

# Assessing energy performance and critical issues of a large wastewater treatment plant through full-scale data benchmarking

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## ABSTRACT

The wastewater sector accounts for 25% of the global energy demand in the water sector. Since this consumption is expected to increase in the forthcoming years, energy optimization strategies are needed. A truly effective planning of energy improvement measures requires a detailed knowledge of a system, which can only be achieved through energy audit and real-time monitoring. In order to improve the identification of critical issues related to the use of energy resources within a wastewater treatment plant (WWTP), the paper shows the results of a monitoring campaign performed on a large WWTP in southern Italy. Data obtained for the audit cover a 4-year timeframe (2014–2017). Energy–environmental performance has been evaluated through the benchmarking of: system variables, specific consumptions, and operational indicators. Moreover, by using a real-time data measurement and acquisition system it has been possible to evaluate the real performance of the most energy-intensive apparatus of the plant (a turbo-blower), over a period of 8 months. The main results indicate that (a) the plant is mainly affected by a massive capture of infiltrations, working in conditions close to the maximum hydraulic capacity, (b) real-time energy measurements are necessary to accurately characterize plant consumptions and adequately assess their critical aspects.

**Key words** | energy audit, energy management system, infiltrations, inflows, key performance indicators, wastewater

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## INTRODUCTION

The water sector requires large amounts of electric energy to fulfil its processes: almost 4% of global electricity consumption per year has been used to extract, distribute and treat water and wastewater (IEA 2016). Moreover it is estimated that, following the same management conditions, the energy share used for this sector is projected to more than double by 2040, with the largest increase coming from desalination, followed by water transfer operations and the growing need to ensure higher levels of wastewater treatment (Luck *et al.* 2015; Bijl *et al.* 2016; Wada *et al.* 2016).

In particular, wastewater treatment requires 25% of the total energy spent in the water sector on a global scale, rising to 42% for the most developed countries, and the total electricity consumption may increase by more than 60% by 2040, due to the strong increase of polluted water requiring treatments (IEA 2016). Factors that mostly affect

energy consumption in the wastewater sector are: the amount of collected and treated wastewater; the amount of groundwater and precipitation collected by the sewerage system (infiltrations and inflows); the level of contamination; the level of treatment required for discharge and the energy efficiency of operations (Plappally & Lienhard V 2012; WRF & EPRI 2013).

There are several possibilities to reduce these energy consumptions: (i) increasing performance of apparatuses through the adoption of frequency converters (Metcalf & Eddy 2014); (ii) improving aeration effectiveness in the aerobic reactors (Battistoni *et al.* 2003; Ferrentino *et al.* 2018); (iii) reusing the biogas recovered from the sludge digestion (Bachmann 2015; Mema *et al.* 2017). With the same aim, it is possible to reduce the amount of inflows and infiltrations, thus achieving a reduction in the flows to

be treated and, consequently, the energy needed for pumping operations (Metcalf & Eddy 2014).

To achieve optimal results in the power saving, Foladori *et al.* (2015) underlines how crucial is the role of dynamic monitoring in addition to system audit, as it allows real-time tracking of system parameters and active monitoring of the operating conditions of the facility units. Along with Foladori *et al.* (2015), many studies have attempted to assess how to approach the audit of wastewater treatment plants (WWTP) (Sánchez *et al.* 2009; Balmer & Hellstrom 2012; Belloir *et al.* 2015; Silva & Rosa 2015; Thurlimann *et al.* 2015; Longo *et al.* 2016; Panepinto *et al.* 2016).

In this framework, the present work aims to show how these methodologies can be useful when applied to a specific case study, i.e. a large WWTP located in the city of Salerno (Campania Region – company S.I.I.S. s.p.a.). For this plant, it is not feasible to realize an in-depth analysis of energy efficiency at each stage of the treatment process (as is the case in Foladori *et al.* (2015)), because not all the electromechanical units are equipped with energy meters and the data provided by the company refers to the full-scale WWTP.

In order to get over these limitations and be able to extrapolate as much information as possible with the available data and resources, the study has been divided into two phases. The first step (*static monitoring*) is the audit of the process variables, over a 4-year timeframe (2014–2017), using the major key performance indicators (KPIs) and operational indicators found in the literature (Campanelli *et al.* 2013; Foladori *et al.* 2015; Silva & Rosa 2015; Longo *et al.* 2016). As an element of novelty, the research proposes a distinction between organic load and hydraulic load in the evaluation of population equivalent and load factor, aimed at better detecting the presence of inflows and infiltrations. The second step (*dynamic monitoring*) consists of (i) defining a theoretical model for the assessment of the energy contribution of each plant sector and (ii) developing a real-time monitoring system on an energy-intensive unit.

## MATERIALS AND METHODS

### Site description

The S.I.I.S. WWTP started working in 1988 with the aim of treating mixed civil (>90%) and industrial sewage from the city of Salerno and several neighbouring municipalities. The WWTP (DEP) is located in a very sensitive area, from a

hydrogeological point of view, and it collects wastewaters from an 85-km network of collectors, dating between the first half of 1900 and early 1990s, with almost entirely gravitational flow. The circular section collectors are made of fibreglass, with diameters ranging from 300 mm to 1,400 mm; the rectangular section collectors have sloping pitches and are made of reinforced concrete. The network also includes 10 sewage lifting stations (S1, S2, S3, S4, S5, S6, S8, S9, S10, S11).

With a maximum capacity of 700,000 PE (population equivalent) and designed to treat an average flowrate of about 157,000 m<sup>3</sup>/d (according to less stringent limits of the former reference regulation – L. 319/76), the WWTP only uses electricity as energy source for the technological services of the facility and performs its treatments with a CAS (conventional activated sludge) process scheme (Metcalf & Eddy 2014). According to current regulation, the process needs to comply with the following discharge thresholds (listed as chemical oxygen demand (COD), biochemical oxygen demand (BOD<sub>5</sub>), total suspended solids (TSS), total nitrogen (N<sub>TOT</sub>) and total phosphorus (P<sub>TOT</sub>): concentration up to 125, 25, 35, 15, and 2 mg/L; minimum removal rate of 75, 80, 90, 70, and 80%. After the initial pre-treatments (solids and oil removal, pre-aeration) and primary sedimentation, pollutants removal is guaranteed by oxidation with activated sludge. Secondary sedimentation and final disinfection (chlorination) ensure the complete stabilization of the treated wastewater. Sludge generated by the process is first conveyed to a mechanical thickener, then stabilized through anaerobic digestion and finally dried by centrifuges.

In recent years, the WWTP has suffered a significant increase in inflows and infiltrations, enormously amplified in the years 2013–2015. Additionally, due to the secondary sedimentation sector and increasingly stringent regulatory limits, the current treatment capacity has decreased by about 15% compared to the original planned one (700,000 PE). Table 1 summarizes the main design parameters and, for each of them, a comparison with the actual values currently achieved.

Static monitoring concerns the evaluation of the overall operating conditions of the WWTP, through the study of performance indicators and process-related parameters, obtained from measurements and documentation provided by the company (e.g. energy consumption billing, wastewater analysis reports). In dynamic monitoring, the focus is on studying the performances of machinery used in wastewater treatment processes, by means of a pilot energy monitoring system for the collection and analysis of real-time consumption data.

**Table 1** | Main design parameters (top): comparison between original and currently achieved values; average wastewater composition, in terms of the pollutants to be removed (bottom)

Parameters	Design data	Current data
Maximum capacity (PE)	700,000	600,000
Design water supply (L PE <sup>-1</sup> day <sup>-1</sup> )	280	320
Return coefficient of inflow into the sewer	0.8	0.8
Average black flowrate (m <sup>3</sup> /d)	157,000	120,000–157,000
Max. flowrate dry time (m <sup>3</sup> /d)	245,000	138,000–190,000
Max. rainfall time flowrate (m <sup>3</sup> /d)	704,000	311,000
Main wastewater pollutants	Average values	
COD input (mg/L)	330	
BOD5 input (mg/L)	140	
TSS input (mg/L)	420	
N <sub>TOT</sub> input (mg/L)	7,5	
P <sub>TOT</sub> input (mg/L)	5	

### Static monitoring

Investigations refer to a period of 4 years, from January 2014 to December 2017. Data were provided by the company on a monthly basis, and include: (i) total electricity consumption with corresponding tonnes of oil equivalent (0.187 toe/MWh<sub>el</sub>, according to Legislative Decree 102/2014 as amended) and CO<sub>2</sub> equivalent emissions (0.483 tonCO<sub>2eq</sub>/MWh<sub>el</sub>, according to IPCC (2014)); (ii) total volume of wastewater treated by the facility; (iii) average daily input and output of COD, BOD5 and TSS. On the basis of the data collected, the following specific performance indicators were determined.

- (i) Biochemical composition of incoming wastewater was evaluated through the ratio between COD and BOD5, defined as *biodegradability index* (Metcalf & Eddy 2014); for civil wastewater the values for this index are usually between 1.5 and 2.5; values lower than 1.5 indicate a wastewater that is easy to treat by biological processes; values above 3 indicate a wastewater mainly composed of non-biodegradable substances, or containing pollutants which are toxic for an activated sludge plant (Papadopoulos *et al.* 2001; Turak & Fsar 2004; Abdalla & Hammam 2014).
- (ii) The population equivalent actually served by the plant ( $PE_{served}$ ): for this indicator two different methods

were used, in view of the fact that the facility accommodates a considerable amount of inflows and infiltrations.

- a. The first method is based on the indication coming from Italian legislation, which defines 1 PE as 'biodegradable organic load with an oxygen biochemical request for 5 day (BOD5) equal to 60 grams of oxygen per day' (Legislative Decree 152/2006 as amended), and it uses the amount of organic matter to be removed as primary information.

$$PE_{served}^{organic} = \frac{\text{daily BOD5 load entering the plant} \quad [n \text{ gBOD5}_{in} * \text{day}^{-1}]}{\text{daily oxygen biochemical request for 5 day} \quad [60 \text{ gO}_2 * \text{PE}^{-1} * \text{day}^{-1}]}$$

- b. The second method is based on per capita wastewater production and allows characterization of the hydraulic stress which the plant is subjected to. It is known, in fact, that only a portion of the population water supply is released in the wastewater sewer system (Metcalf & Eddy 2014). Because of that, starting from the incoming wastewater flowrate, it is possible to estimate the number of served inhabitants as:

$$PE_{served}^{hydraulic} = \frac{\text{daily wastewater flowrate} \quad [L * \text{day}^{-1}]}{[\text{L} * \text{PE}^{-1} * \text{day}^{-1}] * \text{return coefficient} * \text{water supply}}$$

where the *return coefficient* is less than 1, assuming no inflows/infiltrations and no leakage along the sewer system (Metcalf & Eddy 2014).

- (iii) Operational data provided by the company were also used to determine, as an average value, the percentage of collected inflows and infiltrations, according to Metcalf & Eddy (2014):

$$\text{Inflows} = \text{peak hourly wet weather flow (meteoric event)} - \text{peak hourly wet weather flow (day before)}$$

$$\text{Infiltrations} = \text{average wet weather flow} - \text{average dry weather flow}$$

- (iv) Moreover, the following *operational indicators* were determined. *Wastewater Flow per PE* and *Organic Load Factor* comply with the literature (Longo *et al.* 2016). *Hydraulic Load Factor*, instead, was introduced as a new parameter based on the definition of

$PE_{served}^{hydraulic}$  given above.

$$\begin{aligned} \text{Wastewater flow per PE} &= WF_{PE} \\ &= \frac{\text{daily wastewater flowrate [L * day}^{-1}\text{]}}{\text{population equivalent served [PE}_{served}^{organic}\text{]}} \times 100; \end{aligned}$$

$$\begin{aligned} \text{Organic load factor} &= LF_{organic} \\ &= \frac{\text{population equivalent served [PE}_{served}^{organic}\text{]}}{\text{project population equivalent [PE}_{design}\text{]}} \times 100; \end{aligned}$$

$$\begin{aligned} \text{Hydraulic load factor} &= LF_{hydraulic} \\ &= \frac{\text{population equivalent served [PE}_{served}^{hydraulic}\text{]}}{\text{project population equivalent [PE}_{design}\text{]}} \times 100 \end{aligned}$$

$WF_{PE}$  and *load factors* provide immediate information on the actual operating conditions of the system with respect to the design capacity; *load factor* makes it possible to determine whether the system works in conditions of over- or under-sizing (in this case, also from a hydraulic point of view), while *wastewater flow per PE* gives the actual amount of wastewater (per PE) collected by the plant.

- (v) The energy performances of the plant were evaluated through the following KPIs, defined by Campanelli et al. (2013):

$$KPI1 = \frac{\text{energy consumption [kWh]}}{\text{unit of volume treated [m}^3\text{]}};$$

$$KPI2 = \frac{\text{energy consumption [kWh]}}{\text{population equivalent served * year [PE}_{served}^{organic} \text{ * year]}};$$

$$KPI3 = \frac{\text{energy consumption [kWh]}}{\text{unit quantity of removed COD [kgCOD}_{removed}\text{]}};$$

$$KPI4 = \frac{\text{energy consumption [kWh]}}{\text{unit quantity of removed BOD5 [kgBOD5}_{removed}\text{]}};$$

$$KPI5 = \frac{\text{energy consumption [kWh]}}{\text{unit quantity of removed TSS [kgTSS}_{removed}\text{]}}.$$

These indexes express a specific energy consumption, evaluated with respect to process variables. Depending on the parameter chosen for the calculation, KPIs may be more or less effective in identifying problems (Longo et al. 2016), as it will be highlighted in the section on the presentation of results.

## Dynamic monitoring

With the goal to analyse the energy consumption distribution among the facility sectors and discover the most energy-intensive treatments and equipment, general information about the operational characteristics (e.g. location of machinery within the facility, rated power of machinery, estimated daily operating hours, machinery condition) of single apparatuses was collected. Starting from the data, the total annual energy consumption of the plant ( $E_{TOT}$ ) was first estimated as follows:

$$E_{TOT} = \sum_{j=1}^n \left[ \sum_{i=1}^m (P_i^j \times t_i^j \times K_{u,i}^j) \right] \quad (1)$$

where  $i$  is the electromechanical unit installed in compartment  $j$ ,  $P_i^j$  is the rated power of the machinery and  $t_i^j$  its estimated annual running time.  $K_{u,i}^j$  is the *utilization factor* and represents the ratio between the power that the consumer device is expected to absorb in ordinary operation and the maximum power that the consumer device can absorb (CEI 64-8; CEI (2007)); the value of  $K_{u,i}^j$  depends on the rated power of the instrument. The energy and power shares of each sector ( $E_{0j}^j$  and  $P_{0j}^j$ , respectively) are then given by the expressions:

$$E_{0j}^j = \frac{\sum_{i=1}^m (P_i^j \times t_i^j \times K_{u,i}^j)}{\sum_{j=1}^n \left[ \sum_{i=1}^m (P_i^j \times t_i^j \times K_{u,i}^j) \right]} \times 100 \quad (2)$$

$$P_{0j}^j = \frac{\sum_{i=1}^m (P_i^j)}{\sum_{j=1}^n \left[ \sum_{i=1}^m (P_i^j) \right]} \times 100 \quad (3)$$

The results obtained from this model were then taken into account to implement a monitoring system on a turbo-blower at the service of an oxidation tank, with 500 kW of rated power and a continuous duty cycle (24 h/7 d).

The monitoring system consists of a Schneider Electric multifunction meter (model PM5110), which measures energy consumption and power absorbed by the machine each 60 seconds; the meter is connected to a Schneider Electric data logger (model Com'X 510), which collects and sends data to a user-friendly web platform (DAVID – david.energgreenup.it). The reference period for the measurements is between 5 August 2017 and 28 March 2018, with some interruptions for maintenance reasons. In total, 299,477 measurements were recorded, corresponding to a period of 208 days. The following statistical quantities were evaluated: average value of daily energy consumption,

average value of absorbed power, standard deviation of power measurements, frequency distribution of recorded power measurements, and comparison between real energy consumptions and estimated values.

## RESULTS AND DISCUSSION

### Static monitoring

Figure 1 shows, for every year, the total energy consumptions of the sites included in the audit (WWTP 'DEP' and 10 sewages lifting stations). The energetic consumptions of the whole system are about 10 GWh per year (Figure 1), corresponding to an emission of 4,800 tons of CO<sub>2eq</sub> and a consumption of over 1,800 tons of oil equivalent, with an energy bill of almost €2 million. As can be seen, the wastewater treatment plant requires more than 80% of the total energy demand managed by the company. Restricting the field to the WWTP, the time trend of the wastewater volumes entering the plant shows a gradual reduction in the average monthly input of about 39%, observed over the entire period of 4 years (Figure 2).

Regarding the loads of COD, BOD<sub>5</sub> and TSS over the years, the amount removed is very high, demonstrating the proper functioning of the depuration process, which complies with all legal limits imposed by current legislation both for output values and for removal rates (Legislative Decree 152/2006 as amended). The biodegradability index shows an average value of 2.5; for this value, treated wastewater can be classified as medium biodegradable civil sewage (Abdalla & Hammam 2014). It can be assumed that the sewer system collects a large amount of wastewater in which either the inorganic matter is significant, or the bacteria involved in the process require time to adapt and take part in the treatment.

Very interesting are the results obtained for the *population equivalent served*. This data, in fact, should always be lower than the design value, taking into account any seasonal fluctuations (e.g. intense rainfall, tourist season) (Corominas *et al.* 2010). A significant statistical difference is evident between  $PE_{served}^{organic}$  and  $PE_{served}^{hydraulic}$ ; the real organic load is much lower than the design value (700,000 PE) while the hydraulic load is closer to it, and in some months it exceeds the maximum capacity (Figure 3). Also, hydraulic load shows a decreasing trend from March to November

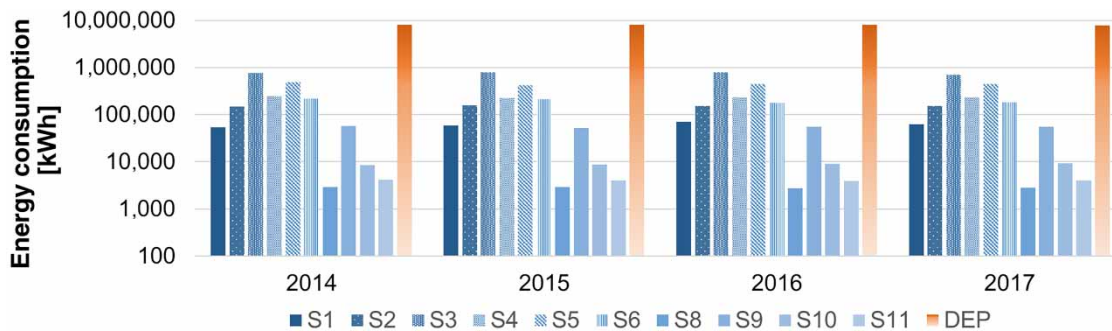


Figure 1 | Total annual energy consumption of the analysed sites.

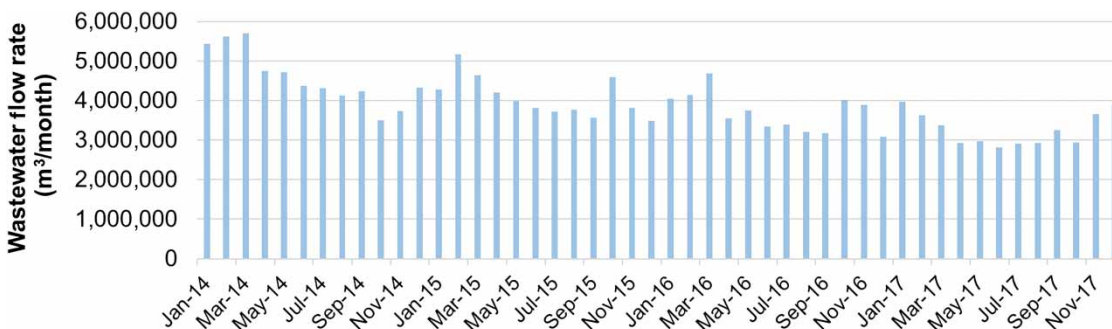


Figure 2 | Monthly wastewater flowrate entering the WWTP.

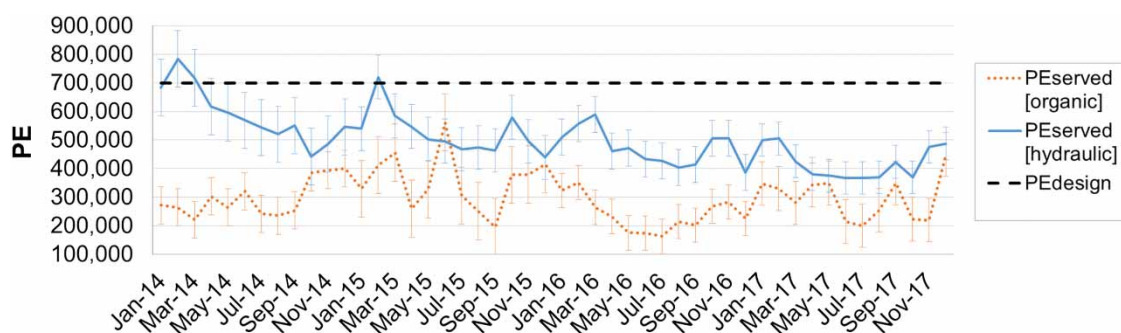


Figure 3 | Trend of the PE served by the WWTP.

for all years (Figure 3), thus testifying to the presence of seasonal fluctuations.

With the aim of understanding the functional dependencies of energy consumption on process variables, performance indicators described in the ‘Static monitoring’ section of ‘Materials and methods’ have been evaluated. Table 2 shows the annual average results for each index.

As suggested from Longo et al. (2016), it was considered appropriate to use  $KPI3$  ( $\text{kWh}/\text{kgCOD}_{\text{removed}}$ ) as a reference index in describing energy performance of the pollutants removal, since it better reflects the pollutant load due also to inflows and infiltrations. The average value obtained for this indicator ( $0.7 \text{ kWh}/\text{kgCOD}_{\text{removed}}$ ) is consistent with data found in the literature for all the variables: wastewater treatment technology (CAS), country where the plant is located (Italy) and plant capacity ( $\text{PE} > 100,000$ ) (Longo et al. 2016). As far as the  $KPI2$  is concerned, the obtained average value ( $29 \text{ kWh PE}^{-1} \text{ year}^{-1}$ ) is coherent with data found in the literature for plants of the same size ( $\text{PE}_{\text{design}} > 100,000$ ): Campanelli et al. (2013), for example, reports an average value of  $37 \text{ kWh PE}^{-1} \text{ year}^{-1}$  (standard

deviation 23). Results obtained for the operational indicators also clearly confirm the presence of dilution waters.

The WWTP was designed based on a water supply of  $280 \text{ L PE}^{-1} \text{ day}^{-1}$  and the amount of wastewater produced by the population is related to water supply through the so-called *return coefficient*, which here equals 0.8 (Table 1) and is usually less than 1 (Metcalf & Eddy 2014). Water supply has currently reached a value of  $320 \text{ L PE}^{-1} \text{ day}^{-1}$  (Table 1); therefore, supposing no infiltrations or inflows, the volume of wastewater produced and discharged into the sewerage should not exceed  $256 \text{ L PE}^{-1} \text{ day}^{-1}$  (*water supply*  $\times$  *return coefficient*), while in this case the facility receives an average flowrate of  $461 \text{ L PE}^{-1} \text{ day}^{-1}$ . This can only be achieved by adding a large volume of inflows and infiltrations to wastewater discharged by users. In this regard the study of inflow/infiltration ratio reveals that inflows represent the greater item, accounting for at least 70% of total dilution waters.

The phenomenon of dilution is also witnessed by results achieved for  $KPI1$ . It is well known that plants affected by collection of inflows and dilutions show high energy efficiency with respect to the wastewater flowrate (Campanelli et al. 2013; Vaccari et al. 2018). The increase in wastewater volumes entering the plant, with a diluted organic load, implies an increase in energy costs only for wastewater pumping units, while the machinery responsible for secondary treatment (e.g. blowers, recirculation pumps, digesters), which represents the most energy-intensive sector of the system (WERF 2010; Metcalf & Eddy 2014), is not clearly affected by this volume increase. Confirming the above, the average value of  $KPI1$  for the S.I.I.S. plant is  $0.18 \text{ kWh}/\text{m}^3$ , which is half of the average value of  $0.39 \text{ kWh}/\text{m}^3$  found in literature for energy efficient plants (Campanelli et al. 2013).

The excessive dilution of wastewater has, obviously, important repercussions also on the concentration of the incoming pollutant load and on the work performed by

Table 2 | Annual average values of KPIs and operational indicators

Index	Annual mean				Overall mean
	2014	2015	2016	2017	
$KPI1$ ( $\text{kWh m}^{-3}$ )	0.15	0.17	0.18	0.20	0.18
$KPI2$ ( $\text{kWh PE}_{\text{served}}^{\text{organic}-1} \text{ year}^{-1}$ )	28	24	35	28	29
$KPI3$ ( $\text{kWh kgCOD}_{\text{removed}}^{-1}$ )	0.64	0.57	0.86	0.68	0.69
$KPI4$ ( $\text{kWh kgBOD5}_{\text{removed}}^{-1}$ )	1,52	1,28	1,98	1,49	1,57
$KPI5$ ( $\text{kWh kgTSS}_{\text{removed}}^{-1}$ )	0,47	0.39	0.67	0.44	0.49
$WF_{PE}$ ( $\text{L PE}_{\text{served}}^{\text{organic}-1} \text{ day}^{-1}$ )	537	403	523	380	461
$LF_{\text{organic}}$ (%)	42%	51%	34%	42%	42%
$LF_{\text{hydraulic}}$ (%)	84%	75%	67%	60%	72%

the machinery for its removal. Considering the definition previously given for the *organic* and *hydraulic* load factor, Figure 4 shows that as the  $WF_{PE}$  increases, the concentration of the organic fraction decreases and, consequently, a reduction can be observed in the number of  $PE_{served}^{organic}$  and in the organic load factor. An average  $WF_{PE}$  of  $461 \text{ L PE}^{-1} \text{ day}^{-1}$  corresponds to a load factor of 40%, and the system is oversized by 2.5:1. On the other hand, as was predictable, hydraulic load factor tends to increase with the  $WF_{PE}$  (dilution of wastewater), showing an average value of 72% over the entire period; from a volumetric point of view, therefore, the system works in conditions close to the maximum plant capacity.

Negative effects of excessive dilution, in terms of energy performance, can be also noticed in the  $KPI3$  trend. As can be seen in Figure 5, there is a positive correlation between the  $KPI3$  and the *wastewater flow per PE*: the presence of dilution waters induces an increase in the energy required for removal treatments of a unit quantity of COD. At the same time, as the *organic load factor*

decreases, the specific consumption of the depuration process rapidly increases (Figure 5), proving that the system works truly efficiently when the biodegradable pollutant load ( $BOD5$ ) is present in a more concentrated form and when the plant sizing is effective ( $PE_{served}^{organic} \rightarrow PE_{design}$  and *organic load factor*  $\rightarrow 100\%$ ). The trend shown in Figure 5 is consistent with the one reported in the literature for similar plants (Campanelli *et al.* 2013; Longo *et al.* 2016). It is important to notice that, if the system worked in conditions of undersizing ( $PE_{served}^{organic} > PE_{design}$ ;  $LF_{organic} > 100\%$ ), the depuration process would appear to be more energy efficient ( $KPI3 \rightarrow 0$ ); actually, the plant would be in conditions of inefficiency with respect to the pollutants removal degree, due to treatment units not large or powerful enough to meet the needs of depuration treatments (Longo *et al.* 2016).

### Dynamic monitoring

Starting from the technical data supplied by the company and applying the energy model presented in the 'Dynamic monitoring' section of 'Materials and methods', the energy share of the different apparatuses has been obtained. The results agree with the main data found in the literature (WERF 2010; Metcalf & Eddy 2014). In detail, turbo-blowers and augers are the elements that absorb most of the power, respectively 36% and 33%; then pumps (18%) and centrifuges (8%) categories are also important, while all the other sectors have less than 2% of the total installed power.

To better understand whether the estimated operating conditions of the apparatuses are consistent with the real ones, an *in situ* monitoring was performed on a turbo-blower of the oxidative treatment sector. The machine,

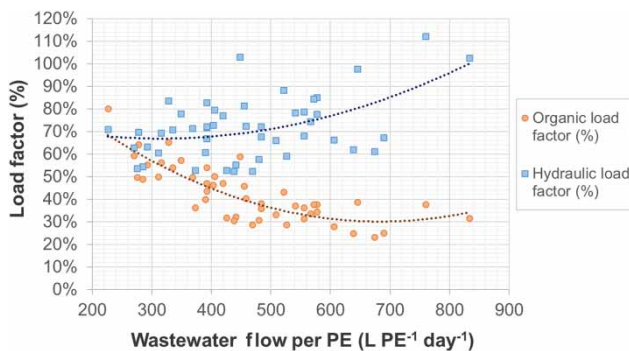


Figure 4 | Organic and hydraulic load factor as a function of wastewater flow per PE.

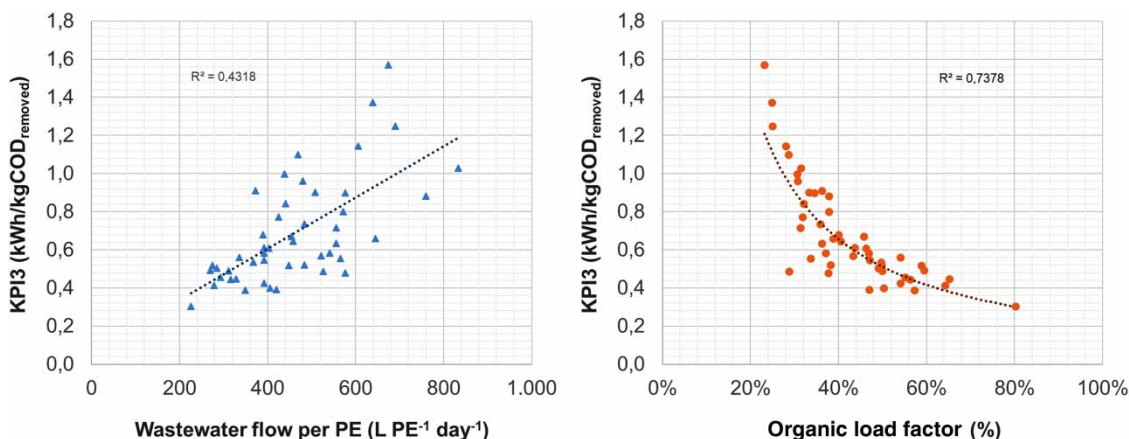
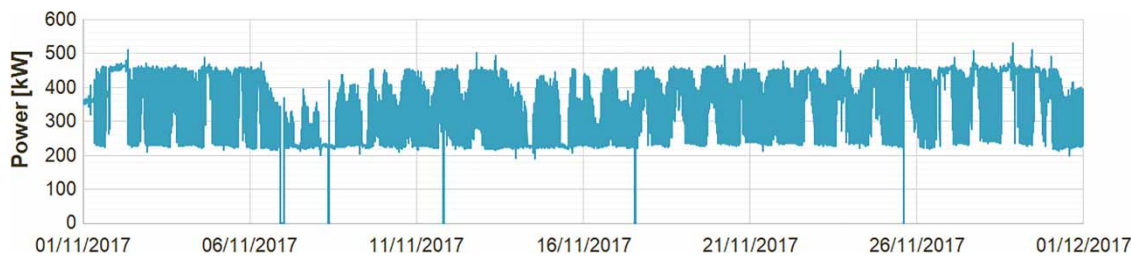


Figure 5 |  $KPI3$  vs wastewater flow per PE (left) and organic load factor (right).



**Figure 6** | Time trend of the power absorbed by the turbo-blower over a period of 30 days (excerpt of the total period of 208 days).

with a rated power of 500 kW, is estimated to work 24 h/day, with a maximum annual energy consumption of about 4,380,000 kWh, and a  $K_u$  factor of 0.80 for machinery with rated power greater than 10 kW (CEI 64–8; CEI (2007)). To give an example, Figure 6 shows the power absorbed by the apparatus over a period of 30 days, which is representative of the operation observed over the entire period. As can be seen, the machinery works continuously (24 h/7 d). This is consistent with the estimated operating hours and it justifies the high percentage energy share obtained with the theoretical model for the turbo-blower category (36% of the total installed power and 42% of the total energy consumption). The apparatus works in a power range of 220 kW to 460 kW, with an average value over the entire observation period of 288 kW (Figure 6).

Starting from these results, a comparison between estimated and actual annual consumption of the turbo-blower shows a real consumption of the apparatus that is about 28% lower than the initially estimated one (2,518,191 kWh/year versus 3,504,000 kWh/year). From the technical data supplied by the company, it is known that this turbo-blower accounts for more than 90% of the category's consumption; therefore, its real energy share (32%) is also lower than the value obtained with the energy model (42%).

## CONCLUSIONS

The paper presented the results of an energy audit, performed on a system consisting of a 700,000 PE WWTP and 10 sewage lifting stations, serving the city of Salerno (Italy). The study has the principal goal to identify critical issues related to the use of energy resources within the plant. Research on the system was carried out following the methodologies and main performance indicators used in the literature, with particular attention to the KPIs and the operational indicators (*wastewater flow per PE* and *load factor*). In the calculation of the *population equivalent* and the *load factor*, this work introduces the

distinction between *organic load* and *hydraulic load*, as a term of discrimination to investigate the impact of any infiltration or inflow. From the comparative analysis of the data, the following conclusions can be drawn.

- (i) The plant shows performances comparable to similar case studies, especially as regards the relationship between the *KPI3* (energy efficiency for COD removal) and operational indicators (*wastewater flow per PE* and *load factors*).
- (ii) The system is affected by a massive collection of rain-water inflows and groundwater infiltrations, which dilute the wastewater and are still treated by the plant. For this reason, there seems to be no direct correlation between the overall plant consumption and the amount of pollutants removed by the process. The wastewater dilution also justifies the result obtained for the specific consumption calculated with respect to the volumes treated (*KPI1* – kWh/m<sup>3</sup>), which is about half of the average value reported in the literature for similar plants; this result confirms what has been observed in the literature, namely that this indicator is not very representative of the overall performance of a wastewater treatment plant.
- (iii) Finally, on-site monitoring activities showed that the actual energy consumption of energy-intensive equipment was about 70% of the theoretical value initially estimated, confirming once again the accurate real-time control as an irreplaceable tool for effectively quantifying the energy consumption of installed devices.

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