ENERGY AUDIT IN SMALL WASTEWATER TREATMENT PLANTS – METHODOLOGY, ENERGY CONSUMPTION INDICATORS AND LESSONS LEARNED

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Abstract

Energy audits in wastewater treatment plants (WWTPs) reveal large differences in the energy consumption in the various stages, depending also on the indicators used in the audits. This work is aimed at formulating a suitable methodology to perform audits in WWTPs and identifying the most suitable key energy consumption indicators for comparison among different plants and benchmarking. Hydraulic-based stages, COD-based stages, sludge-based stages and building stages were distinguished in WWTPs and analysed with different energy indicators. Detailed energy audits were carried out on 5 small WWTPs treating less than 10,000 population equivalent and using continuous data for 2 years. The plants have in common a low design capacity utilization (52% on average) and equipment oversizing which leads to waste of energy in absence of controls and inverters (a common situation in small plants). The study confirms that there are several opportunities for reducing energy consumption in small WWTPs: in addition to the pumping of influent wastewater and aeration, small plants demonstrate low energy efficiency in recirculation of settled sludge and in aerobic stabilization. Denitrification above 75% is ensured through intermittent aeration and without recirculation of mixed liquor. Automation in place of manual controls is mandatory in illumination and electrical heating.

Keywords: benchmarking; energy analysis; energy audit; energy consumption indicators; energy efficiency; wastewater treatment plant.

1. INTRODUCTION

The total electricity consumption in municipal wastewater treatment plants (WWTPs) corresponds to about 1% of the total electricity consumption per year of a country (Cao, 2011). In Italy, the electricity consumption in WWTPs is about 3,250 GWh/year which corresponds to about 0,5 billions Euros per year (Campanelli et al., 2013).

A detailed knowledge about energy consumption in WWTPs is becoming increasingly relevant, with the aim of saving costs, reducing GHG emissions and global warming (Krampe, 2013), because energy reduction is an environmental and economical challenge (Gallego et al., 2008). The main energy form required in WWTPs is electrical energy and it accounts for about 25-50% of operating costs in conventional activated sludge systems (Vera et al., 2013; Gallego et al., 2008). Although it is often stated that wastewater pumping and aeration of bioreactors are responsible for the higher electrical energy consumption in WWTPs (*inter alia* WERF, 2010), in some plants they may account for less than 40% of the total energy consumption, thus shifting attention to other electromechanical equipment.

The experience demonstrates that only a detailed energy analysis (energy audit), performed at each stage/process/unit of a WWTP, permits to understand where and how the energy footprint can best be reduced. “What gets measured gets managed” is a maxim which means that producing measurements gives a basis for improving management and thus efficiency. A detailed energy analysis shows that an energy saving potential is almost always present in WWTPs and at least one stage exists where energy consumption can be reduced.

In Europe (EU-26), small WWTPs having agglomeration size from 2,000 to 10,000 PE account for the largest number, with a percentage of 65% of total plants, leading to a considerable total energy consumption which should definitely be reduced. The increase in energy efficiency does not involve necessarily significant investments. Operational adjustments or moderate investments on controls and automation (*inter alia* Olsson, 2012; 2013) can be done immediately and without loss of treatment efficiency. This is important especially in small WWTPs, which have relatively low energy consumption due to their size (even though they have high specific energy consumption), and often discourage additional investments because they are considered too expensive or complicated.

Performance indicators have been proposed in WWTPs (*inter alia* Matos et al., 2003a, 2003b; Quadros et al., 2010, Balmér and Hellström, 2012; Gordon and McCann, 2015) to focus on environmental, operational, personnel, physical, quality of service and economic and financial performance, but not many details were given about energy consumption in the single stages of WWTPs.

In this paper, detailed energy analyses and specific energy indicators are proposed, on the basis of the experience acquired in 5 small WWTPs located in the North of Italy and treating up to 10,000 Population Equivalent (PE). All the equipment installed in the WWTPs are considered here, including those with low power rating, which are often neglected in energy audits because they are considered (sometimes erroneously) responsible for low energy consumption.

In particular, the paper focuses on three key issues: (1) formulation of a detailed methodology for energy audit and its validation; (2) proposal of the most suitable key energy consumption indicators in each stage/process/unit; (3) identification of aspects causing excessive energy consumption and lessons learned towards opportunities for its reduction.

This work contributes to answering some questions not yet completely or exhaustively presented in the literature: What is a detailed and valued methodology to perform energy audits in each stage/process of a WWTP? How to choose energy indicators, among various proposals in the numerous case studies in the literature? How to identify suitable benchmarks, which could be used in understanding excessive energy consumption?

This paper, even though not exhaustive on energy consumption in small WWTPs, has the scope of adding some proposals and new results, thus contributing to the discussion in an area which requires continuous research and efforts for increasing energy efficiency.

2. METHODS

2.1. Full-scale WWTPs

Five small WWTPs with an average population equivalent (PE) served from 582 to 9,727 PE were selected for the energy analysis (Table 1). The PE served was calculated considering 120 gCOD PE^{-1} d^{-1}. In these plants, as frequently observed in small plants, the PE served resulted remarkably lower than the design capacity, which ranged here from 1,050 to 20,000 PE. The WWTPs were all characterized by a similar configuration (Table 1): pumping, pre-treatments (coarse or fine screen, sieving, degritting), activated sludge stage (pre-denitrification, nitrification/oxidation, secondary settling), sludge treatments (thickening, aerobic digestion, mechanical dewatering). Only in the smallest plant (WWTP 5) was the configuration simplified, due to the absence of pumping, denitrification and mechanical dewatering. In WWTP1 and WWTP2, intermittent aeration was applied for nitrogen removal instead of using separated stages for pre-denitrification and nitrification. All WWTPs included artificial lighting, heating and electrical devices (control panels, transformers).

All WWTPs treat separate sewer systems and municipal wastewater. Wastewater collection and pumping along the sewerage were excluded from the energy analysis. The removal efficiency in the WWTPs (Table 1) was above 90% for BOD_5, COD, TKN and NH_4-N in all the plants. Total N was removed with efficiency higher than 70% in all the plants, except for the smallest WWTP5 where the denitrification was absent (according to European Directive 91/271/EC, 1991, the requirement of total N for agglomeration smaller than 2,000 PE is not so strict).

Table 1. PE served, design capacity, configurations and pollutant removals in 5 small WWTPs. Legend: H = hydraulic head; V = volume of the unit; No = not present or present but not used (thus not considered in energy audit); In = influent concentration; Out = effluent concentration; η = removal efficiency.

	WWTP 1	WWTP 2	WWTP 3	WWTP 4	WWTP 5
Population equivalent					
PE served	9,727	5,500	3,751	2,129	582
Design capacity (PE)	20,000	13,500	6,000	5,000	1,050
Flow rate (Q_{in})					
Influent flow rate (m^3/d)	3,088	2,444	1,064	474	102
Configuration					
Pumping of wastewater	4 pumps; H=15 m	No	5 pumps; H=8 m	4 pumps; H=5 m	No
Screen/sieving	fine screen	fine screen	fine screen + sieving	coarse screen + sieving	fine screen
Degritting	aerated degritting	aerated degritting	aerated degritting + scrapper	aerated degritting	aerated degritting
Pre-denitrification	V = 2840 m^3 +intermittent aeration (mixed + aerated)	V = 1620 m^3 +intermittent aeration (mixed + aerated)	V = 387 m^3 (mixed)+recirc. mixed liquor	V = 422 m^3 (mixed)	No
Oxidation			V = 600 m^3 (aerated)	V = 626 m^3 (aerated)	V = 180 m^3 (aerated)
Final settling	circular+scrapper	circular+scrapper	circular+scrapper	circular+scrapper	static
Tertiary filtration	No	No	No	Drum filtration	-
Sludge thickening	scrapper	Scrapper	static	scrapper	static
Aerobic stabilisation	aerated	Aerated	aerated	aerated	aerated

Sludge dewatering	centrifuge			filter belt press			centrifuge			filter belt press			No		
Removal	***In***	***Out***	***η***	***In***	***Out***	***η***	***In***	***Out***	***η***	***In***	***Out***	***η***	***In***	***Out***	***η***
COD (mg/L)	378	24	94%	344	9	97%	422	26	94%	539	21	96%	685	39	94%
BOD_5 (mg/L)	202	9	96%	133	5	96%	198	10	95%	261	7	97%	335	15	96%
TKN (mg/L)	59	2	97%	38	3.1	92%				58	2.1	96%	70	6.4	91%
NH_4-N (mg/L)							35	1	97%						
Total N (mg/L)	59	14	76%	39	5.8	85%	50	10	80%	59	5.8	90%	70	47	33%

2.2. Monitoring period

Data acquired continuously over 2 years was considered in the energy audits, with the aim to include possible seasonal differences in the energy consumption.

2.3. Inventory of the equipment for the energy audits

A detailed inventory of all the power-consuming devices installed in a WWTP is made on the basis of a complete energy audit. A number from 11 (in the smallest WWTP5) to 48 power-consuming devices (in the largest WWTP1) were assessed in the energy audits, consisting of:

- Electro-Mechanical units (EM-units), which include electrical motors of pumps, blowers, aerators, air compressors, mixers, scrappers, screen bars, presses, belts, filters, air-lifts, dewatering units, centrifuges, conveying equipment;
- Electrical Devices (ED-units), which consume electrical energy even though not directly involved in the movement and treatment of wastewater, such as artificial lighting, electrical heaters, hydrostatic tanks, ventilation fans, control panels and transformers.

Motorized valves or measuring/control instrumentation (such as pH meters or oxygen meters) were excluded from the energy audits because they were seen as responsible for negligible electric energy consumption. Emergency generators supplied with fuels were not considered in the energy audits due to the very few hours per year of operation.

2.4. Energy consumption calculations in the energy audits

The electric parameters measured on-site for each EM-unit and ED-unit operating with alternating current were the followings:

- supply voltage (V, expressed in Volt), which was 220 V (single-phase line) or 380 V (3-phase line) depending on the unit;
- electric current intensity (I, expressed in Ampere);
- power factor or load ($\cos\varphi$, adimensional).

The electric power (P, expressed in kW) was calculated according to the following expressions:

$$P[kW] = V \cdot I \cdot \cos\varphi / 1000 \qquad \text{(single-phase electric power)}$$

$$P[kW] = V \cdot I \cdot \sqrt{3} \cdot \cos\varphi / 1000 \qquad \text{(3-phase electric power)}$$

which give instantaneous values of P, because the current might vary over time. For example, a 10 kW blower equipped with a variable-frequency drive (inverter) may use an actual electric power that is significantly lower than 10 kW for most of the time and, in this case, a continuous measurement of I or P is mandatory. With the aim of taking into account this situation, but avoiding unnecessary efforts, in this study the equipment was divided in two categories:

- EM-units or ED-units with constant V and I: the instantaneous electric readings, acquired in each plant during a one-day campaign, were considered enough to obtain a constant value of P that is sufficiently accurate (P is not supposed to vary over time);

- EM-units with constant V and time-varying I: the measurements of I or P were carried out continuously with the installation of on-board ammeters or wattmeters. Continuous data was acquired every 5 min and stored with a remote monitoring.

The calculation of the electrical energy (EE) consumed by each EM-unit or ED-unit involves P and t (time when the device is running, expressed in h/d), according to the following formula:

$$EE\,[kWh/d] = P \cdot t$$

In this study, the time of operation was measured continuously by on-board hour-meters, and only occasionally estimated by the plant operators in the case of very small equipment.

2.5. Validation of the energy audit through a checksum

Firstly, the electrical energy consumed by each unit (EE_i) was summed up to calculate the "estimated" total energy consumption in the WWTP ($EE_{checksum}$):

$$EE_{checksum} = \sum_{i=1}^{n} EE_i$$

where i is an indexed variable and n is total number of EM-units and ED-units considered in the energy audit.

Secondly, the "actual" total energy consumption per day in the WWTP (EE_{bill}) was calculated from the on-board energy meter used by the local utility to calculate the energy bill.

Finally, the time-profile of $EE_{checksum}$ during one year was compared to that of EE_{bill} (example of WWTP1 in Figure 1) with the purpose of detecting errors which may have been introduced during the energy audit. The absolute error, calculated as follows, was used to compare the series (example of WWTP1 in Figure 1):

$$absolute\ error = \frac{|\mathrm{EE_{bill}} - \mathrm{EE_{checksum}}|}{\mathrm{EE_{bill}}} \cdot 100$$

In this work, a mean absolute error (MAE) lower than 10% between $EE_{checksum}$ and EE_{bill} was considered acceptable in our energy audits. Conversely, a MAE higher than 10% would suggest the presence of significant errors occurring in the acquisition of V, I, P or t, indicating the need for further work before validating the energy audit.

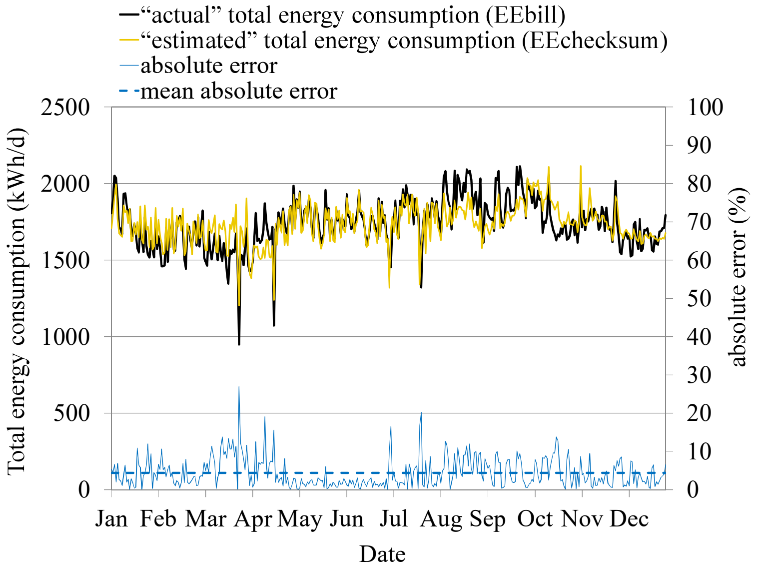

Figure 1. Comparison of total energy consumption ($EE_{checksum}$ and EE_{bill}) in the validation of the energy audit for the WWTP1. and absolute error

2.6. Key energy consumption indicators

The following energy consumption indicators (ECI), expressed as ratios between variables, were calculated for each stage:

- EE_{m3}: electric energy consumption per unit of volume of influent wastewater processed (expressed as kWh/m^3);
- EE_{BOD} or EE_{COD}: electric energy consumption per unit of removed load of BOD_5 or COD (expressed as kWh/kg$BOD_{5,rem}$ or kWh/kgCOD_{rem});
- $EE_{PE,served}$: electric energy consumption per year and per PE served (expressed as kWh PE_{served}^{-1} y^{-1});
- $EE_{PE,design}$: electric energy consumption per year and per PE assumed in the plant design (expressed as kWh PE_{design}^{-1} y^{-1}).

These indicators are intentionally simple, easy to understand and immediate to calculate, in order to exploit data commonly available in WWTPs without additional efforts.

2.7. Indicator of design capacity utilisation

The indicator of capacity utilization (CU) of a WWTP was calculated as the ratio between the mean actual influent COD load over the design capacity (expressed as COD load), according to the following expression:

$$CU = \frac{\text{mean influent COD load (kgCOD/d)}}{\text{design COD load (kgCOD/d)}}$$

which can be rewritten in the following alternative form:

$$CU = \frac{PE_{served}}{PE_{design}}$$

For a better comparison, the WWTPs analysed in this research have similar CU values.

3. RESULTS AND DISCUSSION

3.1. Different energy consumption indicators for different stage/process/units

The description of energy consumption in the stages of a WWTP in terms of percentages (for example 40% of total energy consumption in aeration or 20% in pumping) gives only a relative indication. Conversely, the use of ECIs defined in Section 2.6 (EE_{m3}, EE_{COD}, EE_{PE}) allows absolute comparisons among similar stages of different plants and benchmarking.

The suitability of each ECI was critically evaluated for each stage of the WWTPs. For instance, the indicator EE_{m3} is suitable for pumping stations and the other stages designed on the basis of hydraulic parameters, while it is not suitable for aeration or mixing in biological tanks. For example, we can consider two plants having the same PE, the same influent organic load and the same energy consumption for aeration of activated sludge, but the first has a higher flow rate due to infiltrations in the network and a lower influent concentration due to dilution. If using EE_{m3} (expressed in kWh/m^3), the aeration in the first plant would result (erroneously) more energy efficient, due to the higher volume of water treated. The use of EE_{m3} thus leads to an unreasonable result, because a higher amount of infiltrations would lead to an apparently better energy performance in aeration. Conversely, using the indicators EE_{COD} or EE_{PE}, the two plants will have the same energy efficiency, as expected.

In this paper the following four categories of stages were identified:

1) *hydraulic-based stages*: stages designed using hydraulic loads and typically equipped with pumps, screens, sieving, scrappers and filters, in which energy depends on the volume of the influent wastewater pumped/processed and thus EE_{m3} is more suitable;

2) *COD-based stages*: stages designed on the basis of the organic load applied or removed, such as oxidation tanks, where the use of EE_{COD} is more suitable. Although the use of aeration efficiency expressed as the oxygen transferred per unit of energy consumed (kgO_2/kWh) would be generally preferable in the oxidation stage, it requires oxygen transfer tests which appear laborious or onerous in small plants. Conversely, the amount of COD removed is a common and well-known datum in such plants;

3) *sludge-based stages*: stages for sludge movement and treatment, where energy consumption depends on the flow rate of excess sludge and the dry mass of solids; because this data is not always easily available in small WWTPs (flow meters are rarely installed in the sludge line), the use of a more general indicator such as EE_{COD} was here considered more feasible, considering that sludge production depends on the COD removed in the water line;

4) *building stages*: units generally located in buildings, such as artificial lighting, electrical heaters, control panels, transformers, etc., which depend on the size of the plant, and can thus be evaluated using $EE_{PE,design}$.

The values of ECIs calculated for each stage of the 5 WWTPs (mean, minimum and maximum values between plants) are summarised in Table 2, where the gray areas indicate the ECIs proposed as the most suitable in this paper.

The ECI values indicated in Table 2 refer to small WWTPs and thus they may be higher than the values expected for medium-large WWTPs, due to a scale effect which leads to a reduction of the specific energy consumption.

The five small WWTPs considered here have a design capacity utilization (CU) of 0.52±0.06, which means that approximately one half of the design capacity of these plants was not utilized under the mean load conditions. Low CU values are commonly found in small plants, where EM-units and ED-units are often oversized. Conversely, we observed an increase in CU to 0.8 (or above) for WWTPs with a design capacity around 100.000 AE (data not shown). Oversizing in small WWTPs results in higher ECIs than right-sized equipment, especially in the absence of variable-speed motors.

Table 2. Energy consumption indicators (ECIs) suitable for the various WWTP stages (level of suitability: ■ suitable; □ suitability may depend; × not suitable). ECIs calculated for the 5 small WWTPs are indicated (mean value, min-max values in the brackets). Grey areas indicate ECIs proposed as the most suitable in this paper.

				Energy consumption indicators (ECIs)		
	WWTP stage	EM-units and ED-units included in the stage	Load used for design	EE_{m3} (kWh/m^3)	EE_{COD} ($kWh/kgCOD_{rem}$)	$EE_{PE,design}$ ($kWh\ PE_{design}^{-1}\ y^{-1}$)
Hydraulic-based	Pumping of influent wastewater	Pumps	hydraulic	■ 0.054 (0.032-0.076)	× 0.133 (0.082-0.216)	□ 2.70 (1.83-4.31)
	Screen, sieving	Pumps, conveying equipments	hydraulic	■ 0.010 (0.004-0.017)	× 0.022 (0.011-0.049)	□ 0.47 (0.26-0.98)

	Degritting, deoiling	Pumps, scrappers, air-lifts, aerators	hydraulic	■ 0.027	× 0.068	□ 1.73
	Final settling	Scrappers, scum breakers	hydraulic	■ 0.012 (0.010-0.014)	× 0.031 (0.022-0.039)	□ 0.66 (0.39-0.90)
	Recirculation of mixed liquor	Pumps	hydraulic	■ 0.014	× 0.035	□ 0.83
	Recirculation of settled sludge	Pumps	hydraulic	■ 0.123 (0.030-0.226)	× 0.259 (0.076-0.351)	□ 5.44 (1.82-8.03)
	Tertiary filtration	Pumps, drive motors	hydraulic	■ 0.004	× 0.007	□ 0.125
COD-based stage	Denitrification (mixers used in pre-denitrification or intermittent aeration)	Mixers	-	× 0.072 (0.030-0.121)	□ 0.176 (0.076-0.249)	□ 3.58 (1.82-4.96)
	Oxidation	Blowers	organic	× 0.375 (0.068-0.799)	■ 0.753 (0.204-1.237)	□ 16.2 (4.69-28.3)
Sludge-based stage	Excess sludge pumping	Pumps	hydraulic	× 0.009 (0.002-0.017)	■ 0.027 (0.005-0.049)	□ 0.44 (0.11-1.14)
	Sludge thickening	Pumps, scrappers	excess sludge	× 0.006 (0.001-0.011)	■ 0.012 (0.004-0.020)	□ 0.27 (0.17-0.36)
	Aerobic stabilisation	Blowers	excess sludge	× 0.167 (0.009-0.530)	■ 0.304 (0.027-0.821)	□ 6.70 (0.53-18.8)
	Sludge dewatering	Pumps, drive motors	excess sludge	× 0.030 (0.009-0.073)	■ 0.068 (0.027-0.141)	□ 1.34 (0.62-2.53)
Building	Lighting	Internal/external lamps	-	× 0.044 (0.010-0.122)	× 0.083 (0.024-0.188)	■ 1.77 (0.58-4.31)
	Electrical devices	Control panels, transformers	-	× 0.064 (0.012-0.188)	× 0.112 (0.033-0.291)	■ 2.44 (0.66-6.67)

3.2. Energy consumption in hydraulic-based stages expressed as EE_{m3}

Stages designed on the basis of hydraulic parameters were compared using the indicator EE_{m3} (Figure 2A). The main results are the following:

1) Pumping of influent wastewater causes EE_{m3} of 0.054 kWh/m^3 on average, which depends on the hydraulic head; the highest EE_{m3} of 0.076 kWh/m^3 was found in presence of the highest hydraulic head (11 m) in WWTP1.
2) Screens or sievings have low values of EE_{m3}, as expected, with an average value of 0.010 kWh/m^3.
3) Final settling equipped with scrapper has similar EE_{m3} in all the WWTPs, with a mean of 0.012 kWh/m^3.
4) Recirculation of mixed liquor from oxidation/nitrification to the pre-denitrification is rarely used (0.014 kWh/m^3 in WWTP3). Intermittent aeration in one tank (WWTP1, WWTP2) or the only recirculation of settled sludge in pre-denitrification (WWTP4), were enough to obtain a total N removal of 76-90%, similar to WWTP3 (80%). In these cases, energy saving was obtained by avoiding mixed liquor recirculation.
5) Sludge recirculation from the final settler presented EE_{m3} values that were very different among WWTPs, varying of one order of magnitude from 0.030 kWh/m^3 in WWTP3 to 0.226 kWh/m^3 in WWTP5. Despite the high energy consumption, energy efficiency in sludge

recirculation is erroneously ignored in small WWTPs. It may surpass EE_{m3} for the pumping of influent wastewater, although the recirculated flow is similar to the influent flow and the hydraulic head in recirculation is usually lower. EE_{m3} increases much more when the WWTP capacity decreases. The best performance was obtained in WWTP3 (0.030 kWh/m^3) which can be assumed as a benchmark value in view of the optimization of the other plants.

6) Tertiary filtration was included only in the WWTP4: drum filtration caused a negligible EE_{m3} of 0.004 kWh/m^3.

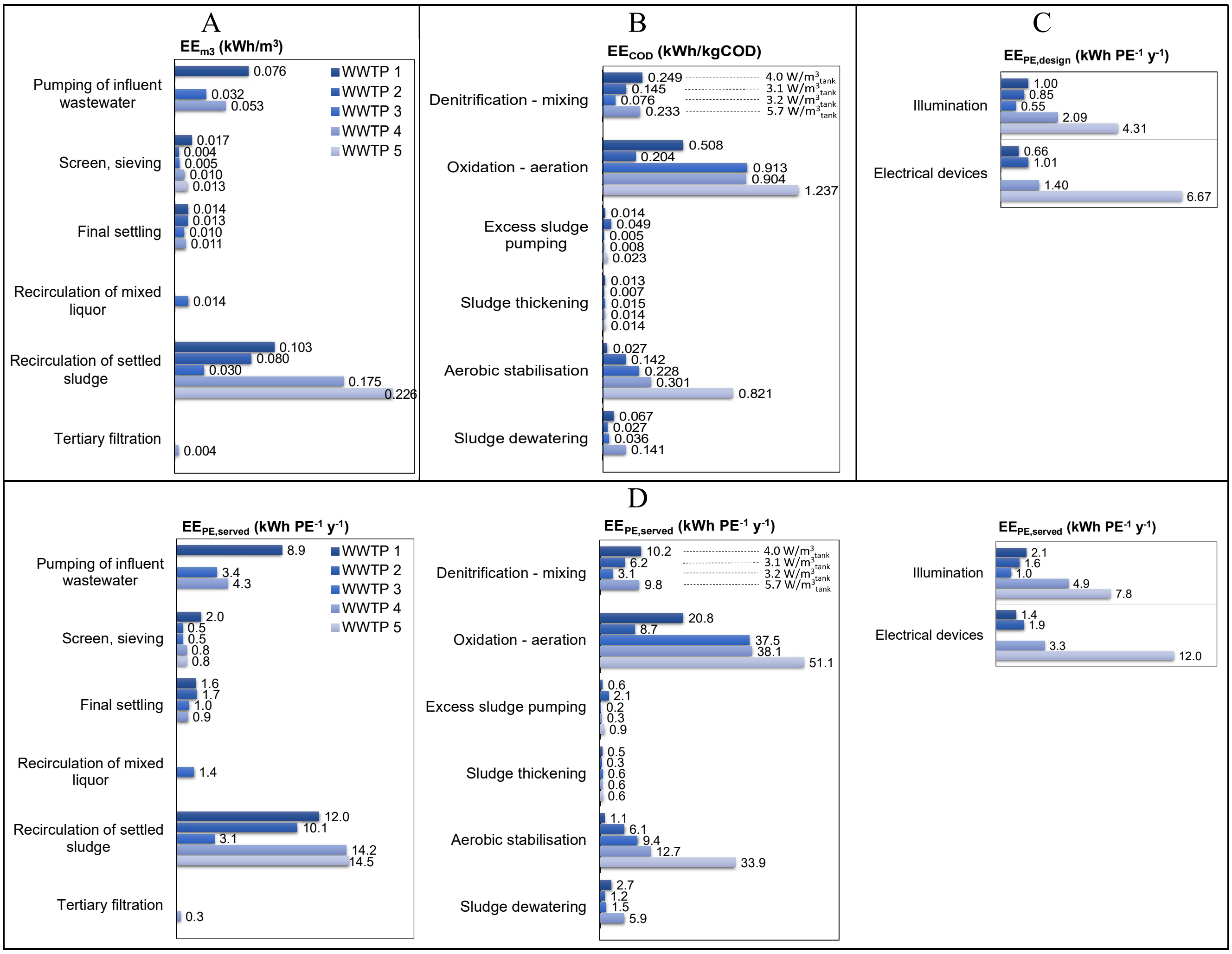

Figure 2. Comparison of ECIs between the stages of the small WWTPs: (A) indicator EE_{m3} for hydraulic-based stages; (B) indicator EE_{COD} for COD-based stages; (C) indicator $EE_{PE,design}$ for building stages; (D) indicator $EE_{PE,served}$ used to compare all the stages of the plant.

3.3. Energy consumption in COD-based stages and sludge treatments expressed as EE_{COD}

The indicator EE_{COD}, shown in Figure 2B, was used to compare the energy consumption in the biological reactors and in the sludge treatments. Results are summarized as follows.

1) In the plants implementing denitrification, the use of mixers caused quite variable EE_{COD} (0.076-0.249 kWh/kgCOD, mean 0.176 kWh/kgCOD). However, EE_{COD} is not the best energy indicator for mixing and it is preferable to use the watts per cubic meter of the mixed

tank (that is, the power of mixers divided by the tank volume, expressed in W/m^3). In this case the specific energy consumption becomes 3.1-4.0 W/m^3, except for WWTP4 where mixers consume 5.7 W/m^3 indicating space for energy saving. A value around 3 W/m^3 can be considered a benchmark value, even though further reduction could be pursued.

2) Intermittent aeration implemented in the oxidation tanks of WWTP1 and WWTP2 permitted a significant energy saving: EE_{COD} was 0.20-0.51 kWh/kgCOD in oxidation stages with intermittent aeration and 0.90-1.24 kWh/kgCOD with full aeration. The lowest EE_{COD} (0.20 kWh/kgCOD) was found in WWTP2, which coupled intermittent aeration and blowers with frequency inverters to enhance energy saving. The highest EE_{COD} found in WWTP5 was caused by a too-high dissolved oxygen concentration (DO, median of 4 mgO_2/L) in the oxidation tank and the absence of any DO controls and inverters. This situation is frequently observed in small plants which are equipped with oversized fixed capacity compressors or are lacking in controls and automation, because investments might be generally considered too expensive. In the small WWTP5, the reduction of energy consumption for aeration to one half could permit a saving of about 2,000 Euros per year. In this context the proposal of simple, inexpensive, but efficient controls based on DO would be advisable.

3) Extraction of excess sludge by pumping and its thickening is associated with very low EE_{COD} values (negligible in the overall balance).

4) The aerobic stabilization caused EE_{COD} values which strongly depend on the size of the plant: EE_{COD} passed from the lowest value 0.027 kWh/kgCOD in WWTP1 (9,727 PE served) to the highest value 0.821 kWh/kgCOD in WWTP5 (582 PE served). In some small plants, one or two blowers are connected to a distribution line of compressed air commonly built between the oxidation tank (which has a fixed hydraulic level) and the aerobic stabilization (which has a varying hydraulic level). The difference in hydraulic levels causes continuous differences in air pressure and difficulties in manually setting the desired air flow in the aerobic stabilisation. As an effort for energy saving in small plants, the installation of devices such as separate blowers, pressure meters, electrovalves, DO controls or intermittent aeration in the aerobic stabilization would be advisable.

5) Mechanical dewatering is not always present in small plants because it is not always economically sustainable. Although the installed power of centrifuges or filter belt presses is relevant, the time of operation is not so long in small plants, resulting in low values of EE_{COD} (0.03-0.14 kWh/kgCOD) without particular differences between the types of dewatering.

To complete the overview, the cost for final sludge disposal (total costs for thermal drying and reuse in agriculture, excluding transportation) in the WWTPs was approximately 400 Euro per ton of dry matter, which corresponds to about 4.8 Euro PE^{-1} y^{-1} (roughly equivalent to 32 kWh PE^{-1} y^{-1}).

3.4. Energy consumption of building stages expressed as $EE_{PE,design}$

Illumination and electrical devices, which depend on the size of the plant rather than the treated loads, were compared using the indicator $EE_{PE,design}$ (Figure 2C). The results are summarized as follows.

1) Artificial lighting showed the highest $EE_{PE,design}$ in the smallest WWTP (4.31 kWh PE^{-1} y^{-1}). The construction in a covered building does not necessarily cause higher values: WWTP2, which is completely covered, has a moderate $EE_{PE,design}$ of 1.57 kWh PE^{-1} y^{-1}.

2) Electrical devices, which include control panels and transformers, show lower $EE_{PE,design}$ for in increasing sizes of plants, indicating an evident scale effect.

Particular attention should be given to electrical heating in buildings. In some winter months, electrical heating systems, if left unchecked, could cause significant energy consumption (even of 10 kWh PE^{-1} y^{-1} in the smallest WWTP4 and WWTP5). In these cases, energy consumption could be considerably reduced by replacing manual controls with programmable thermostats, with small investments.

4. CONCLUSIONS - LESSONS LEARNED

The energy audits of five full-scale WWTPs, treating less than 10,000 PE, were performed to evaluate energy consumption, weaknesses and energy saving opportunities for a better energy efficiency in a small community's wastewater treatment plants. This study confirms once more that there are several opportunities for reducing energy consumption in WWTPs. The lessons learned are summarized as follows:

- most small WWTPs exploit only one half of their capacity (design capacity utilization of 0.52 on average) working with oversized equipment and leading to energy waste in absence of any controls, automation and inverters;
- although pumping and aeration are the most well-known energy intensive stages, recirculation of settled sludge and aerobic stabilisation have comparably high energy consumption, but are often erroneously ignored in small WWTPs; a way for energy savings in aerobic stabilisation is based on the optimisation of the air distribution;
- energy consumption in oxidation tanks (reduced to 0.20 kWh/kgCOD) was obtained with intermittent aeration and blowers equipped with frequency inverters; however, further simple, inexpensive, yet efficient controls based on DO would be advisable to pursue energy efficiency in small plants;
- denitrification obtained through intermittent aeration and without recirculation of mixed liquor was enough to obtain total N removal of 76-90%, while allowing a reduction in energy consumption;
- efficiency of mixing should be calculated per unit of tank volume, considering as enough an installed power of about 3 kW/m^3;
- operational adjustments using controls and automation in place of manual controls are mandatory to save unnecessary energy consumption in illumination and electrical heating.

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Figure 1

Figure 1. Comparison of total energy consumption ($EE_{checksum}$ and EE_{bill}) in the validation of the energy audit for the WWTP1. and absolute error

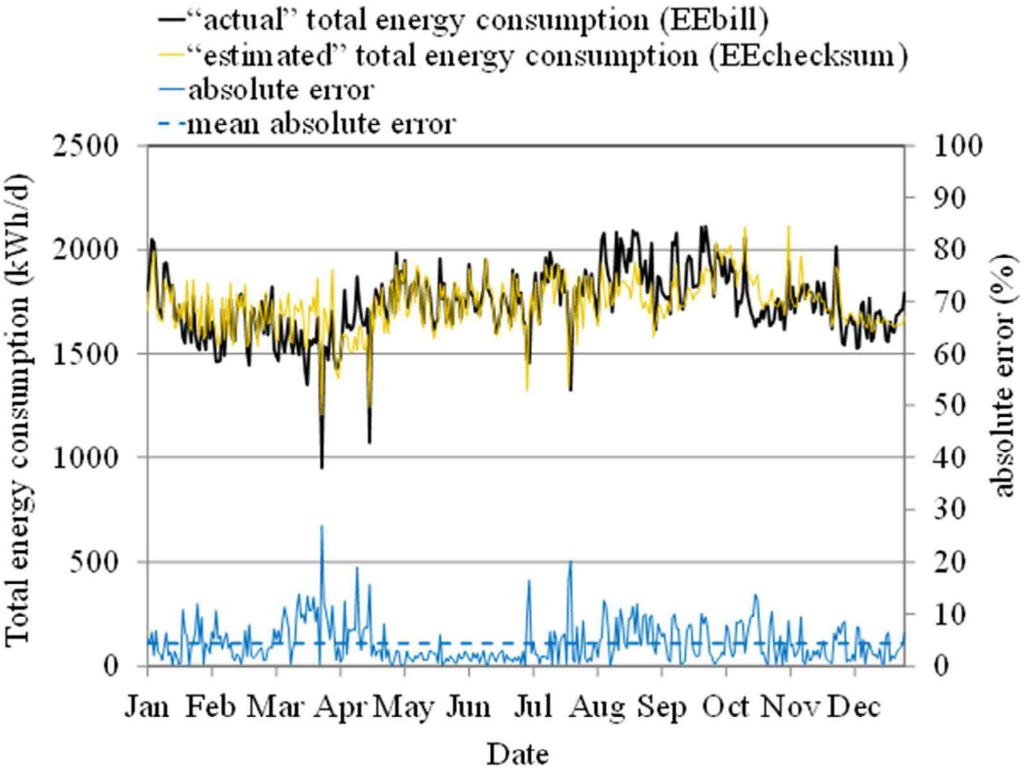

Figure 2

Figure 2. Comparison of ECIs between the stages of the small WWTPs:
(A) indicator EE_{m3} for hydraulic-based stages; (B) indicator EE_{COD} for COD-based stages;
(C) indicator $EE_{PE,design}$ for building stages; (D) indicator $EE_{PE,served}$ used to compare all the stages of the plant.