a consumption in the range 0.30–1.89 kWh/m³ for the conventional activated sludge plants. In China, the 22 WWTPs of Shenzhen referred to by Li *et al.* (2016) have ECI_{m3} in the range 0.12–0.38 kWh/m³, very low in comparison with other developed countries, due to the more energetically efficient equipment installed in the recent plants but also due to a lower water quality of wastewater treatment in some plants (Li *et al.* 2016; Zhang *et al.* 2016).

The Italian plants with combined sewers show a lower median value (0.35 kWh/m³) than plants with a separate sewer (0.67 kWh/m³), due to the larger amount of volume of water received in the plant. Important dilution of pollutant loads occurs in combined sewer systems (very diffused all over the world and especially in cities where sewerage systems were developed during centuries, like in Europe) as well as in the presence of groundwater infiltrations in aged network. In these cases, ECI_{m3} results are lower due to the higher volume of water treated: in fact, the presence of stormwater offers a generous apparent energy discount due to a higher denominator in the calculation of the indicator kWh/m³. Thus, the use of ECI_{m3} for diluted wastewater may lead to a misleading comparison among plants (Lingsten *et al.* 2011; Balmér & Hellström 2012; Foladori *et al.* 2015). Bodík & Kubaská (2013) observed that all the WWTPs with diluted raw wastewater had a very low specific energy consumption in terms of ECI_{m3}: they observed particularly low values of 0.14 and 0.17 kWh/m³ with the influent BOD₅ concentration of 92 or 122 mg/L, respectively, which are very low in comparison with BOD₅ concentrations commonly expected in raw municipal wastewater.

For these reasons, although the indicator ECI_{m3} is the most common parameter used in the literature to discuss

energy consumption (*inter alia* Kneppers *et al.* 2009; Mizuta & Shimada 2010; Bodík & Kubaská 2013; Garrido *et al.* 2013; Silva & Rosa 2015), here it was not considered meaningful to define a benchmark baseline for evaluating saving potential in Italian plants.

The specific energy consumption indicators ECI_{COD} (kWh/kgCOD) and ECI_{PE} (kWh PE⁻¹ year⁻¹) are equivalent and suitable for a benchmark

The statistical parameters obtained for the specific energy consumption expressed as ECI_{COD} and ECI_{PE} are summarised in the box plots of Figure 3. The median of ECI_{PE} is 70 kWh PE⁻¹ year⁻¹ for the entire data sample, but it decreases significantly for increasing capacity of the plants, passing from 120 kWh PE⁻¹ year⁻¹ for plants <2,000 PE, to 68.3 for plants with 2,000–10,000 PE, to 53.3 for plants with 10,000–100,000 PE and to 35 for plants >100,000 PE. The indicator ECI_{COD} has exactly the same trend, passing from 3.2 kWh/kgCOD for plants <2,000 PE, to 1.76 for plants with 2,000–10,000 PE, to 1.45 for plants with 10,000–100,000 PE and to 0.85 for plants >100,000 PE.

The use of ECI_{PE} or ECI_{COD} leads to different values but analogous conclusions, because they differ only for two factors: (1) the constant per-capita load assumed equal to 120 gCOD PE⁻¹ d⁻¹ and used to convert the organic load into PE; (2) the applied loads are considered in ECI_{PE} while the removed loads are considered in ECI_{COD}, but applied and removed loads do not differ substantially because the COD removal efficiency in WWTPs surpasses 90%. Actually, European plants have similar minimum treatment efficiency requirements (EU Urban Waste Water Directive 271/91).

The statistical analysis confirms that ECI_{COD} and ECI_{PE} have a high positive correlation (one-sided *p*-value = 0.000010), which means that the two indicators provide the same information. Conversely, when ECI_{m3} is compared to ECI_{COD} or ECI_{PE}, very poor correlation was found, as indicated by *p*-values equal to 0.187 and 0.433, respectively. Therefore, it can be concluded that ECI_{PE} and ECI_{COD} are perfectly interchangeable: the use of one or the other can be left to the user's discretion, while ECI_{m3} may lead to significantly different conclusions.

Krampe (2013) used the indicator expressed as kWh PE⁻¹ year⁻¹ as the main parameter for comparison among 11 WWTPs in South Australia and relative benchmarking. Lingsten *et al.* (2011) considered the index ECI_{PE} definitely more meaningful than ECI_{m3} in the evaluation of energy

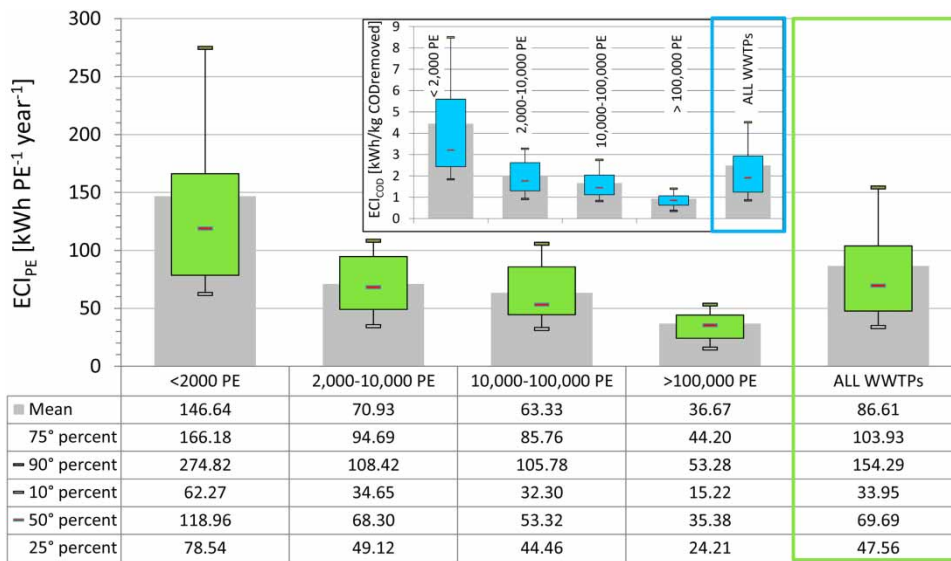


Figure 3 | Specific energy consumption ECI_{PE} ($\text{kWh PE}^{-1} \text{ year}^{-1}$) and ECI_{COD} (in the small figure, kWh/kg COD) of Italian WWTPs and statistical parameters of four classes of capacity (the box includes statistical data of all WWTPs).

use in Swedish WWTPs: again, the authors underlined that ECI_{m3} is an inaccurate picture of energy consumption because the outcome highly depends on flow and tends to decrease with increasing amount of infiltration water. Haber Kern *et al.* (2008) considered ECI_{PE} as a preferable index to evaluate energy in German WWTPs. Analogously, Haslinger *et al.* (2016) used the specific energy consumption expressed per PE, because the organic pollution load correlates best with energy consumptions and also ensures a better comparison among different studies. Torregrossa *et al.* (2016) considered the energy key performance indicators expressed per PE as the best choice to compare performances for plants with different loads.

For all these reasons, the indicator ECI_{PE} was selected in this paper as the most appropriate choice for energy benchmarking purposes for the Italian plants.

Parameters of influence on the specific energy consumption

Influence of the plant size

From Figure 3 it is immediate to observe that the indicator ECI_{PE} decreases significantly for the increasing size of the plant. Comparing the 10th and 90th extremes in Figure 3, the range passes from 62–275 $\text{kWh PE}^{-1} \text{ year}^{-1}$ in small plants (<2,000 PE) to 35–108 for plants with 2,000–10,000 PE, to 32–106 for plants with 10,000–100,000 PE and to 15–53 for plants >100,000 PE. A significantly lower specific

energy consumption in the largest plants is due to: (1) advantage of economies of scale, sharing some fixed quota of energy consumption on a greater organic load; (2) more stable operating conditions, while small plants undergo frequent transitional periods which are particularly energy-intensive; (3) more frequent automation and optimised controls of the process (e.g. variable-frequency drives in aeration or pumping). For these reasons, aggregation and centralisation of small into medium-large treatment systems may originate substantial improvements in energy efficiency in the plants (but additional costs for conveyance and pumping along the network should be considered).

Influence of COD concentration in influent wastewater

Figure 4 shows the relationship between ECI_{PE} and the influent COD concentration. Although the largest plants with PE >100,000 appear quite independent from the COD concentration, a decreasing trend was observed for plants up to 100,000 PE. The WWTPs which receive the more diluted wastewater, characterised by low COD concentrations, have the highest specific energy consumption, due to: (1) the fixed quota of energy utilised in the plant which is divided by a lower removed load; (2) the additional consumption for pumping a higher amount of water.

Silva & Rosa (2015) confirm that higher specific energy consumption per PE may indicate diluted inflow (e.g. from stormwater), whereas lower values may act as an alert for industrial (highly charged) inflows.

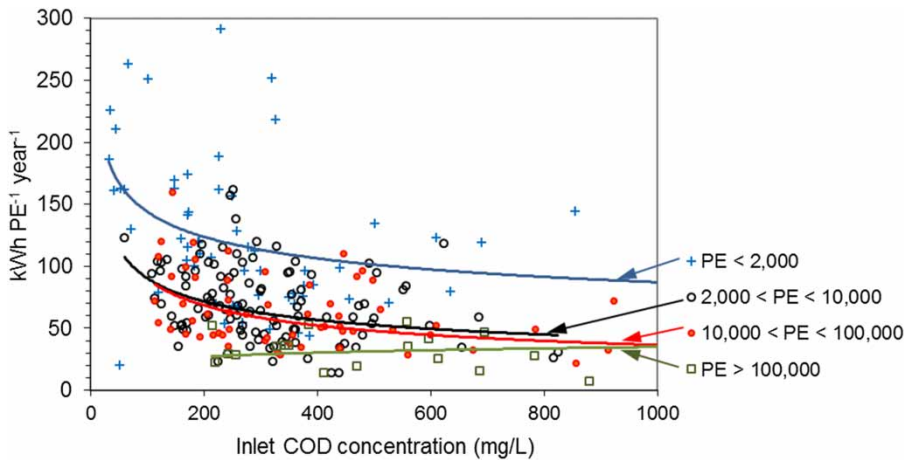


Figure 4 | The specific energy consumption indicator ECI_{PE} ($\text{kWh PE}^{-1} \text{ year}^{-1}$) versus the influent COD concentration, distinguished in four size classes.

Influence of hydraulic load per capita

Municipal wastewater is typically generated from domestic and industrial sources and a certain presence of stormwater runoff in combined sewers. A percentage of 72% of the Italian plants in the survey (171 WWTPs) treats combined sewer systems with a high presence of stormwater runoff, while the rest of the plants treat a separate sewer system (only black water).

Statistical analysis revealed that the median of ECI_{PE} is substantially comparable between combined or separate sewer systems for all the size classes, because the indicator ECI_{PE} depends on the organic load to be treated which is not necessarily reduced by dilution.

Figure 5 shows the specific indicator ECI_{PE} as a function of the hydraulic load expressed as $\text{L PE}^{-1} \text{ d}^{-1}$. When the

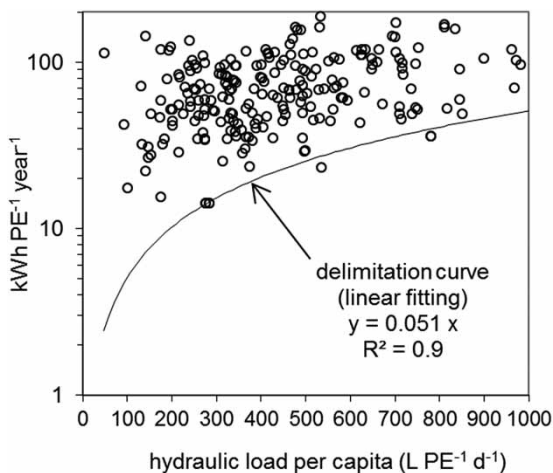


Figure 5 | The specific energy consumption indicator ECI_{PE} ($\text{kWh PE}^{-1} \text{ year}^{-1}$) as a function of the hydraulic load per capita.

value on the horizontal axis surpasses $200\text{--}250 \text{ L PE}^{-1} \text{ d}^{-1}$, it indicates a certain presence of stormwater originated from combined sewers or infiltrations. In fact, although the daily volume of water supplied to the population may vary hugely depending on the region; in developed countries it may assume values more or less in the order of magnitude of $150\text{--}250 \text{ L PE}^{-1} \text{ d}^{-1}$ (Metcalf and Eddy Inc. 2003). ECI_{PE} assumes values above a linear threshold ($y = 0.051 x$; displayed as a curve in the semilogarithmic graph) which increases for increasing hydraulic load. For example, for hydraulic loads of $200 \text{ L PE}^{-1} \text{ d}^{-1}$ no ECI_{PE} below $10 \text{ kWh PE}^{-1} \text{ year}^{-1}$ can be found. Conversely, when the hydraulic load increases considerably to 400 or $600 \text{ L PE}^{-1} \text{ d}^{-1}$ no ECI_{PE} below 20 or $30 \text{ kWh PE}^{-1} \text{ year}^{-1}$ can be found, respectively. Again, this demonstrates that WWTPs with combined sewers and thus with the presence of stormwater runoff and consequent higher hydraulic loads require more energy which may be very difficult to reduce below a threshold.

Influence of plant oversizing

WWTPs are commonly designed for a capacity larger than the PE actually served. The concepts of 'operational capacity' or 'capacity utilisation' or 'plant utilisation factor', defined as the percent of facility design capacity at which a plant is operating, were introduced to distinguish between the design capacity and the capacity really exploited (*inter alia* WERF 2011; Zhang et al. 2016).

A large percentage (88%) of the Italian WWTPs utilises a capacity lower than the design capacity, resulting oversized to a certain extent. Figure 6(a) shows the indicator ECI_{PE} as a function of the capacity utilisation. Although a

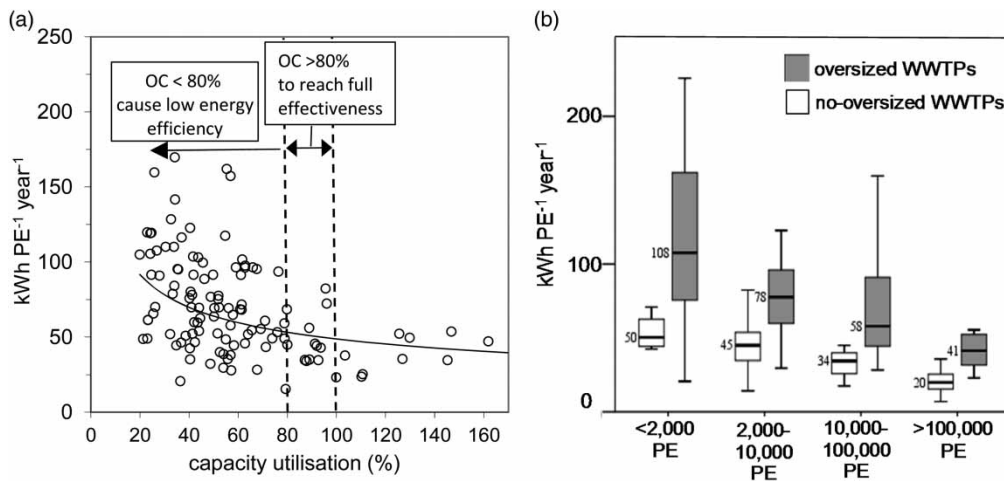


Figure 6 | The specific energy consumption indicator ECI_{PE} ($\text{kWh PE}^{-1} \text{ year}^{-1}$) is displayed: (a) as a function of the capacity utilisation; (b) with statistical parameters for oversized and not-oversized plants, distinguished in four size classes.

certain degree of oversizing is required in WWTPs to ensure a high removal efficiency in presence of fluctuating loads, a too low capacity utilisation may cause high ECI_{PE} values and thus inefficiencies in energy consumption.

Figure 6(b) displays the statistical comparison of the two categories of plants: oversized and not oversized. The box plots indicate always a higher energy consumption in the oversized plants, which are characterised by a median ECI_{PE} approximately one and a half or twice the median of the not oversized plants: 108 vs. 50 $\text{kWh PE}^{-1} \text{ year}^{-1}$ for small plants (<2,000 PE) or 41 vs. 30 $\text{kWh PE}^{-1} \text{ year}^{-1}$ for the large plants (>100,000 PE).

In WWTPs, energy consumption is a less priority in comparison with the meeting of discharge limits which drives most efforts in the plants due to the risk of penalties. This is the reason of redundancy, unnecessary volumes and oversizing of electro-mechanical equipment in WWTPs (for example expensive aeration and mixing), which ultimately results in a higher energy consumption.

Krampe (2013), in the evaluation of some Australian plants, observed energy inefficiency in a plant significantly oversized and underloaded because designed for a significant industrial waste stream that was no longer received. In this case, the optimisation of energy usage should take into account the option to take some machines off line which often consists in reducing expenses for pumping or aeration. High specific energy demand was also observed by Bodík & Kubaská (2013) in plants with low actual load in comparison to the design load (40%). Foladori et al. (2015) in 5 small WWTPs with average capacity utilisation of 52%, observed low energy efficiency due to equipment oversizing. In WWTPs with flow rate of 5,000–

100,000 m^3/d , WERF (2011) demonstrated that when the capacity utilisation passes from 50% to 80%, the specific energy consumption decreases by 28–45% (data extrapolated by us).

Lindtner et al. (2008), in the evaluation of the operational costs of Austrian WWTPs, introduced the 'plant utilisation factor' as the ratio between the 85% of the yearly COD-load and the design capacity expressed as percentage. The specific operating costs (which include energy) were significantly influenced by the plant utilisation factor; the lowest specific operating costs (<10 Euros $\text{PE}^{-1} \text{ year}^{-1}$ for large WWTPs with a design capacity >100,000 PE) were only observed with a utilisation factor >80% (Lindtner et al. 2008).

All these results confirm one more time that the closer the WWTP is to its design capacity, the more efficient the energy utilisation is (Silva & Rosa 2015). Some surveys concord that a capacity utilisation above 70–80% is enough to reach full effectiveness (Lindtner et al. 2008; Lingsten et al. 2011). Conversely, a further increase of the operational capacity from 80% to 120% results again in a particularly low specific energy consumption, but the plants are overloaded and the wastewater treatment performance decreases to a large extent, especially in terms of removal of N and P, as observed in Chinese plants (Zhang et al. 2016).

Influence of the treatment layout

Bioreactors are usually considered the part that consumes the most electricity in WWTPs. One can then easily conclude that reactors with high organic loads have higher

specific electricity consumption than reactors with less organic loads. Figure 7 shows, paradoxically, it is rather the opposite. Figure 7 displays the specific energy consumption ECI_{PE} as a function of the specific organic load in the activated sludge bioreactors (expressed per unit of BOD_5), together with the COD removal efficiency. Although the high COD removal efficiency in almost all the plants, there is a decreasing relationship between the specific energy consumption and the specific organic load. In low-loaded bioreactors, more suspended solids (including endogenous + inert + active biomass) and larger volumes are required with a consequent higher consumption of electrical energy for aeration and mixing.

The survey highlighted that the presence of a tertiary treatment did not result in a significantly higher specific

energy consumption compared to WWTPs without such treatments.

With regard to the sludge treatment line, different configurations were considered including thickening, digestion, and dewatering. Despite the differences in the stages among the plants, no significant relationship was found between the configuration of the sludge treatment and the specific energy consumption of the entire WWTP.

The reason for these observations might be that conventional physico-chemical tertiary treatments such as filtration or precipitation (excluding energy-intensive processes like chemical oxidation) and the conventional physical sludge treatments such as thickening or dewatering are responsible for a marginal energy consumption in WWTPs, in comparison to other more energy-demanding stages (like those equipped with aeration, mixing, and pumping).

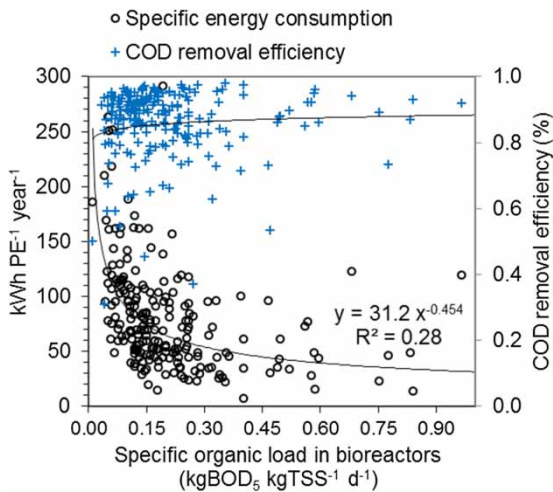
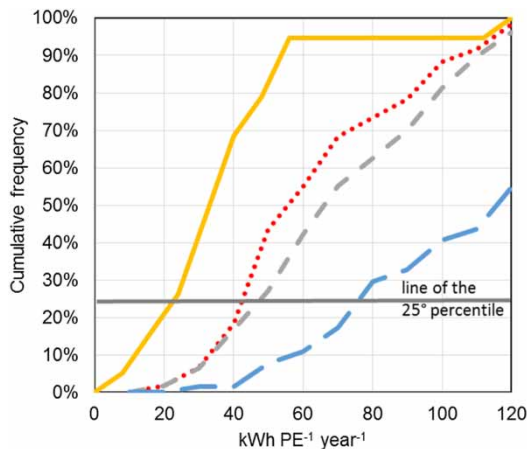


Figure 7 | The specific energy consumption indicator ECI_{PE} ($kWh PE^{-1} year^{-1}$) and the COD removal efficiency as a function of the specific organic load in bioreactors.

Proposal of benchmark values

From the cumulative frequency distribution of ECI_{PE} (Figure 8), the first top performance quartile (25th) is proposed as a benchmark for Italian WWTP to represent the best performance of specific energy consumption. The 25th percentile is a reasonable and feasible objective, whilst minimum values represent too low a target which is much too ambitious to reach and might originate excessive capital costs. The benchmark value depends on the size class: energy consumption of or below $23 kWh PE^{-1} y^{-1}$ is the objective of large plants with more than 100,000 PE, while a higher benchmark of $76 kWh PE^{-1} y^{-1}$ is reasonable for small plants. In the intermediate range of 2,000–100,000 PE the benchmark is $42\text{--}48 kWh PE^{-1} y^{-1}$.



Class of plants	Benchmark (25 th percentile) ($kWh PE^{-1} year^{-1}$)
> 100,000 PE	23
10,000 < PE < 100,000	42
2,000 < PE < 10,000	48
< 2,000 PE	76

Figure 8 | Cumulative frequency distribution of ECI_{PE} , distinguished in four size classes, and 25th percentile proposed for benchmark of Italian plants.

Using the benchmark values indicated in the table of Figure 8, the energy efficiency of a plant can be rated: facility operators can see how their facility compares with that of peers. Considering that data about plant loading and energy consumption are quick to be obtained and easy to be compared to the benchmarks, this work may take no more than a couple of hours for a plant. In the case of large discrepancies between actual consumption and the benchmark, more in-depth evaluations and detailed energy audits can be planned. The theoretical amount of energy which could be saved in the plants is the difference between the benchmark value and the actual energy consumption.

The benchmark value obtained here for large Italian plants (>100,000 PE) are in good agreement with other international benchmarking: the value of 23 kWh PE⁻¹ y⁻¹ matches very well with 18 kWh PE⁻¹ y⁻¹ indicated in the benchmark of German plants (Baumann & Roth 2008), 21.5 kWh PE⁻¹ y⁻¹ proposed as 10th percentile of Austrian plants (Haslinger et al. 2016) and 20–22.5 kWh PE⁻¹ y⁻¹ derived from the benchmark of northwest European plants (Torregrossa et al. 2016). Conversely, the value of 42 kWh PE⁻¹ y⁻¹ found for Italian plants with 10,000 < PE < 100,000 is higher than the international benchmarks of 18–32 kWh PE⁻¹ y⁻¹. The difference is even greater for very small plants, where the Italian benchmark of 76 kWh PE⁻¹ y⁻¹ is approximately double the range of international benchmarks.

CONCLUSIONS

The survey on the energy consumption of 241 Italian WWTPs based on activated sludge configuration and covering more than 9 million PE, leads to the following main conclusions:

- (1) The most suitable indicator of the specific energy consumption is expressed as kWh PE⁻¹ y⁻¹, while the indicator expressed as kWh/m³ appeared misleading because plants with significant stormwaters appear erroneously more energy efficient.
- (2) A decreasing trend was observed for specific energy consumption with the increasing PE served, due to the exploitation of economies of scale and more frequent process automation in large plants.
- (3) Plants receiving diluted wastewater (with low COD concentrations) have a higher specific energy consumption.
- (4) Although a certain oversizing is normal in the plant design, high energy efficiency can be ensured in plants exploiting more than 80% of the design capacity.

The first top performance quartile (25th) was used to propose the benchmark for Italian WWTP: energy consumption below 23 kWh PE⁻¹ y⁻¹ is the objective of large plants with more than 100,000 PE, while a higher benchmark of 76 kWh PE⁻¹ y⁻¹ is reasonable for small plants. In the intermediate range of 2,000–100,000 PE the benchmark is 42–48 kWh PE⁻¹ y⁻¹.

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