

Energy consumption in anaerobic and aerobic based wastewater treatment plants in Italy

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Abstract

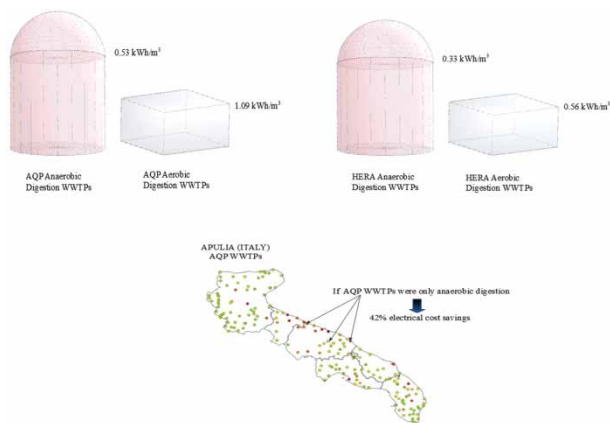
The aim of this study is to carry out an experimental investigation on electricity consumption in wastewater treatment plants in Italy based on aerobic and anaerobic digestion wastewater treatment plants (WWTP). The data refer to plants managed by two major water resources management companies in Italy, Hera and Acquedotto Pugliese (AQP). The survey makes use of statistical tools for data analysis of 202 urban wastewater treatment plants. In order to extend the reliability of the survey, electricity consumption data were analysed through three specific energy demand indicators: kWh/m³, kWh/PE•year, kWh/kgCOD_{removed} referred to each plant. The results show that anaerobic systems are advantageous in terms of electricity consumption per m³ as they achieve more than 50% saving with values ranging from 1.02 kWh/m³ for aerobic plants, instead of 0.43 kWh/m³ for the anaerobic ones. Differences have been found in terms of anaerobic digestion efficiency between the data concerning the plants in northern Italy – Hera Company with an average of 0.33 kWh/m³ and those in Apulia – AQP company with an average of 0.53 kWh/m³. Aerobic systems showed more energy consumption also for HERA-managed WWTP. If anaerobic digestion were implemented on all the AQP WWTP, energy savings should be of approximately 16% and approximately 42% if related to HERA anaerobic-based WWTP average performance.

Key words: anaerobic and aerobic digestion, COD, specific energy demand, wastewater treatment plant

Highlights

- Aerobic digestion WWTP: 1.02 kWh/m³; Anaerobic: 0.43 kWh/m³.
- MPV are 0.92 kWh/m³, 63 kWh/PE•yr and 1.9 kWh/COD.
- The most probable values are for AQP anaerobic plants: 0.53 kWh/m³ and: 1.09 kWh/m³ for aerobic digestion plants.
- MPV for all plants are: 1.9 kWh/kg COD_{removed}.
- If all the AD AQP plants higher than 10,000 PE were converted to anaerobic digestion, we would have a saving equal to 42%.

Graphical Abstract



INTRODUCTION

Stabilization processes represent a consistent part of the electrical costs in a Conventional Activated Sludge (CAS) WWTP. Aerobic digestion involves biologically stabilizing wastewater in an open vessel using an air blower and bacteria under aerobic conditions to convert the organic solids content to carbon dioxide, water, and nitrogen. Pathogens and odors (and the potential to generate odors) are reduced in the process. Aerobic digestion is commonly used by smaller WWTPs due to consistent electrical costs for aeration (McCarty 1964; Gretzschel *et al.* 2014). Anaerobic digestion involves biologically stabilizing wastewater in a tank without a blower to reduce the organic content, mass, odor (and the potential to generate odor), and pathogen content of wastewater. In this process, microorganisms consume a part of the organic portion of the wastewater. Anaerobic archaea that thrive in the oxygen-free environment convert solubilized and fermented organic solids to carbon dioxide, methane (which can be recovered and used for energy), and ammonia resulting in electrical cost savings (Capodaglio & Olsson 2020). As a consequence of the increase of energy costs and to minimize GHG emissions, an efficient use of sludge as a renewable energy resource should be considered, even for smaller WWTP with design capacities more than 10,000 population equivalent (PE) (Gretzschel *et al.* 2014; Soares *et al.* 2017).

In the present study, a comparison between anaerobic and aerobic WWTPs managed by two of the greatest Italian Water Management Companies – HERA, which operates in Emilia Romagna and Acquedotto Pugliese (AQP) Spa, on Apulian territory – is carried out, on the basis of the electrical consumptions in CAS plants. According to the US Environmental Protection Agency EPA (2010), 3% of all US electricity consumption is related to wastewater treatment.

The energy consumption of wastewater treatment plants (WWTPs) is about 4,200 GWh/year only in Germany (Enerwater 2015); in Italy, the electricity consumption in WWTPs is about 3,250 GWh/year (Campanelli *et al.* 2013; Foladori *et al.* 2015), which corresponds to about 0.5 billion Euros per year. So it is fundamental to apply the appropriate technology for more savings in terms of electricity and CO₂ emissions. An increase of 12% of energy required by AQP WWTPs has been shown from 2013 to 2018, reaching a total value of approximately 182 GWh/year. This is due to the increasingly stringent environmental requirements and the need to enhance the plants' capacity, which have led to the upgrading of the main treatment stations, and also the installation of new, more powerful and efficient electromechanical equipment (Acquedotto Pugliese 2019).

An analysis of the COD values in the influent has also been performed considering that the concentration and the nature of the organic matter can have a considerable influence on both energy consumption and on the choice between the two technologies of stabilization.

The average COD values input to the plants show clear differences between the two Italian regions. The average COD input value of the plants managed by HERA was equal to 406 mg/L, while for AQP plants it was 828 mg/L.

It must be considered, however, that the nature of COD can be different depending on the activities carried out in the territory: unlike the one produced in Apulia, which is less industrialized than in Emilia Romagna, where the COD concentrations are quite lower, probably due to a higher degree of pre-treatment at the factory before entering the municipal WWTP.

The electrical consumption in WWTPs is principally due to aeration basins and recirculation of mixed liquor and settled sludge (US EPA 2010; Daw *et al.* 2012; Foladori *et al.* 2015), but the aerobic stabilisation represents a noteworthy energy consumption, with simpler operational maintenance, if compared to anaerobic stabilization (Soares *et al.* 2017; Maktabifard *et al.* 2018; Guo *et al.* 2019).

In order to evaluate the reduction of electricity consumption, electrical costs related to aerobic and anaerobic digestion have been evaluated. Anaerobic digestion produces biogas recoverable and reusable for energy production, instead of aerobic digestion, which consumes more energy for aeration (Capodaglio & Olsson 2020). In addition, anaerobic plants are able to treat all types of organic waste regardless of their humidity, unlike composting, which requires a certain dry matter content in the starting mixture; in fact, anaerobic plants are closed reactors and therefore there is no release of foul-smelling gaseous emissions into the atmosphere, as can occur during the first thermophilic phase of anaerobic digestion. Anaerobic digestion is a biological process in which biodegradable organic matter is broken down by bacteria in the absence of oxygen into biogas consisting of methane (CH₄), carbon dioxide (CO₂), and trace amounts of other gases. Methane production occurs in a limited pH range (about 6.5–8.5): optimal conditions for methanogenic archaea are between 7 and 8, while the optimal range of acid-forming bacteria is at lower values (Capodaglio *et al.* 2016). The pH value can be increased by degradation of proteins into ammonia, and can be lowered by the presence of H₂S and VFAs, produced by hydrolysis, inhibiting the whole methane fermentation process. Manure, with its alkalinity, can help stabilize the process, even if its high-water content tends to dilute the substrate (Nielsen & Angelidaki 2008).

Anaerobic digestion plants require higher initial investments than aerobic plants (Monnet 2003) and retrofitting conventional aerobic plants to anaerobic processes could be costly and would require more concentrated sewage to achieve optimal efficiency (McCarty *et al.* 2011; Ciudin *et al.* 2014; Stazi & Tomei 2018; Mahmoodi-Eshkaftaki & Ebrahim 2019; Capodaglio & Olsson 2020; McAteer *et al.* 2020).

Anaerobic digestion has increasingly been shown as a possible solution to reduce process energy requirements and has the potential to achieve net energy production while meeting stringent effluent standards (He *et al.* 2021). Anaerobic digestion also has the best practical potential for capturing wastewater's embedded energy content and should be considered a preferred option in future design of domestic WWTP where strict effluent standards can be achieved using natural systems like constructed wetlands (Ranieri 2003, 2012; Gikas *et al.* 2015; Borges *et al.* 2016; Butterworth *et al.* 2016). Further, the optimisation of energy efficiency leads to an important reduction of primary energy consumption. Other positive aspects include increased cost stability (due to higher energy self-sufficiency), as well as a reduction of public expenditure (Hobus *et al.* 2010; Ciudin *et al.* 2014), if operational stability is guaranteed by the application of correct maintenance procedures and proper monitoring and adequate control of influent characteristics (Killilea *et al.* 2000; Ranieri & Świetlik 2010; Ranieri *et al.* 2017).

The aim of this investigation is to compare energetic consumptions in conventional WWTP adopting Aerobic Digestion (AD) and Anaerobic Digestion (AnD) as a function of the flow, Population Equivalent (PE) and influent COD. This comparison should give useful information to designers or Water Management Companies about which technology should be used, with the aim of reducing the electrical cost and having a high degree of sludge stabilization.

MATERIAL AND METHODS

Acquedotto Pugliese S.p.a. manages about 180 WWTPs in the entire territory of Apulia. The Hera Group manages the sewerage and treatment service in many municipalities in Emilia Romagna, handling a total of over 382 million cubic metres of wastewater. In the present study, most representative data concerning WWTPs were used for the analysis: 178 managed by AQP and only 24 WWTP managed and deemed more representative by HERA. In [Figure 1](#), the location of the WWTP whose data have been analysed, both managed by AQP Spa and by HERA, is reported.

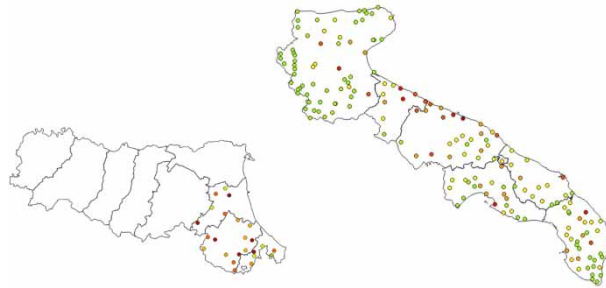


Figure 1 | WWTP managed by HERA (on the left) and by AQP (on the right).

With reference to 202 wastewater treatment plants that have been considered, 146 are equipped with aerobic digestion treatment and 56 are equipped with anaerobic digestion plants managed by both Companies, Hera and AQP. Most of the plants considered, about 88%, are located throughout the Apulian land, while the remaining 12% are located in the Emilia Romagna region.

RESULTS AND DISCUSSION

The analysis of the data showed energy consumption associated with WWTPs using aerobic sludge digestion treatment with a much higher digestion electricity use than with anaerobic digestion. In fact, the energy used by plants in terms of kWh/m³ for all plants with aerobic digestion is on average 1.02 kWh/m³ while for plants with anaerobic digestion it is significantly lower at 0.43 kWh/m³ on average, in line with literature, for similar climate conditions ([Hernández-Sancho et al. 2011](#); [Masłoń 2017](#)). [Curtis \(2010\)](#) reported even higher electrical consumption differences.

A further difference can be found between the average energy consumption data for plants with anaerobic digestion in Emilia Romagna and those in Apulia: in the former case, the average consumption is lower, at 0.33 kWh/m³ compared to 0.53 kWh/m³ of the Apulian plants. In any case, the results are in line, rather slightly lower than other Italian and international studies that report as a range of energy consumption of WWTPs, values between 0.4 and 0.7 kWh/m³ ([Campione & Campodonico 2017](#)) and about 0.6 kWh/m³ specifically in Southern Italy ([Utilitatis 2018](#)). [Mizuta & Shimada \(2010\)](#) report, for 985 Japanese WWTPs, the distribution of specific power consumptions (SPCs) for the oxidation Ditch (OD) method and for the CAS method without incineration. On the one hand, the amount of inflow was between 100 and 8,500 m³/day, and the SPC was between 0.44 and 2.07 kWh/m³ for the OD method.

Energy consumption and flow rates

The frequency histogram in [Figure 2](#) shows that the distribution is quite similar to Gauss distribution. In most cases, the consumption of kWh/m³ is in a range between 0.21 and 1.90 kWh/m³. The values are comparable with those referred to Japanese WWTP ([Mizuta & Shimada 2010](#)).

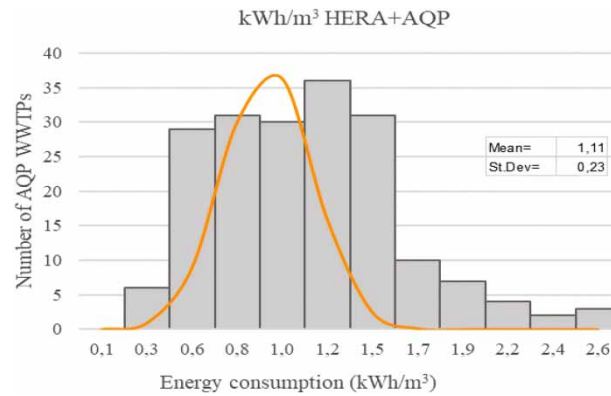


Figure 2 | Distribution of energy consumption in Italian municipal WWTPs in terms of kWh/m³.

Figure 3(a) and 3(b) report the energy consumption for AQP WWTP versus influent flow (Q) highlighting a decreasing trend both for aerobic and anaerobic WWTP.

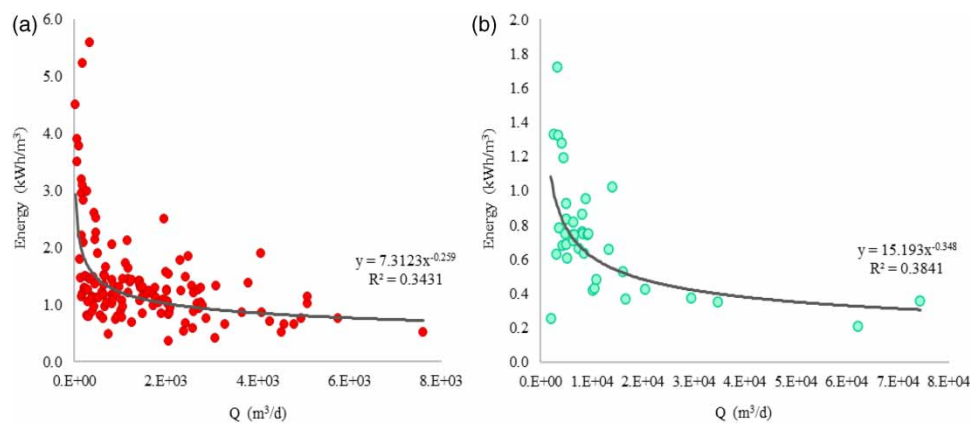


Figure 3 | (a, b) Correlations between energy consumption and flow rates of AQP WWTP with AD (a) and AnD (b).

For plants equipped with AD, the equation of the exponential curve that best fits the energy consumption data in relation to flow rates is: Energy (E) = 7.31 Q^{-0.259} with linear regression equal to R² = 0.34, while the one for AnD plants is E = 15.19 Q^{-0.348} with linear regression equal to R² = 0.38.

The analysis of AQP data shows that the parametric value kWh/m³ decreases exponentially as a function of the influent flow, for both aerobic and anaerobic digestion plants, but the one for AD plants decreases faster than the other. This means that, on the basis of the analysis of energy consumption data alone, anaerobic digestion should be more cost-effective above all for plants with an high capacity.

In fact, case studies developed in Germany (Gretzschel *et al.* 2014) have shown that, depending on rising energy prices and interest rates, and in the case of a presumed interest rate of 3% and price increase of 5%, a conversion of existing aerobic stabilization plants into anaerobic digestion plants can be the most cost efficient choice, even for plants larger than 7,500 PE a conversion could also be an option for digestion plants with a project capacity greater than 7,500 PE. It follows that, when choosing the type of sludge treatment in the plants, it is important to take into account additional factors, such as the COD load in the incoming effluent, in addition to the capacity of the plant itself.

This is confirmed by the data relating to the plants managed by HERA, as shown in the following Figure 4(a) and 4(b).

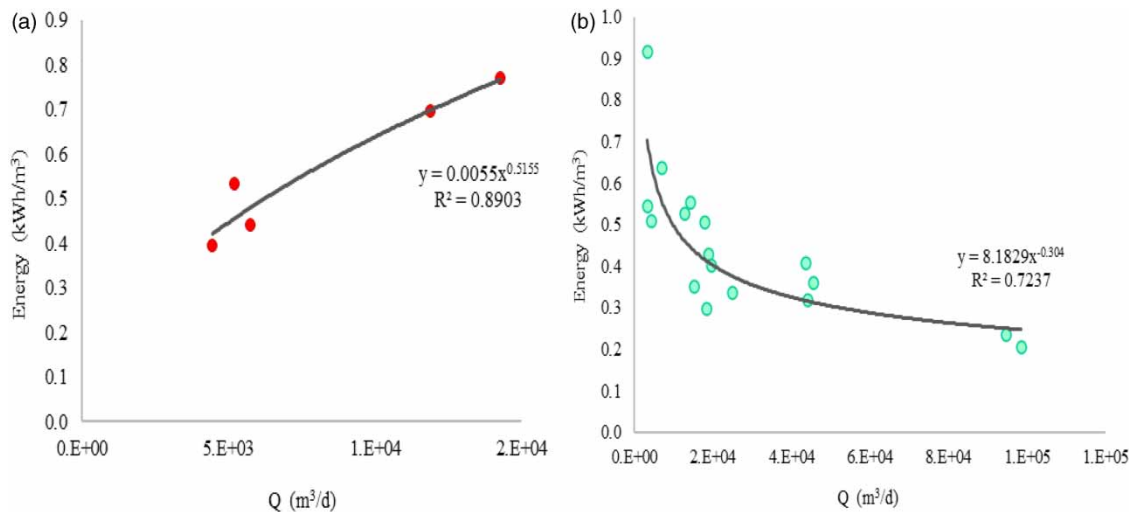


Figure 4 | (a, b) Correlations between energy consumptions and flow rates of HERA WWTP with AD (a) and AnD (b).

For plants based on AnD, the equation of the interpolation curve that best fits the energy consumption data in relation to flow rates has the following equation, $E = 8.18 Q^{-0.304}$, with linear regression equal to $R^2 = 0.724$, while for plants equipped with aerobic treatment the trend is not very clear due to the low number of available data, and the most probable interpolation curve is $E = 0.0055 Q^{0.515}$.

It should be considered that only anaerobic Hera WWTP satisfies the same order for both: less than 7,500 PE or more. While for aerobics, there is a change of order from negative to positive when exceeding 7,500 PE, the costs increased. It follows that a larger plant capable of accommodating and treating higher incoming flow rates is advantageous from an environmental point of view only for plants with AnD treatment, where higher energy consumption per cubic meter is associated with systems treating low flow rates.

There is a clear difference between the order of magnitude of the energy values present along the Abscissa axis for aerobic digestion and that of the values for anaerobic digestion; in fact, the former vary in a range between 0.37 kWh/m³ and 5.59 kWh/m³ as illustrated in Figure 5 where the last two energy values, for larger WWTP, are slightly higher, probably due to a lower degree of pre-treatment at the factory before entering the municipal WWTP. The range of the energy values, for anaerobic treatment, varies between 0.21 and 1.72 kWh/m³, as illustrated in Figure 6. The lower value of

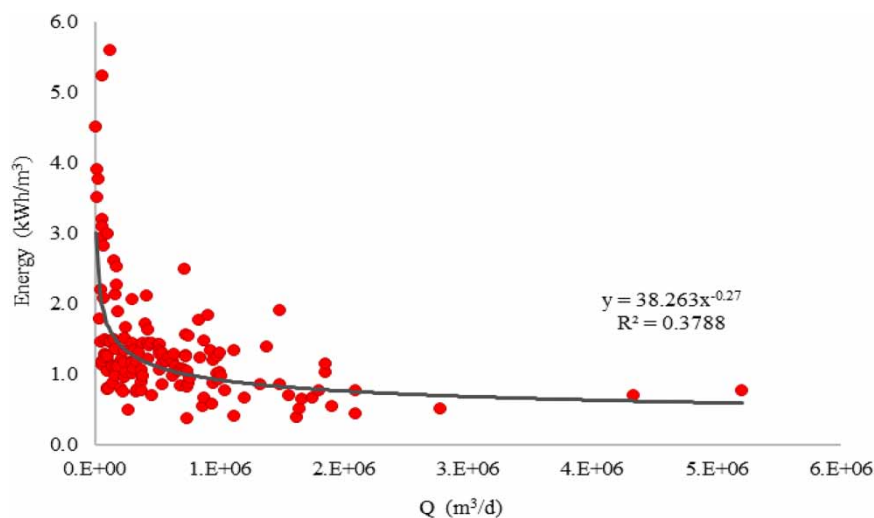


Figure 5 | Correlation between energy consumption and flow rates for all AD WWTP.

0.21 kWh/m³ were found in two plants, one managed by AQP, the other by Hera. Both are associated with high inlet flow rates corresponding respectively to approximately 62,175 m³/d and 98,552 m³/d. Only 9% of all WWTPs with anaerobic digestion report an energy consumption value greater than 1.0 kWh/m³.

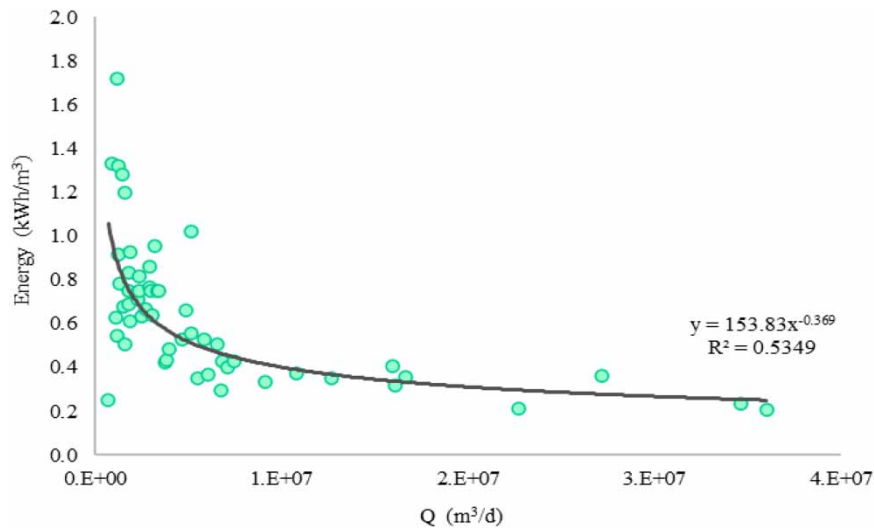


Figure 6 | Correlation between energy consumption and flow rates for all AnD plants.

In addition, all the data of both managing companies have been analysed separately with respect to the type of treatment.

For all plants equipped with AD, the equation of the exponential curve that best fits the energy consumption data in relation to flow rates has the following equation: $E = 38.263 Q^{-0.27}$ with linear regression equal to $R^2 = 0.379$, while the one for AnD plants of both corporations is $E = 153.23 Q^{-0.369}$ with linear regression equal to $R^2 = 0.535$. Trend curves decrease one order of magnitude of difference, the degrowth is slightly faster for plants with AD treatment.

The ratio between kWh and flow rates is a widely used parameter as an indicator of specific energy consumption. However, it is more likely that larger volumes of wastewater are received in the WWTP due to some factors such as stormwater flow, groundwater infiltrations system that could possibly offers an apparent energy discount due to higher denominator in the calculation of the kWh/m³ (Gurung *et al.* 2018).

Finally, it is important to note that the use of kWh/m³ as unique index should not give all information useful to select uniquely the technology more appropriated (Enerwater 2015). Based on these reasons, the correlations between energy consumed and PE served and COD input have been also investigated.

Energy consumption and population equivalent

The energy consumption per PE is considerably depending on the type of process. In fact, it goes from an average value of energy per year consumed equal to 24.4 kWh/PE per year for treatment with AnD, to an average value per year for plants with AD higher than double and about 50.9 kWh/PE per year. Campione & Campodonico (2017) report similar electrical consumptions for other italian WWTP ranging from 10 to 40 kWh/PE per year for treatment with AnD and ranging from 40 to 70 kWh/PE per year for treatment with AD.

The frequency histogram was therefore produced in Figure 7, which indicates approximately 63 kWh/PE per year the most frequent value, and higher values of specific consumption are related to smaller WWTPs. Most of the energy consumption data in relation to the population served is between 11 kWh/PE per year and 126 kWh/PE per year. The data range has been divided into 25 classes for an extension of each class equal to 25 kWh/PE per year.

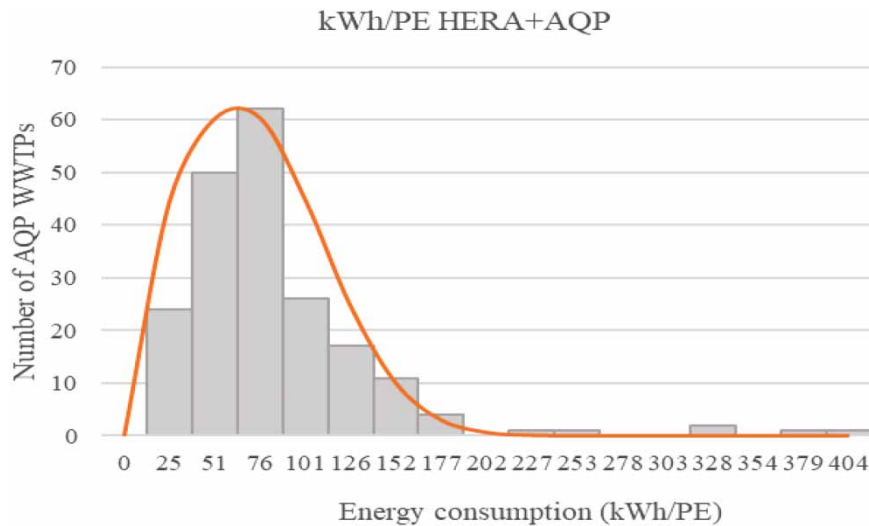


Figure 7 | Distribution of energy consumption in Italian municipal WWTPs in terms of kWh/PE per year.

For all plants equipped with AD, the equation of the exponential curve (Figure 8) that best fits the energy consumption data in relation to flow rates has the following equation: $E = 1.395 e^{-1.00E-05 (PE)}$ with linear regression equal to $R^2 = 0.19$, while for AnD plants (Figure 9) of both companies the equation is $E = 0.77 e^{-3.00E-06 (PE)}$ with linear regression equal to $R^2 = 0.37$; the degrowth is faster for plants with AD treatment.

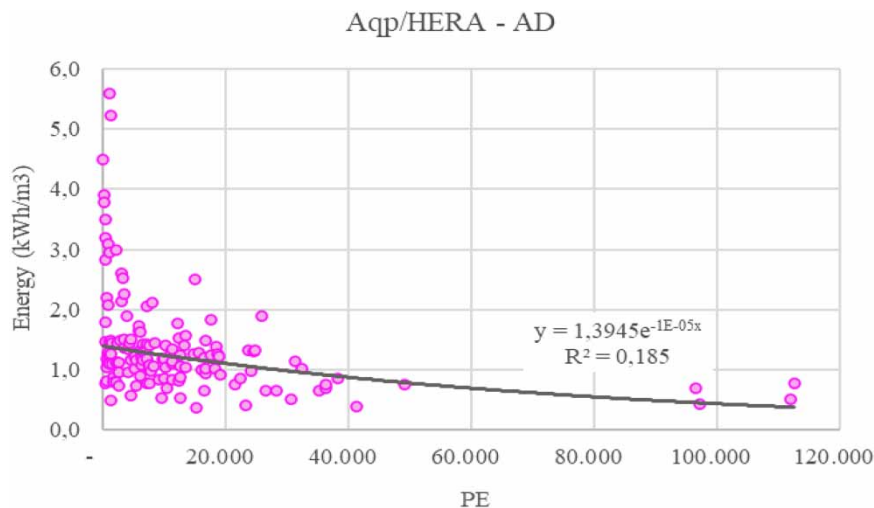


Figure 8 | Correlation between energy consumption and PE for all AD plants.

As a general trend, the specific energy consumption tends to decrease with the increase of number of PE and influent flow rate. This behaviour should be enhanced reaching economies of scale in larger systems, leading to larger but efficient equipment, better performing automation and regulation and, often, more and better trained staff operating the plant (Enerwater 2015).

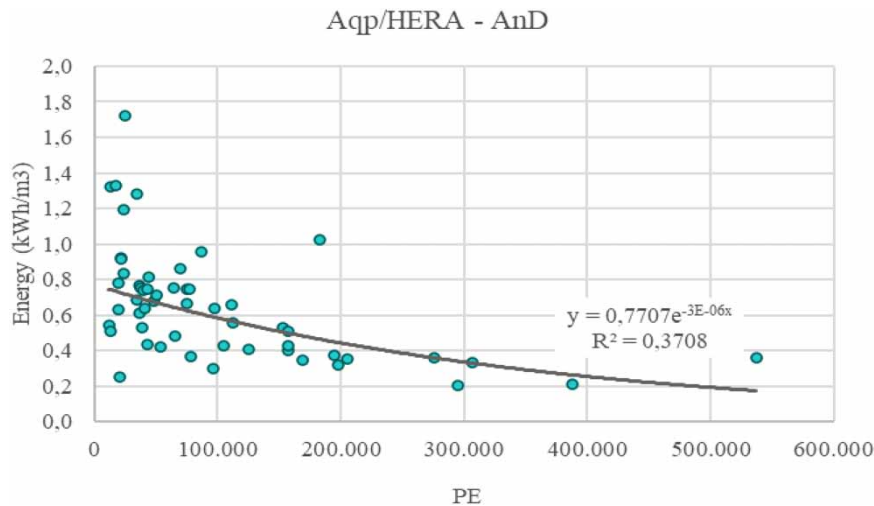


Figure 9 | Correlation between energy consumption and PE for all AnD plants.

Correlation between energy consumptions and COD

The European community claims that general energy consumption indexes such as kWh/m³; kWh/PE-year should be completed with an index that gives information on the variability of the influent characteristics in WWTP (ENERWATER 2018). Then the index that express the unit energy consumption per unit of COD removed (kWh/kg COD) should be also suitable (Vaccari *et al.* 2018).

The distribution curve has been determined through a function that returns the normal distribution for the specified mean and standard deviation.

On the basis of all WWTPs' electrical consumption, the cumulative distribution functions have been calculated in terms of COD removed (Figure 10) where the most probable value is approximately 1.9 kWh/kgCODrem, corresponding to approximately 1.6 kWh/kgCODin (Figure 11). Most values are concentrated in the range: 0.7 kWh/kg COD and 3 kWh/kg COD.

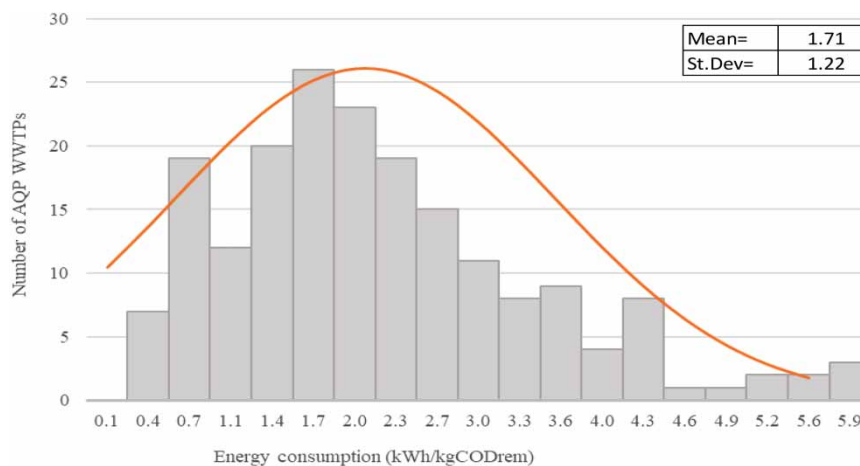


Figure 10 | Distribution of energy consumption in Italian municipal WWTPs in terms of kWh/kg CODrem.

For AQP plants (Figure 12(a) and 12(b)), the inputs have higher COD values; in fact, the average COD input is equal to 828 mgCOD_{in}/L; on the contrary, for the HERA plants (Figure 13(a) and 13(b)), the incoming COD is equal to about half of that found for the Apulian plants and is equal to 406 mgCOD_{in}/L.

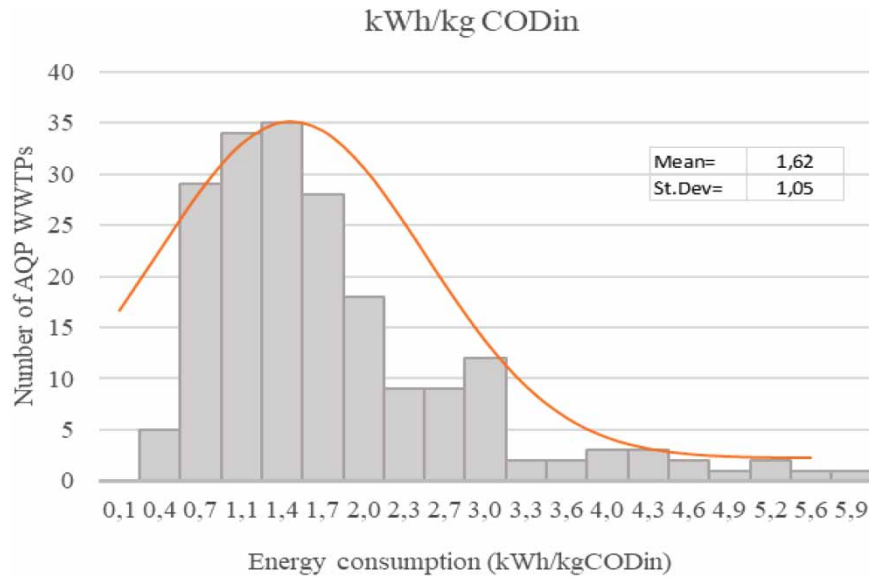


Figure 11 | Distribution of energy consumption in Italian municipal WWTPs in terms of kWh/kg CODin.

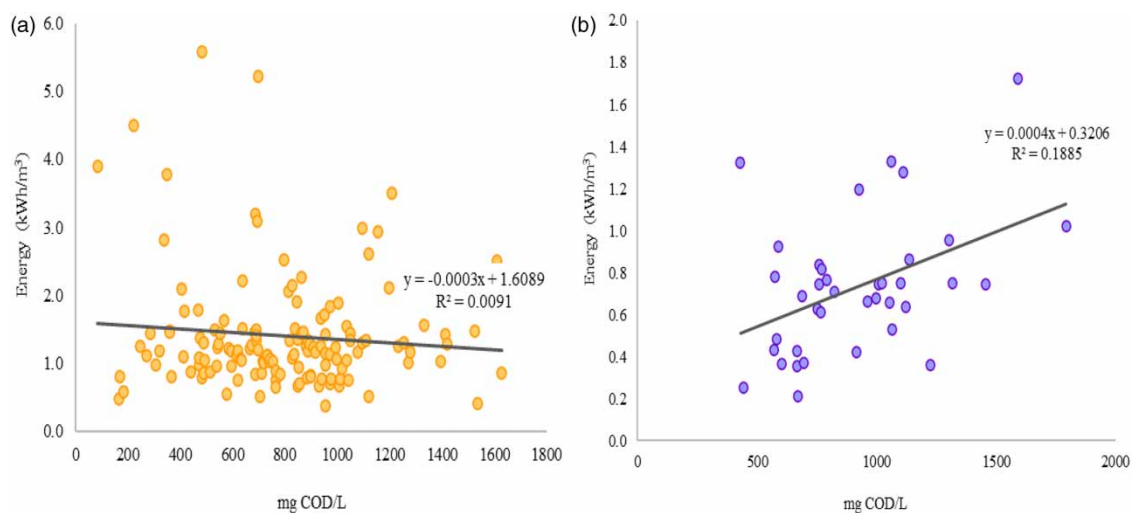


Figure 12 | (a, b) Correlations between energy consumptions and mg COD_{in}/L of AQP WWTPs with AD (a) and AnD (b).

While the tendency for AD plants, either managed by AQP (Figure 12(a)) or by HERA (Figure 13(a)), is represented by a decreasing line ($y = -0.0003x + 1.6$ for AQP and $y = -0.0002x + 0.64$ for Hera), only for anaerobic WWTP managed by AQP, there is an increasing trend with the interpolating curve (line) equal to $y = 0.0004x + 0.32$ with R^2 equal to 0.19.

This should be explained by the probable presence of a more refractory COD in the influent WWTP that has higher COD values, and this results in greater difficulty in undertaking the treatment and to higher electricity operating costs. Moreover, low COD concentration in the wastewater entering the plants can be associated with lower energy consumption, as less energy will be used for the oxidation of organic compounds (Hao *et al.* 2015), resulting in plants equipped with anaerobic digestion having a well-defined trend with increasing energy consumption as a function of a higher input COD value.

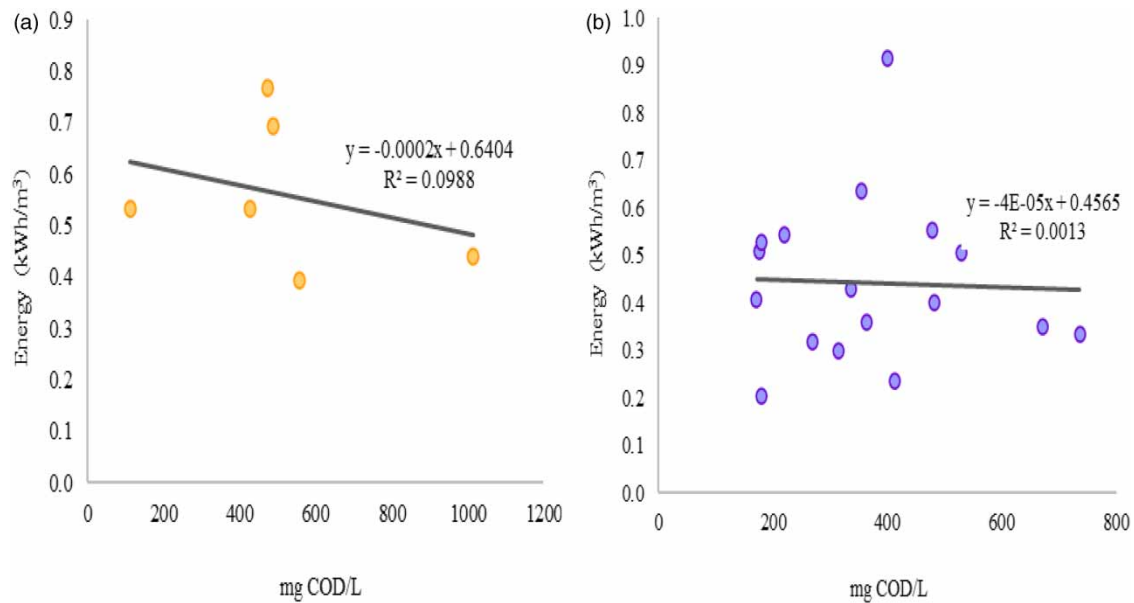


Figure 13 | (a, b) Correlations between energy consumptions and mg CODin/L of HERA WWTP with AD (a) and AnD (b).

CONCLUSIONS

The results of the analysis show an overall average consumption for urban wastewater treatment plants in Emilia Romagna and Apulia regions with aerobic sludge digestion of 1.02 kWh/m^3 , which is more than double compared to plants with anaerobic digestion of 0.43 kWh/m^3 on average.

For all the AD and AnD treatment and for all WWTP flows, the most probable value has been calculated resulting in 0.92 kWh/m^3 , 63 kWh/PE*yr and $1.9 \text{ kWh/COD}_{\text{rem}}$.

For all the Apulian region WWTPs, the average COD value in the WWTP influents is equal to 828 mg/L , the average energy per cubic meter consumed in aerobic based plants is approximately 1.09 kWh/m^3 , and 0.53 kWh/m^3 for anaerobic digestion-based WWTPs.

For all the WWTPs in the Emilia Romagna region, where the average COD concentration, equal to 406 mg/L , is quite lower, this is probably due to a higher degree of pre-treatment at the factory before entering the municipal WWTP. The average value of energy consumed per cubic meter is equal to 0.56 kWh/m^3 for AD plants; AnD plants are more efficient with an average value equal to 0.33 kWh/m^3 .

As regards the most probable values of kWh as a function of COD, this is equal to approximately $1.9 \text{ kWh/kg COD}_{\text{removed}}$ in Apulia and approximately $1.6 \text{ kWh/kg COD}_{\text{in}}$ in Emilia Romagna.

In any case, it should be estimated the savings that would be achieved if anaerobic treatment were adopted on all the plants for which it is advantageous compared to the total of the plants considered. In fact, on the basis of the present analysis, if all the Apulian AD plants with a capacity higher than 10,000 PE were converted to anaerobic digestion, an energy saving, calculated on all plants, of about 16% would be achieved and by considering the Emilia Romagna anaerobic plants consumption index, it would be possible to reach a total saving equal to 42%.

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AUTHOR CONTRIBUTIONS

The contribution of the authors is parithetic.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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