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A Comprehensive Derivation and Application of Reference Values for Benchmarking the Energy Performance of Activated Sludge Wastewater Treatment

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Abstract: Wastewater treatment plants (WWTPs) are facing challenges concerning the service's effectiveness and reliability, as well as the efficiency and sustainability of resource utilization, where energy represents one of the higher costs in activated sludge (AS) treatment. This paper presents the latest developments in the new energy performance indices (PXs) we have been developing for benchmarking, i.e., assessing and improving the performance of this widely used treatment. PXs compare the energy consumption with the energy requirements for the carbon and nitrogen removals needed for the plant's compliance with the discharge consents (the closer they are, the better the performance). PXs are computed by applying to the state variables a performance function that is defined by the reference values for excellent, acceptable, and unsatisfactory performance. This paper shows the rationale for selecting the state variables for the AS energy performance and the comprehensive derivation of the equations to determine the reference values for energy consumption, which incorporate the effect of key parameters (flows, concentrations, and operating conditions). Reference values for the operating conditions affecting the energy performance are also proposed. A sensitivity analysis identified the key parameters for improving the aeration performance: α, F, and SOTE for air diffusers, and α and N_0 for mechanical aerators. Fourteen Portuguese urban WWTPs (very diverse in size and inflows) were analyzed, and aeration (0.08–1.03 kWh/m^3) represented 25–80% of total energy consumption (0.23–1.30 kWh/m^3). The reference values for excellent performance were 0.23–0.39 kWh/m^3 (P25–P75) for AS systems with air diffusers and 0.33–0.80 kWh/m^3 for those with mechanical aerators. A comprehensive application in one WWTP (16–18 d solids retention time) showed the system's ability at identifying which operating conditions to adjust (to F/M ratio lower than 0.09 d^{-1} and decreasing aeration during the low season) to improve the energy performance/savings while maintaining the treatment's effectiveness and reliability.

Keywords: activated sludge treatment; air diffusers; energy performance; mechanical aerators; wastewater treatment plants

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1. Introduction

Wastewater services are currently facing challenges concerning the services' effectiveness and reliability, as well as the efficiency and sustainability of resource utilization. Additionally, consumers' demands on the quality of the service provided by the water utilities and their awareness of the importance of assuring the sustainable management of public water resources are increasing. Decarbonization and affordable prices for equitable access to safe and sustainable sanitation are among the top priorities. Wastewater treatment plants (WWTPs) are key elements of wastewater services, and energy usually represents the second largest part of the running costs of a WWTP [1–5].

The energy consumption in WWTPs depends on (i) treatment processes [6–10] and plant fingerprints, (ii) mass removed [11–13] and treated wastewater quality requirements (e.g., carbon or carbon and nutrients control, filtration, and disinfection), (iii) treated wastewater volume [6,10–19] and the percent of facility design capacity at which a plant is operating [10,17,20,21], (iv) operation and maintenance practices [22–24], and (v) plant aging [25,26].

Generally, aeration and pumping are the major energy uses in wastewater treatment [6,12,22,27,28]. For instance, in urban WWTPs with activated sludge (AS) systems, aeration may be responsible for 25% to 60% of the total energy consumption depending on the treatment type and season [2,9,23,29–33]. It is therefore crucial to develop guidance and strategies to increase the energy efficiency of the currently most widely used AS variants [2,6,10], as well as new AS variants developments [34].

According to ISO 50001:2011, energy performance is defined by measurable results related to energy efficiency, energy use (manner or kind of application of energy) and energy consumption, with the latter expressing the quantity of energy.

Yang et al. [16], Balmer and Hellström [35], and Foladori et al. [36] developed a framework of energy-performance indicators (PIs) of WWTPs, and the former also proposed benchmarks for influent flow pumping, aeration, and sludge processing.

We have also been developing a system integrating performance indicators (PIs) and performance indices (PXs) and the corresponding reference values [37]. The PIs address the overall performance of the plant, on an annual basis [5], and the PXs address the daily operational performance in terms of the treated water quality [38], the removal efficiency [39], and the operating conditions of each treatment step. Regarding the energy performance, the system integrates the PIs of unit energy consumption, production, net consumption, and costs of the whole plant [10,40], whereas the PXs address the energy consumption in each treatment step. The integrated use of PIs and PXs allows one to identify "why", "where", and "when" unsatisfactory, acceptable, good, and excellent performances were obtained. Actions for improving the energy performance may then be proposed. For both metrics, the reference values for judging the performance are the key elements for the assessment.

This paper presents the latest developments in the new metrics for benchmarking the energy performance of activated sludge systems, that is, the energy PXs, and the associated state variables and reference values. A comprehensive derivation of the equations proposed for determining the reference values considering the aspects affecting the energy consumption (e.g., pumping head, concentrations, detention time, and other operating conditions regularly monitored by the water utilities) is presented. A sensitivity analysis was conducted to identify the key parameters for the improvement measures in aeration, the major energy use in AS treatment. The PX system was applied to 14 activated sludge WWTPs in the scope of a iEQTA—Portuguese Initiative on Water Quality, Treatment, and Energy, and the aggregated results are presented. Its comprehensive application in one WWTP is also shown to illustrate the PX system's ability for assessing and improving the WWTP energy performance.

2. Performance Indices of Energy Efficiency and Related Operating Conditions

2.1. The General Framework Developed

The indices are obtained by applying a processing rule (performance function) that converts state-variable data, expressing the operational performance assessment aspects of the plant, into dimensionless performance indices. The developed PXs vary between 0 and 300, where PX 100 corresponds to the minimum acceptable performance and PX 300 to the excellent performance. This scale defines three performance levels: unsatisfactory performance in the [0, 100] range, acceptable in the [100, 200] range, and good performance in the [200, 300] range [38,39].

The performance functions are state-variable-specific and can be (Figure 1): (i) decreasing functions (type 1), e.g., for energy consumption; (ii) increasing functions (type 2), e.g., for removal efficiencies; or (iii) functions where good and excellent performance indices correspond to a range of values (type 3), mostly used for operating conditions, e.g., for hydraulic loading and detention time. To define the performance function, reference values are required for each level, namely, R_0, R_{100}, $R_{200,}$ and R_{300}.

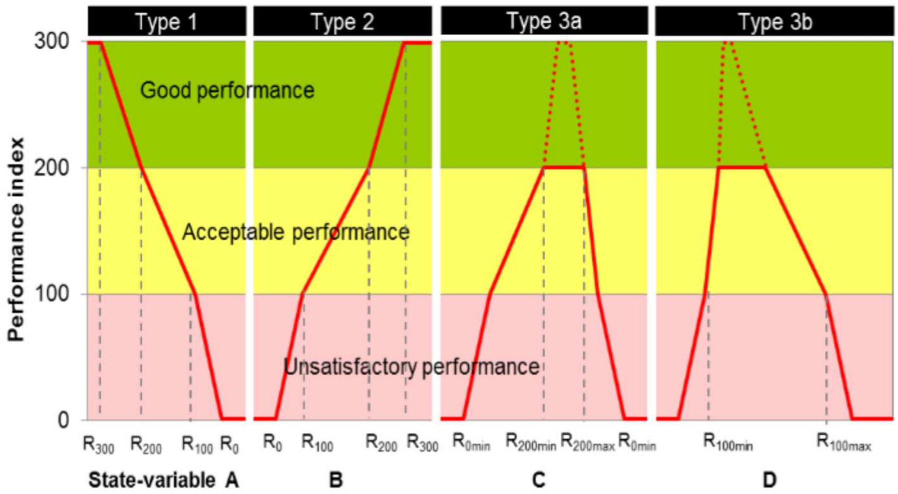

Figure 1. The types of performance functions to assess the operational performance of WWTPs.

The reference values are mostly based on legislation and literature values. For example, for type 3 performance functions: (i) minimum acceptable performance is limited between $R_{100\ min}$ and $R_{100\ max}$ and is based on the recommended literature range; (ii) performance is null (R_0) when it exceeds 25% tolerance (or other, customized) over the lower and the upper limits of the recommended range; and (iii) good performance ($R_{200\ min}$; $R_{200\ max}$) is based on a technical-economic balance, obtained from the literature (a broader range for R_{100} and a narrower range for R_{200}) and/or using a general criterion of cost-effectiveness illustrated in Figure 1:

- The R_{200} range is on the upper side of the R_{100} range if the higher the state variable, the lower the cost associated (type 3a, Figure 1), e.g., for hydraulic loading; half of the broader range, $(R_{100\ min} + R_{100\ max})/2$, is considered $R_{200\ min,}$ and $R_{200\ max}$ is obtained by applying a margin of tolerance to $R_{100\ max}$;
- The R_{200} range is on the lower side of R_{100} range if the lower the state variable, the lower the cost associated (type 3b, Figure 1), e.g., for detention time; half of the broader range, $(R_{100\ min} + R_{100\ max})/2$, is considered $R_{200\ max,}$ and $R_{200\ min}$ is obtained by applying a margin of tolerance to $R_{100\ min}$.

R_{300} depends on the specific operating conditions of each treatment facility. Thus, a WWTP wishing to extend these indices to the 200–300 range (good–excellent performance) must determine the optimal conditions of each treatment step, which represent the best balance between effectiveness (achievement of the target) and efficiency (minimum resource consumption).

For energy-performance indices, the reference values are often obtained through equations to incorporate the effect of key parameters, namely, inflow quantity and characteristics, pumping head, and operating conditions. Thus, the methodology herein proposed addresses the rational selection of energy state variables and the comprehensive derivation of the equations used to determine the reference values.

2.2. State-Variables Selected for Energy Performance of AS Systems

Figure 2 shows the portfolio of the state variables of energy performance proposed for AS systems taking into account the different uses of energy in the biological treatment and the operating conditions influencing the energy consumption.

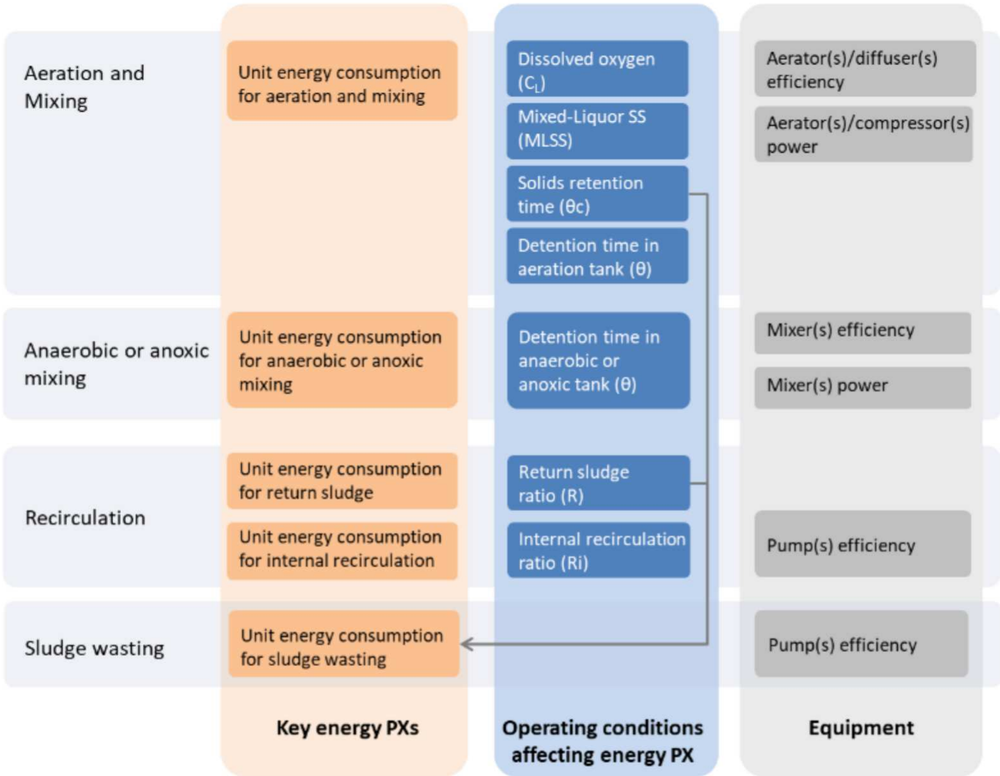

Figure 2. The state variables selected for assessing the energy performance of AS systems.

In activated sludge systems, energy is consumed for aeration and mixing, recirculation, and sludge wasting.

For unit energy consumption indices, a type 1 performance function is used, i.e., the higher the consumption, the lower the performance (Figure 1). A minimum energy consumption is needed for each use, but this is indirectly assessed by the complementary indices of the operating conditions, e.g., of the recirculation ratio, using type 3 functions. The equipment efficiency is not directly assessed, but the reference values of energy PXs take the typical efficiencies into consideration. Thus, the integrated analysis of energy PXs and operating conditions indices allows one to identify opportunities for improvement in daily operations or in equipment inefficiencies.

Unit energy consumption, Ev, expressed in Wh/m^3 of treated wastewater, is the key state-variable in each use and is given by Equation (1):

$$\mathrm{Ev} = \frac{\mathrm{P}}{\mathrm{Q}} \tag{1}$$

where

P = power (W);
Q = treated wastewater flowrate (m^3/h).

2.3. Reference Values Derived for the State Variables of AS Energy Performance

2.3.1. Aeration and Mixing

The reference values of unit energy consumption for aeration and mixing and for the complementary state-variables were comprehensively derived.

The unit energy consumption for aeration ($E_{V\ O2}$) is calculated based on the oxygen requirements for the biodegradation of carbonaceous material (R_{O2}, Equation (2)) and on the oxygen transferred under field conditions (N). When nitrification is to take place, the oxygen requirements include the oxygen required for oxidizing ammonia and nitrite to nitrate [41,42], as expressed in Equation (2):

$$R_{O2} = Q\ (S_0 - S) - 1.42\ P_{X,bio} + 4.57\ Q\ (NO_x) - 2.86\ Q\ (NOx - NO_{3out}) \tag{2}$$

where

R_{O2} = total oxygen required (g O_2/h);
S_0, S = influent and effluent soluble BOD_L, ultimate carbonaceous BOD (mg O_2/L);

BOD = biochemical oxygen demand;

1.42 = stoichiometric ratio (g O_2/g VSS);

VSS = volatile suspended solids (mg/L);

$P_{X,bio}$ = biomass as volatile suspended solids (g VSS/h):

$$P_{X,bio} = P_{X,VSS} - nbVSS\ Q \tag{3}$$

$P_{X,VSS}$ = the net waste activated sludge produced each day (g VSS/h):

$$P_{X,VSS} = \frac{VX}{24\ \theta_c} \tag{4}$$

V = reactor volume (m^3);
X = mixed-liquor VSS (mg/L);
θ_c = solids retention time (d);
nbVSS = nonbiodegradable VSS in influent (mg/L);
4.33 and 2.86 = stoichiometric ratios (g O_2/g N);
NO_x = amount of NO_3-N produced from the nitrification of NH_4-N (mg N/L):

$$NO_x = Nt_{in} - NH_{4out} - 0.12\ P_{Xbio}/Q \tag{5}$$

Nt_{in} = influent N concentration (mg N/L);
NH_{4out} = effluent ammonia concentration (mg N/L);
0.12 = stoichiometric ratio (g N/g VSS);
NO_{3out} = effluent nitrate concentration (mg N/L).

By disregarding the oxygen fractions related to the (low) allowable BOD in the WWTP discharge (an assumption that overestimates the oxygen requirements), considering S_0 = 1.6 BOD_5 (the concentration of total 5-d biochemical oxygen demand influent to the reactor, in mg/L), and substituting Equations (3), (4) and (5) in Equation (2), one obtains:

$$R_{O2} = Q\ 1.6\ BOD_5 + 1.71\ Q\ (Nt_{in} - NH_{4out}) + 2.86\ Q\ NO_{3out} - 1.625 \left(\frac{VX}{24\ \theta_c} - nbVSS\ Q\right) \tag{6}$$

Dividing R_{O2} (g O_2/h, Equation (6)) by the oxygen transferred under field conditions (N, kg O_2/(kWh)) yields P (W), which is substituted in Equation (1) to obtain the unit energy consumption for aeration (Ev_{O2}, Wh/m^3):

$$Ev_{O2} = \frac{1.6\ BOD_5 + 1.71\ (Nt_{in} - NH_{4out}) + 2.86\ NO_{3out} - 1.625 \left(\frac{X\theta}{24\ \theta_c} - nbVSS\right)}{N} \tag{7}$$

where

θ = hydraulic detention time in aeration tank (h);

$$\theta = V/Q \tag{8}$$

For mechanical aerators, N may be computed from [40]:

$$N_m = N_0 \left(\frac{\beta C_{walt} - C_L}{C_{s,\,20}} \right) 1.024^{T-20} \alpha \tag{9}$$

where

N_{m} = N for mechanical aerators (kg O_2/(kWh));
N_0 = oxygen transferred to water at 20°C and zero-dissolved oxygen (kg O_2/(kWh)), an equipment-specific value;
β = salinity-surface tension correction factor (typically 0.9-0.99 [9]);
α = oxygen transfer correction factor for water (typically 0.4-0.8 [9]);
C_L = operating oxygen concentration (mg/L);
C_{walt} = oxygen saturation concentration = C_sF_a;
C_s = oxygen saturation concentration at sea level with temperature (T, °C);
F_a = oxygen solubility correction factor for altitude (h, m) = 1 −0.0001 h;
$C_{s,20}$ = C_s at 20 °C = 9.08 mg/L [41].

For air diffusers, N is based on the power requirements of each blower (P_w, kW):

$$N_d = AOR/P_w \tag{10}$$

$$AOR = SOR \left(\frac{\beta C_{walt} - C_L}{C_{s,\,20}} \right) 1.024^{T-20} \alpha\, F \tag{11}$$

where

N_{d} = N for air diffusers (kg O_2/(kWh));
AOR = actual oxygen transfer rate (under field conditions) (kg O_2/h) (Equation (11) adapted from [9]);
SOR = standard oxygen transfer rate (under standard conditions, 20 °C, 1 atm, 0 mg O_2/L) (kg O_2/h):

$$SOR = 835.2\ w\ SOTE \tag{12}$$

835.2 is the conversion factor of w units, from kg air/s to kg O_2/h (0.232 (kg O_2/ kg air) multiplied by 3600 (s/h));
w = weight of air flow (kg air/s);
SOTE = standard oxygen transfer efficiency (unitless), equipment/specific value
F = fouling factor (typically 0.65–0.90 [41,42]);
P_w = power requirements of each blower (kW) [42]:

$$P_w = \frac{wRT}{8.199\ e} \left[\left(\frac{p_2}{p_1} \right)^{0.283} - 1 \right] \tag{13}$$

R = universal gas constant for air (8.314 J/(mol K));
T = absolute inlet temperature (K);
8.199 = conversion factor (g/mol) = 28.97 n, with n = (k − 1)/k, where k is the specific heat ratio. For single-stage centrifugal blower power calculations, a value of 1.395 is used for k for dry air and n = 0.283;
e = compressor efficiency (typically 0.7–0.9 [40,41]);
p_1, p_2 = absolute inlet and outlet pressure, respectively (kPa).

Substituting Equations (11)–(13) in Equation (10), results in the following (with T in °C):

$$N_d = \frac{90.7\, e\, (\beta C_{walt} - C_L) \times 1.024^{\,T-20} \alpha\, F\, SOTE}{(T + 273.15)\left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right]} \tag{14}$$

To ensure a complete mix flow regime of the mixed liquor, the typical power requirements vary from 20 to 40 kW/10^3 m^3 for mechanical aerators and, in the case of diffusors, mixing rates of 10–15 m^3 air/(10^3 m^3 water.min) are generally used [41,42].

For mechanical aerators, the unit energy requirements for mixing ($Ev_{mix\ m}$, Wh/m^3) depend on the detention time (θ, h) in the aerobic zone:

$$Ev_{mix\ m} = \frac{M_m\, V}{Q} = M\, \theta \tag{15}$$

where

M_m = specific power requirements in mechanical aeration (kW/10^3 m^3).

For diffused-air systems, the specific power requirements for mixing (M_d, m^3 air/(10^3 m^3 water.min)) may be computed as:

$$M_d = \frac{60\, w}{\rho\, V \times 10^{-3}} \tag{16}$$

where

ρ = density of air (kg/m^3) = 353.07/T, with T in K.

Substituting ρ in Equation (16) and rearranging in terms of w, one obtains:

$$w = \frac{5.88 \times 10^{-3}\, M_d V}{T} \tag{17}$$

Substituting Equation (17) in Equation (13) and considering Equation (1) yields the unit energy requirements for mixing in diffused-air systems ($Ev_{mix\ m}$, Wh/m^3):

$$Ev_{mix\ d} = \frac{5.96\, M_d\, \theta}{e}\left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right] \tag{18}$$

The energy for aeration must satisfy the oxygen requirements (Ev_{O2}) and must provide oxic conditions throughout the reactor, expressed by the dissolved oxygen concentration, while ensuring perfect mixing conditions. The reference values proposed in Table 1 reflect this issue: R_{300} is is the highest value between Ev_{O2} and the typical minimum for Ev_{mix}; R_{100} is the highest value between 1.5 Ev_{O2} (i.e., allowing a 50% tolerance) and the average value of the typical range for Ev_{mix}; and R_0 is the highest value between a 100% tolerance to Ev_{O2} and the typical maximum for Ev_{mix}. Figure 3 summarizes the stepwise procedure developed to obtain the reference values (R_0 to R_{300}) to build a performance function.

Table 1. The reference values of energy consumption for aeration in AS systems.

Assumptions	Ev_{O2} Reference Values (Wh/m^3)	
Mechanical Aerators		
$R_{300} \leftrightarrow Ev_{O2}$ (Equation (7)) or Ev_{mix} m Equation (15) with $M_m = 20\ W/m^3$ (the highest value)	R_{300} ●	$\frac{1.6\ BOD_5 + 1.71\ (Nt_{in} - NH_{4out}) + 2.86\ NO_{3out} - 1.625\ \left(\frac{X\theta}{24\ \theta_c} - nbVSS\right)}{N}$ or 20θ, the highest
$R_{100} \leftrightarrow 1.5\ Ev_{O2}$ or $Ev_{mix\ m}$ (Equation (15)) with $M_m = 30\ W/m^3$ (the highest value)	R_{100} ●	1.5 R_{300} or 30 θ, the highest
$R_0 \leftrightarrow 2\ Ev_{O2}$ or $Ev_{mix\ m}$ (Equation (15)) with $M_m = 40\ W/m^3$ (the highest value)	R_0 ●	2 R_{300} or 40 θ, the highest
Air diffusers		
$R_{300} \leftrightarrow Ev_{O2}$ (Equation (7)) or Ev_{mix} d Equation (18) with $M_d = 10\ m^3/(10\ m^3.min)$ and e = 0.9 (the highest value)	R_{300} ●	$\frac{1.6\ BOD_5 + 1.71\ (Nt_{in} - NH_{4out}) + 2.86\ NO_{3out} - 1.625\ \left(\frac{X\theta}{24\ \theta_c} - nbVSS\right)}{N}$ or $66.25\ \theta\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right]$, the highest
$R_{100} \leftrightarrow 1.5\ Ev_{O2}$ or $Ev_{mix\ d}$ (Equation (18)) with $M_d = 12.5\ m^3/(10^3\ m^3.min)$ and e = 0.9 (the highest value)	R_{100} ●	$1.5\ R_{300}$ or $82.81\ \theta\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right]$, the highest
$R_0 \leftrightarrow 2\ Ev_{O2}$ or $Ev_{mix\ d}$ (Equation (18) with $M_d = 15\ m^3\ /(10^3\ m^3.min)$ and e = 0.7 (the highest value)	R_0 ●	$2\ R_{300}$ or $127.77\ \theta\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right]$, the highest

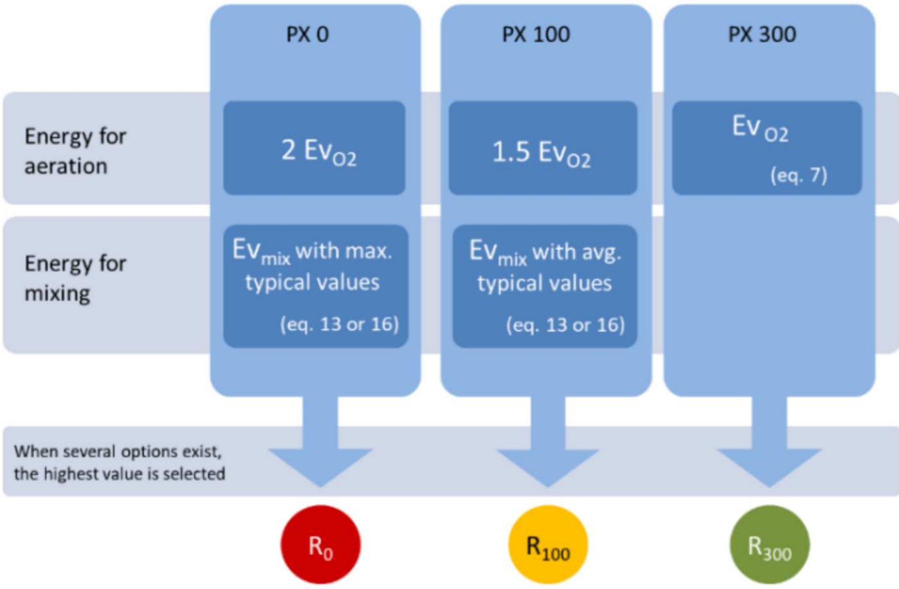

Figure 3. The stepwise procedure to obtain the reference values (R_0 to R_{300}) of the performance function of energy consumption for aeration and mixing in AS systems.

In practice, aeration is controlled by the dissolved oxygen concentration in the reactor (C_L) and it is typically maintained at about 1–2 mg/L [41–43] or 0.5–2 mg/L [9]. The reference values shown in Table 2 were therefore established based on these ranges.

Table 2. The reference values for the dissolved oxygen concentration in the AS reactor.

C_L Reference Values (mg/L)		Typical Values (mg/L)
R_{200} (min; max) ●	0.8; 1	0.5–2 [9]; 1–2 [41–43]; 2–3 [44]
R_{100} (min; max) ●	0.5; 2	
R_0 (min; max) ●	0.3; 2.5	

The reference values proposed for the operating conditions influencing the energy consumption in aeration and mixing, namely, the mixed-liquor suspended solids (MLSS) (Table 3), the solids retention time (Table 4), and detention time (Table 5), are based on the literature values for urban WWTPs and are AS-type specific.

Table 3. The reference values for MLSS in AS systems.

Activated Sludge	MLSS Reference Values (mg/L)			Typical Values (mg/L)
AS-Type	**R_{200} (min; max)** ●	**R_{100} (min; max)** ●	**R_0 (min; max)** ●	
Complete mix	3000; 4000	1500; 6000	1200; 7000	3000–6000 [44,45] 2000–3000 [43] 1500–4000 [41,42]
Conventional plug flow	1500; 2500	1000; 3000	800; 3600	1500–3000 [44,45] 2000–3000 [43] 1000–3000 [41,42,46]
Extended aeration	3000; 5000	2000; 6000	1600; 7000	3000–6000 [44,45] 2000–5000 [41,42] 3000–5000 [46] 2000–6000 [43]
Oxidation ditch (C removal)	3500; 5000	3000; 6000	2400; 7000	3000–6000 [44] 3000–5000 [41,42] 2000–6000 [43]
Oxidation ditch (C+N removal)	2500; 3500	2000; 4000	1600; 4800	2000–4000 [41,42,47] 2000–6000 [43]
Anoxic/Aerobic (MLE)	3200; 3800	3000; 4000	2400; 4800	3000–4000 [41,42,47]
Bardenpho (4-stage)	3200; 3800	3000; 4000	2400; 4800	3000–4000 [41,42,47]
Bardenpho (5-stage)	3000; 4000	2000; 5000	1600; 6000	3000–4000 [41,42,47] 2000–5000 [44]
A/O (Anaerobic/Aerobic)	3200; 3800	3000; 4000	2400; 4800	3000–4000 [41,42,47]
A2/O	3000; 3500	2000; 4000	1600; 4800	2000–4000 [44] 3000–4000 [41,42,47]
UCT	3000; 4000	2000; 5000	1600; 6000	2000–5000 [44] 3000–4000 [41,42,47]
VIP	2000; 3000	1500; 4000	1200; 4800	1500–3000 [44] 2000–4000 [41,42,47]

Table 4. The reference values for the solids retention time in AS systems.

Activated Sludge	θ_c Reference Values (d)			Typical Values (d)
AS-Type	**R_{200} (min; max)** ●	**R_{100} (min; max)** ●	**R_0 (min; max)** ●	
Complete mix	5; 8	3; 15	2.5; 18	5–15 [44] 3–15 [41,42] 3–10 [43] 4–15 [45]
Conventional plug flow	5; 8	3; 15	2.5; 18	5–15 [44,47] 3–15 [41,42] 3–10 [43] 4–15 [45]
Extended aeration	22; 30	20; 40	15; 50	20–30 [43–45,47] 20–40 [41,42]
Oxidation ditch (C removal)	20; 25	15; 30	12; 35	20–30 [43,44,48] 15–30 [41,42] 20 [47]
Oxidation ditch (C+N removal)	22; 25	20; 30	15; 35	20–30 [41,42,47]
Anoxic/Aerobic (MLE)	9; 15	8; 20	7; 25	7–20 [41,42,47]
Bardenpho (4-stage)	11; 15	10; 20	8; 25	10–20 [41,42,47]
Bardenpho (5-stage)	12; 20	10; 30	8; 40	10–20 [41,42,47] 10–40 [44]
A/O (Anaerobic/Aerobic)	2.2; 4	2; 5	1.8; 6	2–5 [41,42,47]
A2/O	8; 20	4; 27	3; 34	5–25 [41,42,47] 4–27 [44]
UCT	12.5; 25	10; 30	7.5; 35	10–25 [41,42,47] 10–30 [44]
VIP	8; 9	5; 10	4; 12	5–10 [41,42,44,47]

Table 5. The reference values for the hydraulic detention time in AS systems.

Activated Sludge		**θ Reference Values (h)**			**Typical Values (h)**
AS-Type		**R_{200} (min; max)** ● (green)	**R_{100} (min; max)** ● (yellow)	**R_0 (min; max)** ● (red)	
Complete mix		3.2; 4	3; 5	2.5; 6	3–5 [41,42,44,45] 5–14 [43]
Conventional plug flow		5; 6	4; 8	3; 10	4–8 [41,42,44,45] 5–14 [43]
Extended aeration		20; 27	18; 36	14; 45	20–30 [41–43] 18–24 [45] 18–36 [44] 24 [46]
Oxidation ditch (C removal)		18; 27	15; 36	12; 45	18–36 [44] 15–30 [41,42] 20–30 [43] 18 [47]
Oxidation ditch (C+N removal)		20; 27	18; 36	14; 45	18–30 [41,42,47] 20–30 [43]
MLE	anoxic zone	1.3; 2.2	1; 3	0.7; 3.8	1–3 [41,42,47]
	aerobic zone	5; 9	4; 12	3; 15	4–12 [41,42,47]
Bardenpho 4	1st anoxic zone	1.3; 2.2	1; 3	0.7; 3.8	1–3 [41,42,47]
	1st aerobic zone	5; 9	4; 12	3; 15	4–12 [41,42,47]
	2nd anoxic zone	2.3; 3	2; 4	1.7; 5	2–4 [41,42,47]
	2nd aerobic zone	0.6; 0.8	0.5; 1	0.4; 1.2	0.5–1 [41,42,47]
Bardenpho 5	anaerobic zone	1; 1.5	0.5; 2	0.4; 2.5	0.5–1.5 [41,42,47] 1–2 [44]
	1st anoxic zone	2; 3	1; 4	0.7; 5	1–3 [41,42,47] 2–4 [44]
	1st aerobic zone	5; 9	4; 12	3; 15	4–12 [41,42,44,47]
	2nd anoxic zone	2.3; 3	2; 4	1.7; 5	2–4 [41,42,44,47]
A/O	2nd aerobic zone	0.6; 0.8	0.5; 1	0.4; 1.2	0.5–1 [41,42,44,47]
	anaerobic zone	0.7; 1.1	0.5; 1.5	0.3; 1.9	0.5–1.5 [41,42,47]
	aerobic zone	1.3; 2.2	1; 3	0.7; 3.8	1–3 [41,42,47]
A2/O	anaerobic zone	0.7; 1.1	0.5; 1.5	0.3; 1.9	0.5–1.5 [41,42,44,47]
	anoxic zone	0.6; 0.8	0.5; 1	0.4; 1.2	0.5–1 [41,42,44,47]
	aerobic zone	4; 6	3.5; 8	3; 10	3.5–6 [44] 4–8 [41,42,47]
UCT	anaerobic zone	1.2; 1.5	1; 2	0.8; 2.5	1–2 [41,42,44,47]
	anoxic zone	2.3; 3	2; 4	1.7; 5	2–4 [41,42,44,47]
	aerobic zone	5; 9	4; 12	3; 15	4–12 [41,42,44,47]
VIP	anaerobic zone	1.2; 1.5	1; 2	0.8; 2.5	1–2 [41,42,44,47]
	anoxic zone	1.2; 1.5	1; 2	0.8; 2.5	1–2 [41,42,44,47]
	aerobic zone	3; 4	2.5; 6	2; 8	2.5–4 [44] 4–6 [41,42,47]

2.3.2. Anoxic and/or Anaerobic Mixing

The anoxic and/or anaerobic zones of the AS systems have no aeration but require mixing with typical power requirements of 8–13 kW/10^3 m^3 [41,42]. Similarly to aeration (Equation (15)), the unit energy requirements for mixing depend on the detention time (θ) in the anoxic and anaerobic zone(s) (Table 6).

Table 6. The reference values of energy consumption for mixing in the AS anoxic and anaerobic zones.

Assumptions	$Ev_{mix\ m}$ Reference Values (Wh/m^3), (θ in h)	
$R_{300} \leftrightarrow Ev_{mix\ m}$ (Equation (15)) with M = 8 W/m^3	R_{300} ●	8 θ
$R_{100} \leftrightarrow Ev_{mix\ m}$ (Equation (15)) with M = 13 W/m^3	R_{100} ●	13 θ
$R_0 \leftrightarrow Ev_{mix\ m}$ (Equation (15)) with M = 1.25 × 13 W/m^3	R_0 ●	16.3 θ

2.3.3. Recirculation

In AS systems, energy is consumed for pumping the return sludge from the secondary clarifier to the reactor. The reference values of the return sludge ratio were established based on the typical ranges (Table 7), and the performance functions are type 3b, i.e., the lower the state-variable, the lower the cost.

Table 7. The reference values for the return sludge ratio in the AS systems.

Recirculation	R reference Values (unitless)			Typical Values
AS-Type	**R_{200} (min; max)** ●	**R_{100} (min; max)** ●	**R_0 (min; max)** ●	
Complete mix	0.3; 0.8	0.25; 1	0.2; 1.2	0.25–1 [41,42,44,45]
Conventional plug flow	0.3; 0.5	0.25; 0.75	0.2; 0.9	0.25–0.5 [44,45] 0.25–0.75 [41,42]
Extended aeration	0.75; 1.5	0.5; 2	0.4; 2.4	0.25–2 [44] 0.25–1.5 [41,42,46] 0.75–1.5 [45]
Oxidation ditch (C removal)	0.75; 1.5	0.5; 2	0.4; 2.4	0.5–2 [44] 0.75–1.5 [41,42]
Oxidation ditch (C+N removal)	0.6; 0.8	0.5; 1	0.4; 1.2	0.5–1 [41,42,47]
Anoxic/Aerobic (MLE)	0.6; 0.8	0.5; 1	0.4; 1.2	0.5–1 [41,42,47]
Bardenpho (4-stage)	0.6; 0.8	0.5; 1	0.4; 1.2	0.5–1 [41,42]
Bardenpho (5-stage)	0.8; 0.9	0.5; 1	0.4; 1.2	0.5–1 [41,42] 0.8–1 [44]
A/O	0.3; 0.8	0.25; 1	0.2; 1.2	0.5–1 [41,42,47]
A2/O	0.25; 0.5	0.2; 1	0.16; 1.2	0.2–0.5 [44] 0.25–1 [41,42,47]
UCT	0.82; 0.9	0.8; 1	0.7; 1.2	0.8–1 [41,42,44,47]
VIP	0.8; 0.9	0.5; 1	0.4; 1.2	0.5–1 [44] 0.8–1 [41,42,47]

The unit energy consumption for pumping depends on the hydraulic power (P, W):

$$P = \frac{\gamma\ Q_p\ \Delta H}{3600\ \eta} \quad (19)$$

where

Q_p = pumping flowrate (m^3/h);
ΔH = pumping head (m);
η = pump efficiency (unitless);
γ = specific weight of secondary sludge (N/m^3);
$\gamma/3600$ ~ 2.8, within 5–35 °C, γ for water varies in the 9800–9742 N/m^3 range; this γ variation does not significantly impact the value of $\gamma/3600$, which will vary from 2.71 to 2.72 for water and will be approximately 2.8 for secondary sludge, considering its specific gravity 1.015 [41,42].

Thus, Equation (19) is simplified, and substituting it in Equation (1) results in the general equation of the unit energy consumption for pumping (Ev_p, Wh/m^3):

$$Ev_p = \frac{Q_p}{Q}\frac{2.8\ \Delta H}{\eta} \tag{20}$$

For sludge recirculation, the pumping flowrate (Q_p) corresponds to the return sludge flowrate (Q_r, m^3/h) and the return sludge pumping energy (Ev_R, Wh/m^3) depends on the recirculation ratio, the pumping head, and the pump efficiency:

$$Ev_R = R\frac{2.8\ \Delta H}{\eta} \tag{21}$$

where

R = return sludge ratio = Q_r/Q (unitless)

The pumping head includes the total head losses (continuous and local) plus the geometric elevation. The reference values of energy consumption for return sludge (Table 8) are obtained by considering, in Equation (21), the reference values of R (AS-type specific) proposed in Table 7 and a pump efficiency of 50% for excellent (R_{300}) performance, 30% for the minimum acceptable (R_{100}) performance, and 20% for unsatisfactory performance (R_0) (adapted from ERSAR reference values [49]).

Table 8. The reference values of the energy consumption for the return sludge in the AS systems.

<table>
<tr><th>Assumptions</th><th colspan="4">Ev_R Reference Values (Wh/m^3)</th></tr>
<tr><td rowspan="12">$R_{300} \leftrightarrow Ev_R$ (Equation (21)) with R = R_{100} min of R (Table 7) and η = 0.5

$R_{100} \leftrightarrow Ev_R$ (Equation (21)) with R = R_{100} max of R (Table 7) and η = 0.3

$R_0 \leftrightarrow Ev_R$ (Equation (21)) with R = R_0 max of R (Table 7) and η = 0.2</td><td>AS-type</td><td>R_{300} ●</td><td>R_{100} ●</td><td>R_0 ●</td></tr>
<tr><td>Conv. plug flow</td><td rowspan="3">1.4 ΔH</td><td>7.0 ΔH</td><td>12.6 ΔH</td></tr>
<tr><td>Complete mix</td><td rowspan="9">9.3 ΔH</td><td rowspan="9">16.8 ΔH</td></tr>
<tr><td>A/O</td></tr>
<tr><td>A2/O</td><td>1.1 ΔH</td></tr>
<tr><td>OD (C + N)</td><td rowspan="5">2.8 ΔH</td></tr>
<tr><td>MLE</td></tr>
<tr><td>Bardenpho 4</td></tr>
<tr><td>Bardenpho 5</td></tr>
<tr><td>VIP</td></tr>
<tr><td>UCT</td><td>4.5 ΔH</td></tr>
<tr><td>OD (C)
Ext. aeration</td><td>2.8 ΔH</td><td>18.7 ΔH</td><td>33.6 ΔH</td></tr>
</table>

Most types of activated sludge systems for nitrogen and for nitrogen and phosphorus removal include internal recirculation (Ri) for anoxic and anaerobic zones [41,42,44,47]. Ri reference values were thus also proposed based on the different ranges found in the literature and taking into account the process cost-effectiveness (Table 9). The reference values of the unit energy requirements for internal recirculation (Table 10) were defined as for return sludge.

Table 9. The reference values for the internal recirculation in AS systems.

Internal Recirculation		R_i Reference Values (unitless)			Typical Values
AS-Type		**R_{200} (min; max)** 🟢	**R_{100} (min; max)** 🟡	**R_0 (min; max)** 🔴	
Anoxic/Aerobic (MLE)		1.2; 1.6	1; 2	0.8; 2.4	1–2 [41,42,47]
Bardenpho 4		2.4; 3.2	2; 4	1.6; 4.8	2–4 [41,42]
Bardenpho 5		3.5; 4.5	2; 6	1.6; 7.2	2–4 [41,42] 4–6 [44]
A2/O		1.2; 3	1; 4	0.8; 4.8	1–3 [44] 1–4 [41,42,47]
UCT	from anoxic zone	2; 4	1; 6	0.8; 7	1–6 [44] 2–4 [41,42,47]
	from aerobic zone	0.8; 1.2	0.5; 3	0.4; 3.6	0.5–1 [44] 1–3 [41,42,47]
VIP	from anoxic zone	1.5; 2.5	1; 4	0.8; 4.8	2–4 [44] 1–2 [41,42,47]
	from aerobic zone	1.2; 2.4	1; 3	0.8; 3.6	1–3 [41,42,47]

Table 10. The reference values of the energy consumption for the internal recirculation in AS systems.

<table>
<tr><th>Internal Recirculation</th><th colspan="3">E_V Reference Values (Wh/m^3)</th></tr>
<tr><th>AS-Type</th><th>R_{200} 🟢</th><th>R_{100} 🟡</th><th>R_0 🔴</th></tr>
<tr><td>UCT aerobic</td><td>2.8 ΔH</td><td rowspan="2">28 ΔH</td><td rowspan="2">50 ΔH</td></tr>
<tr><td>VIP aerobic</td><td rowspan="4">5.6 ΔH</td></tr>
<tr><td>MLE</td><td>19 ΔH</td><td>34 ΔH</td></tr>
<tr><td>VIP anoxic</td><td rowspan="3">37 ΔH</td><td rowspan="3">67 ΔH</td></tr>
<tr><td>A2O</td></tr>
<tr><td>Bardenpho 4</td><td rowspan="2">11.2 ΔH</td></tr>
<tr><td>Bardenpho 5</td><td rowspan="2">56 ΔH</td><td rowspan="2">98 ΔH</td></tr>
<tr><td>UCT anoxic</td><td>5.6 ΔH</td></tr>
</table>

2.3.4. Sludge Wasting

The AS systems also consume energy for sludge wasting, and the consumption is proportional to the pumping flowrate. If sludge wasting is conducted from the return sludge line and a well-clarified effluent is produced (i.e., low-effluent suspended solids), the waste sludge flowrate (Q_w, m^3/h)) may be given by:

$$Q_w = \frac{V}{\theta_c}\frac{X}{X_R} \quad (22)$$

Considering that, in Equation (20), Q_p is Q_W given by Equation (22), the sludge-wasting unit pumping energy (Ev_W, Wh/m^3) is give by:

$$Ev_W = \frac{\theta}{\theta_c}\frac{X}{X_R}\frac{2.8\,\Delta H}{\eta} \tag{23}$$

If the sludge wasting occurs from the return sludge line, the simplified mass balance of the aeration tank yields:

$$X/X_R \sim 1/(1+R) \tag{24}$$

In this case, the reference values of unit energy consumption for sludge wasting (Table 11) were obtained by considering, in Equation (23), the reference values of θ_c and R proposed in Tables 4 and 7, respectively, whose typical ranges are also AS-type-specific.

If sludge wasting is carried out from the aeration tank, X equals X_R. Thus, Equation (23) is simplified (there is no Q_W dependence on R) and the reference values change accordingly (Table 11).

Table 11. The reference values of energy consumption for the sludge wasting in the AS systems.

<table>
<tr><th rowspan="2">Assumptions</th><th colspan="7">Ev_w Reference Values (Wh/m^3), (θ in h, ΔH in m)</th></tr>
<tr><th>Sludge Wasting . . .</th><th colspan="3">. . . From the R Line</th><th colspan="3">. . . From the Aeration Tank</th></tr>
<tr><td rowspan="13">$R_{300} \leftrightarrow Ev_w$ (Equation (23) with
$\theta_c = R_{100\,max}$ of θ_c (Table 4)
$R = R_{100\,max}$ of R (Table 7)
$\eta = 0.5$

$R_{100} \leftrightarrow Ev_w$ (Equation (23) with
$\theta_c = R_{100\,min}$ of θ_c (Table 4)
$R = R_{100\,min}$ of R (Table 7)
$\eta = 0.3$

$R_0 \leftrightarrow Ev_w$ (Equation (23) with
$\theta_c = R_{0\,min}$ of θ_c (Table 4)
$R = R_{0\,min}$ of R (Table 7)
$\eta = 0.2$

The sludge wasting from the aeration tank does not depend on R</td><td>AS-type</td><td>R_{300} ●</td><td>R_{100} ●</td><td>R_0 ●</td><td>R_{300} ●</td><td>R_{100} ●</td><td>R_0 ●</td></tr>
<tr><td>Extended aeration</td><td>0.002 θΔH</td><td rowspan="2">0.013 θΔH</td><td rowspan="2">0.028 θΔH</td><td>0.006 θΔH</td><td rowspan="2">0.019 θΔH</td><td rowspan="2">0.039 θΔH</td></tr>
<tr><td>OD (C+N)</td><td>0.004 θΔH</td><td rowspan="4">0.008 θΔH</td></tr>
<tr><td>OD (C)</td><td>0.003 θΔH</td><td>0.017 θΔH</td><td>0.035 θΔH</td><td>0.026 θΔH</td><td>0.049 θΔH</td></tr>
<tr><td>UCT</td><td rowspan="2">0.004 θΔH</td><td>0.022 θΔH</td><td>0.046 θΔH</td><td rowspan="3">0.039 θΔH</td><td>0.078 θΔH</td></tr>
<tr><td>Bardenpho 5</td><td rowspan="2">0.026 θΔH</td><td rowspan="2">0.052 θΔH</td><td rowspan="2">0.073 θΔH</td></tr>
<tr><td>Bardenpho 4</td><td rowspan="2">0.006 θΔH</td><td rowspan="2">0.012 θΔH</td></tr>
<tr><td>MLE</td><td>0.032 θΔH</td><td>0.060 θΔH</td><td>0.049 θΔH</td><td>0.083 θΔH</td></tr>
<tr><td>A2/O</td><td>0.004 θΔH</td><td>0.081 θΔH</td><td>0.168 θΔH</td><td>0.009 θΔH</td><td>0.097 θΔH</td><td>0.194 θΔH</td></tr>
<tr><td>Complet mix</td><td>0.008 θΔH</td><td rowspan="2">0.104 θΔH</td><td rowspan="2">0.194 θΔH</td><td rowspan="2">0.016 θΔH</td><td rowspan="2">0.130 θΔH</td><td rowspan="2">0.233 θΔH</td></tr>
<tr><td>Conv. plug flow</td><td>0.009 θΔH</td></tr>
<tr><td>VIP</td><td>0.012 θΔH</td><td>0.052 θΔH</td><td>0.104 θΔH</td><td>0.023 θΔH</td><td>0.078 θΔH</td><td>0.146 θΔH</td></tr>
<tr><td>A/O</td><td>0.023 θΔH</td><td>0.156 θΔH</td><td>0.270 θΔH</td><td>0.047 θΔH</td><td>0.194 θΔH</td><td>0.324 θΔH</td></tr>
</table>

3. iEQTA WWTPs Analyzed

In the scope of the national project iEQTA [50], the proposed energy PXs were computed to 14 activated sludge WWTPs with different capacities (489–54,000 m^3/d) and two treatment sequences: (i) activated sludge after primary sedimentation, designed for conventional aeration (CAS); and (ii) activated sludge without primary sedimentation, designed for extended aeration (EA). The five-year (2015–2019) data of these WWTPs are presented in Silva and Rosa [51], where the plant annual reliability for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) was discussed. During the energy-measurement campaigns that were carried out, the WWTPs studied were operated under the conditions summarized in Table 12.

Table 12. The operating conditions of the 14 WWTPs studied during the energy-measurement campaigns.

WWTPs (Labelled as in [51])	**B**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**M**	**N**	**O**	**P**	**P**
Type of treatment	CAS	CAS	CAS	CAS	CAS	EA	EA	EA	EA	EA	EA	EA	EA	EA
Aeration type *	m	d	d	m	d	m	m	d	m	d	d	m	m	d
Design flowrate (m^3/d)	4391	27,922	25,992	18,433	54,000	489	763	11,190	15,120	35,900	25,577	24,881	30,240	14,096
Q (m^3/d)	4562	15,926	13,638	13,640	29,970	440	638	9300	12,238	18,370	22,062	27,733	29,421	12,071
Q_w (m^3/d)	44	482	1017	876	1800	9	32	273	946	919	1999	1799	1800	568
R (%)	77	118	493	180	129	30	175	72.8	144	183	123	88	103	115
BOD_{5in} (mg O_2/L)	185	420	129	322	480	368	508	180	452.55	390	459	271	324	324
BOD_{5out} (mg O_2/L)	20	58	7	24	20	8	10	8	10	6	15	5	16	16
X (mg VSS/L)	3410	2920	1055	2333	4450	1758	4500	2285	3265	3145	3746	4405	3775	4440
MLSS (mg TSS/L)	3680	3340	1138	2687	5245	2790	5020	2830	4090	3700	4460	5435	4620	5480
θ (h)	9.2	23.7	7.5	11.5	12.6	40	37.5	14.7	29.6	20.1	33	20.5	24.7	30
$θ_c$ (d)	9.9	19.7	1.1	4.8	7.2	71	21.2	11.8	17.2	15.6	27.4	23	15.7	29
F/M (d^{-1})	0.14	0.12	0.39	0.3	-	0.13	0.07	0.13	0.1	-	0.09	0.07	0.08	0.06
nbVSS (mg/L)	19	126	19	48	144	37	152	54	138	117	138	81	97	97
Nt_{in} (mg N/L)	56	100	74	99	70	49	82	28	43	67	43	71	93	67
NH_{4out} (mg N/L)	22	70	48	47	1.4	20	40	18	5	18	1.9	5	12	12
NO_{3out} (mg N/L)	0.2	10	1	1	4.5	1	1	0.1	1.1	5.6	1.1	2.5	1.1	11
N_0 (kg O_2/(kWh))	1.5	-	-	1.5	-	2.0	1.5	-	1.5	-	-	1.5	1.5	-
β	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.95	0.95
α	0.69	0.64	0.83	0.69	0.52	0.68	0.53	0.68	0.59	0.62	0.57	0.60	0.56	0.50
C_L (mg/L)	1	0.5	1.4	0.5	2	0.1	0.8	2.6	0.4	0.5	0.6	0.6	0.7	1.4
T in reactor (°C)	22	24	28	23	25	23	23	12	28	23	31	27	23	27
C_{walt} (mg/L)	8.8	8.43	7.87	8.72	8.15	8.72	8.72	10.63	7.9	8.76	7.18	8.06	8.6	8.03
Submergence (m)	6	6.1	5	5	10	4	3.5	5.5	-	10	6	-	-	6
SOTE	-	0.39	0.41	-	0.40	-	-	0.30	-	0.40	0.34	-	-	0.30
F	-	0.8	0.8	-	0.8	-	-	0.8	-	0.8	0.7	-	-	0.7
e	-	0.75	0.75	-	0.75	-	-	0.75	-	0.75	0.7	-	-	0.7
p_2/p_1	-	1.65	1.61	-	1.66	-	-	1.61	-	1.66	1.50	-	-	1.50
ΔH return sludge (m)	-	5	-	-	-	5	4	7	3.8	-	4	-	2.8	-
ΔH sludge wasting from R line (m)	-	10	6	-	-	7	-	-		-		-	-	-
ΔH sludge wasting from reactor (m)	-	-	-	-	-	-	-	-	2.8	-	10	-	-	-
N (kg O_2/(kW.h))	0.9	2.5	3.1	0.9	1.6	1.3	0.7	1.6	0.8	2.4	1.9	0.8	0.7	1.4

* m = mechanical aerators; d = air diffusers.

4. Results and Discussion

4.1. Sensitivity Analysis of Aeration Efficiency

Typically, the oxygen transfer by air diffusers (N_d) is higher than that of mechanical aerators (N_m) and, under field conditions, it depends on many variables as expressed by Equations (14) and (9), respectively. Therefore, a sensitivity analysis was conducted to understand to what extent each parameter affects the oxygen transfer, considering the typical value for each variable except one, which was allowed to vary one at a time within its typical range.

The results of this analysis are presented in Table 13 and illustrated in Figure 4 for air diffuser systems and in Table 14 and in Figure 5 for mechanical aerators.

Table 13. The standard oxygen-transfer variation with each parameter of the air diffusor systems.

Parameter	**Typical Value Considered**	**β Variation**	**T Variation**	**C_L Variation**	**P_2 Variation**	**α Variation**	**F Variation**	**SOTE Variation**
e (-)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
β (-)	0.95	0.95 to 0.98	0.95	0.95	0.95	0.95	0.95	0.95
T (°C)	20	20	5 to 30	20	20	20	20	20
h (m)	10	10	10	10	10	10	10	10
$C_{s,20}$ (mg/L)	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08
C_{walt} (mg/L)	9.25	9.25	9.25	9.25	9.25	9.25	9.25	9.25
C_L (mg/L)	1	1	1	0.5 to 2	1	1	1	1
p_1 (kPa)	101	101	101	101	101	101	101	101
p_2 (kPa)	154.4	154.4	154.4	154.4	151 to 166	154.4	154.4	154.4
α (-)	0.5	0.5	0.5	0.5	0.5	0.4 to 0.7	0.5	0.5
F (-)	0.8	0.8	0.8	0.8	0.8	0.8	0.65 to 0.9	0.8
SOTE (-)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25 to 0.4
N_d (kg O_2/(kWh))	**1.7**	**1.7 to 1.8**	**1.8 to 1.6**	**1.8 to 1.5**	**1.8 to 1.5**	**1.4 to 2.4**	**1.4 to 1.9**	**1.4 to 2.3**

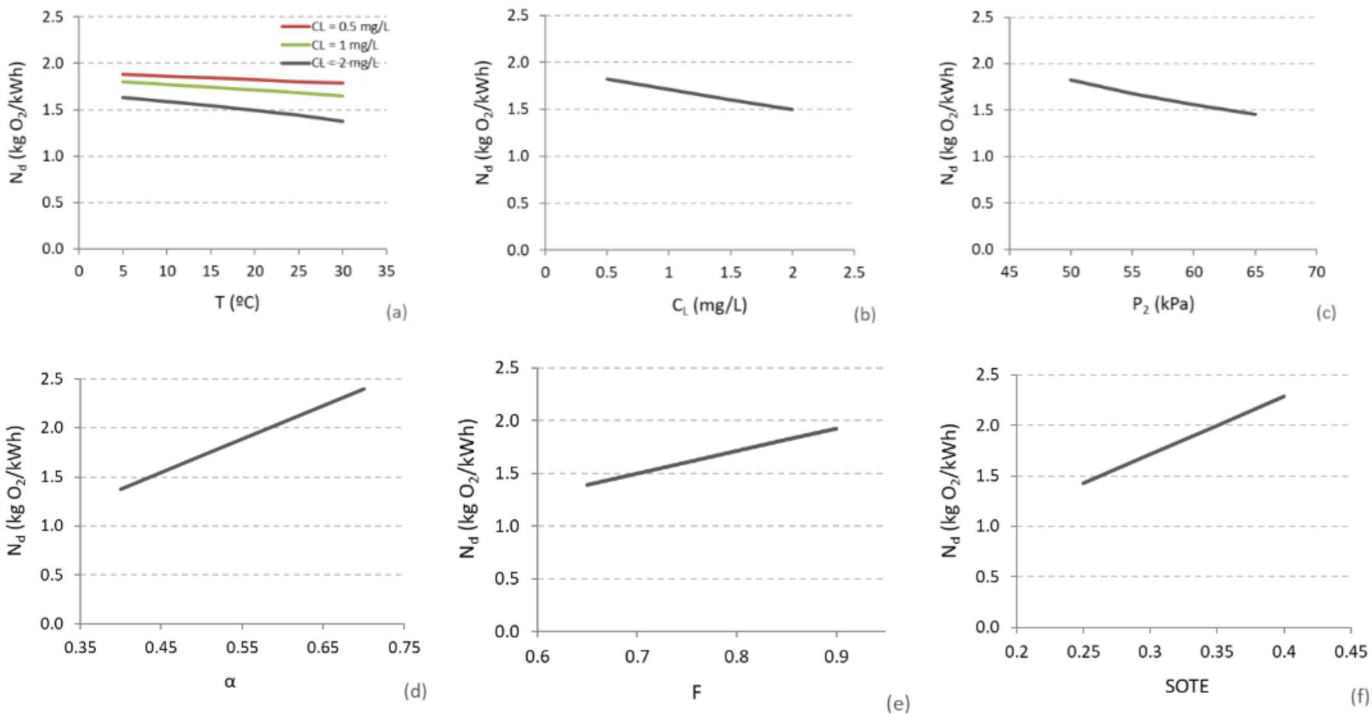

Figure 4. Oxygen transfer by air diffuser systems vs. temperature (**a**), operating oxygen concentration (**b**), outlet pressure (**c**), oxygen transfer correction factor α (**d**), fouling factor F (**e**), and SOTE (**f**) (considering, for the other parameters, their typical values in Table 13.

Considering the typical variation range of each variable, the largest variations of oxygen transfer by air diffusers are with α and SOTE, namely, a 71% increase in N_d when α increases from 0.4 to 0.7 and a 64% increase in N_d when SOTE increases from 0.25 to 0.4 (Figure 4). When F increases from 0.65 to 0.9, i.e., when the fouling decreases, N_d increases 36% (Figure 4). For mechanical aerators, the oxygen transfer mainly varies with α and N_0, namely, N_m increases 76% when α increases from 0.4 to 0.7 and N_m increases 91% when N_0 increases from 1.1 to 2.1 kg O_2/(kWh) (Figure 5).

Table 14. The standard oxygen-transfer variation with each parameter of the mechanical aerators.

Parameter	Typical Value Considered	β Variation	T Variation	C_L Variation	α Variation	N_0 Variation
β (-)	0.95	0.95 to 0.98	0.95	0.95	0.95	0.95
T (°C)	20	20	5 to 30	20	20	20
h (m)	10	10	10	10	10	10
$C_{s,20}$ (mg/L)	9.08	9.08	9.08	9.08	9.08	9.08
C_{walt} (mg/L)	9.25	9.25	9.25	9.25	9.25	9.25
C_L (mg/L)	1	1	1 (0.5 and 2)	0.5 to 2	1	1
α (-)	0.5	0.5	0.5	0.5	0.4 to 0.7	0.5
N_0 (kg O_2/kWh)	1.5	0.3	0.3	0.3	0.3	1.1 to 2.1
N_m (kg O_2/kWh)	**0.64**	**0.64 to 0.67**	**0.64** (0.67 to 0.69 for C_L = 0.5 mg/L) (0.58 to 0.54 for C_L = 2 mg/L)	**0.56 to 0.68**	**0.51 to 0.90**	**0.47 to 0.90**

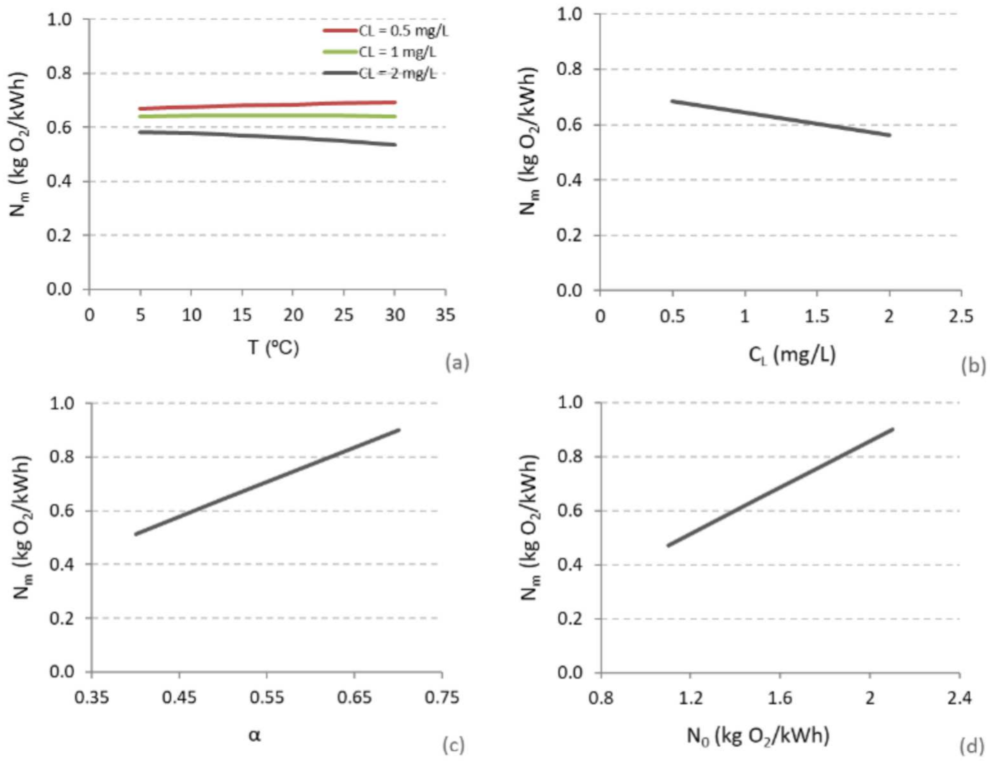

Figure 5. The oxygen transfer by mechanical aerators vs. temperature (**a**), the operating oxygen concentration (**b**), the oxygen transfer correction factor α (**c**), and N_0 (**d**) (considering, for the other parameters, their typical values in Table 14).

Rosso et al. [52] also identified the α-value as the most important parameter affecting the oxygen transferred under field conditions by mechanical aerators or air diffusors; however, it is the most uncertain and difficult-to-establish parameter, influenced by the influent water characteristics, the type of aerators, the operating conditions, and the N-removal conditions (α improvement with nitrification).

The parameters with a lower impact on N_d and N_m are β (Tables 13 and 14) and temperature (Figures 4a and 5a). Drewnowski et al. [53] also found that the influence of the temperature on the oxygen transfer rate is virtually unnoticeable since, on the one hand, the oxygen solubility drops as the temperature increases, while, on the other hand, it raises the diffusion rate. Our results show that for air diffusers, N_d slightly decreases with temperature in the 5–30 °C range, namely, from 1.8 to 1.6 kg O_2/(kWh) for C_L = 1 mg/L (Figure 4a). For mechanical aerators, the temperature effect on N_m is even lower and depends on C_L, with a turning point at 1 mg/L. In the 5–30 °C range, for C_L = 1 mg/L, N_m does not vary with temperature; above 1 mg/L it slightly increases (e.g., 3% for 0.5 mg/L), and below 1 mg/L it slightly decreases (e.g., 7% for 2 mg/L) (Table 14, Figure 5a).

This sensitivity analysis produced a further insight by identifying the key variables for the energy performance and by quantifying their expected impact, thereby assisting the decision-making of the improvement measures. These include (i) for air diffusers, the increase of SOTE (transfer efficiency), for instance, by air flux rate (m^3/(h.m^2)) reduction (e.g., by increasing the diffuser diameter or the number of diffusors), blower system retrofitting to modulate the air flow (e.g., introducing adjustable-frequency drives (AFDs) or most-open-valve (MOV) logic to minimize the system pressure), or diffuser-type replacement [9]; (ii) the cleaning of the diffusers, which decreases the fouling (increasing F) [52]; (iii) for mechanical aerators, the increase of N_0 by equipment replacement; (iv) for both aerator types, the increase of the α-value by a solids retention time increase or by including an anoxic selector, both increasing the water quality [52]; and (v) the adjustment of the dissolved oxygen set point (C_L decrease) [52].

4.2. Energy Performance of iEQTA WWTPs

In the scope of the national project iEQTA, the proposed energy PXs were applied to 14 WWTPs. Field campaigns were conducted for measuring the energy consumption in aeration, recirculation, and sludge-waste pumping. The aggregated results are presented in Figures 6–8. The results of a single WWTP are presented in 4.3 and discussed in terms of energy-performance diagnosis and improvement measures.

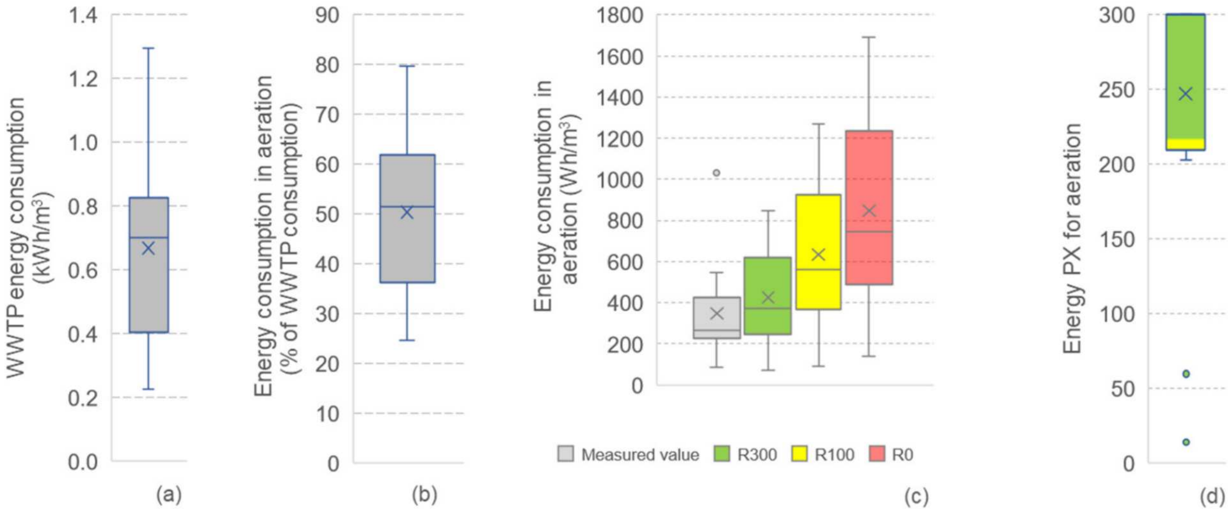

Figure 6. The energy consumption in the iEQTA WWTPs (**a**) and in aeration (**b**,**c**), the computed reference values (**c**), and the performance indices for aeration (**d**).

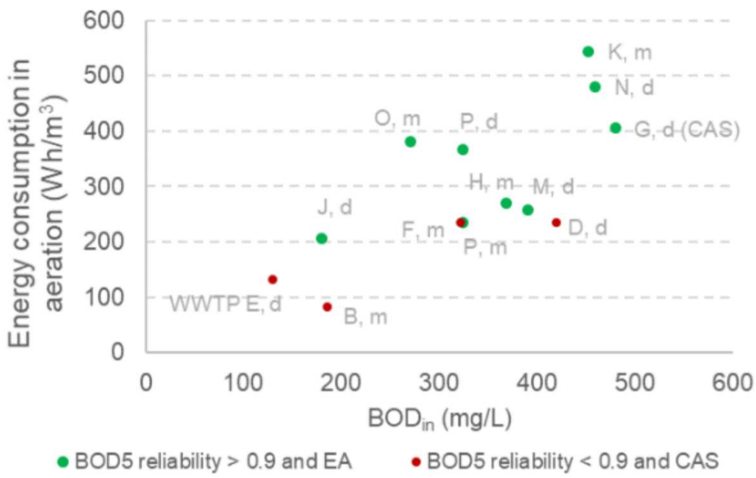

Figure 7. The energy consumption for aeration vs. influent BOD_5 in the iEQTA WWTPs with BOD_5 reliability lower and higher than 0.9 (daily values from the energy-measurement campaigns).

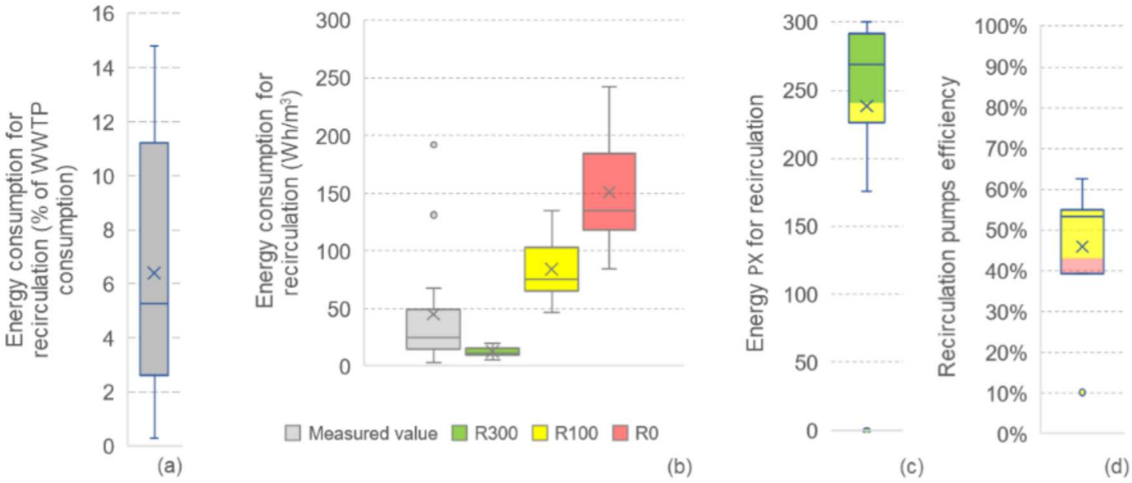

Figure 8. The energy consumption for recirculation in the iEQTA WWTPs (% (**a**) and Wh/m^3 (**b**)), the computed reference values (**b**), the performance indices (**c**), and the pumps efficiency (**d**).

The overall energy consumption in these WWTPs varied from 0.23 to 1.30 kWh/m^3 (median 0.70 kWh/m^3) (Figure 6a). Aeration was the major energy consumer, 83–1031 Wh/m^3 (measured values; Figure 6c), representing 25–80% of the total energy consumption (median 51%) (Figure 6b), values that are consistent with other studies [2,9,23,29–33]. Foladori et al. [36] studied five small WWTPs, and the aeration varied from 68 Wh/m^3 to 799 Wh/m^3, with the lower consumption in the WWTP with intermittent aeration and the higher consumption in the WWTP with 4 mg/L of C_L. The reference values computed for these 14 WWTPs were in the 25–75 percentile range (P25–P75) of 244–618 Wh/m^3 with a median of 373 Wh/m^3 for excellent performance (R_{300}), and 366–926 Wh/m^3 (P25–P75) and 560 Wh/m^3 (median) for acceptable performance (R_{100}) (Figure 6c). Clustering these results per type of aerator, the reference values for excellent performance are, for air diffusers, 232–385 Wh/m^3 (P25–P75), with a median of 324 Wh/m^3, and, for mechanical aerators, 325–800 Wh/m^3 (P25–P75), with a median of 560 Wh/m^3. These values highlight the fact that air diffusers are more energy-efficient than mechanical aerators, in the analyzed conditions (Table 12). Figure 6d shows the majority of WWTPs analyzed, with air diffusers or mechanical aerators, presented excellent-acceptable performance (PX median 300).

However, some WWTPs presenting good energy performance failed to supply the energy required, which compromised the effectiveness and the reliability of the plant. Figure 7 shows, on the one hand, the higher the influent BOD_5, the higher the energy consumption (with no linear correlation). On the other hand, it shows that plants operating with BOD_5 reliability above 0.9 (the minimum reliability needed to comply with EU directive discharge requirements [51]) presented higher energy consumption for aeration than the less reliable WWTPs, which were earlier found to be the CAS WWTPs [51]. Moreover, the type of aerator should be also considered in this analysis since air diffusers (labelled as 'd' in Figure 7) are more efficient than the mechanical aerators ('m' in Figure 7). Namely, for high strength influent (450–480 mg/L BOD_{5in}), CAS treatment with air diffusors (WWTP G) is more energy efficient than EA treatment with air diffusors (WWTP N), and this is more efficient than with mechanical aerators (WWTP K). In turn, for medium-high strength influent, a similar energy consumption allowed >0.9 reliable BOD_5 treatment of a higher influent BOD_5 concentration by air diffusors compared to mechanical aerators, namely, (i) 366 Wh/m^3 for 324 mg/L with air diffusors (i.e., 1.13 kWh/kg BOD_5, WWTP P) vs. 381 Wh/m^3 for 271 mg/L with mechanical aerators (1.41 kWh/kg BOD_5, WWTP O), both with a strong textile effluent input, and (ii) 258 Wh/m^3 for 390 mg/L with air diffusors (i.e., 0.66 kWh/kg BOD_5, WWTP M) vs. 270 Wh/m^3 for 368 mg/L with mechanical aerators (0.73 kWh/kg BOD_5, WWTP H), both with a typical urban inflow. All seven of the abovementioned plants presented significant nitrogen removal (Table 12). No effect was found of the treated volume on the unit energy consumption in aeration.

In 10 WWTPs, sludge recirculation represented a median 6.8% (34 Wh/m^3) of the total energy consumed in the WWTP and varied within 1–15% (min-max; Figure 8a) and 9–192 Wh/m^3 (measured values; Figure 8b). In the five WWTPs studied by Foladori et al. [36], energy for recirculation varied from 30 Wh/m^3 to 226 Wh/m^3.

The reference values computed for seven of these WWTPs (with available data of pumping head) yielded a P25–P75 range of 7.8–14 Wh/m^3, with a median of 11.2 Wh/m^3 for excellent performance (R_{300}), and of 52–94 Wh/m^3 (P25–P75) and 75 Wh/m^3 (median) for acceptable performance (Figure 8b). The WWTPs analyzed presented acceptable to good performance (PX median 266, Figure 8c) and a pump efficiency of 53% (median, Figure 8d).

Sludge wasting represented a minor parcel (0.4% median) of total energy consumption in the 7 WWTPs with available data and corresponded to less than 11 Wh/m^3 (2.7 Wh/m^3 median). The sludge wasting in the five WWTPs studied by Foladori et al. [36] varied from 2 Wh/m^3 to 17 Wh/m^3.

The reference values determined in the 5 WWTPs with the available data of the pumping head were 0.36–2.6 Wh/m^3 for R_{300} and 1.8–24 Wh/m^3 for acceptable performance (R_{100}). Even with a lower impact, the performance for this energy consumption was good (PX median 220).

4.3. Energy Performance Diagnosis and Improvement Measures for the WWTP K

This section illustrates the application of the energy PXs for diagnosing the performance and identifying improvement measures in WWTP K. This WWTP has an extended aeration treatment using mechanical aerators for carbon and nutrients' control; a 15,000 m^3/d capacity; and was operated, on average, at 81% of its capacity (Table 12). 1.8-year data (March 2018–December 2019) were used. During this period, WWTP K operated with the following:

- Influent wastewater: 172–495 mg/L BOD_5 (median 341 mg/L, P25–P75 292–382 mg/L), 245–1611 mg/L COD (median 971 mg/L, P25–P75 769–1125 mg/L), 103–545 mg/L TSS (median 327 mg/L, P25–P75 270–382 mg/L), and 31–90 mg/L N-total (median 59 mg/L, P25–P75 49–66 mg/L);
- Operating conditions: 2930–5380 mg/L MLSS (median 4140 mg/L, P25–P75 3875–4505 mg/L), 17.3–52.3 h θ (median 28.9 h, P25–P75 24.8–35.8 h), 16–18 d θ_c (median 16.8 d, P25–P75 16.5–17.2 d), and 0.04–0.13 d^{-1} F/M (median 0.08 d^{-1}, P25–P75 0.07–0.10 d^{-1});
- Reliability: 0.99–1.00 for BOD_5, 0.98–0.97 for COD, 0.94–0.93 for TSS, and 0.95–0.90 for N–total, i.e., always above 0.9 for all parameters, the cut–off for the compliance [51].

The 1.8-year field data showed aeration was the major use of energy in the WWTP, representing 51–64% (P25-P75) of the total energy consumption. In aeration, as explained in Section 2.3.1, energy performance depends, in addition to the equipment efficiency (aerators), on the difference between the oxygen supplied and the oxygen required (Equation (6)), which is a function of the influent load of organic matter and ammonia and of the biomass wasted. Unlike the influent loads, which are hardly or not at all controlled, the biomass wasted is imposed/adjusted by the WWTP utility and allows one to vary the MLSS and the solids retention time in the activated sludge reactor.

The detention time exhibited unsatisfactory performance (Figure 9a) due to excessive detention times (above 36 h, Table 5), particularly during the dry summer months, because the WWTP serves a combined sewer (urban and stormwater) system and the industries are closed during some summer days. The PXs computed for MLSS showed a good performance (Figure 9b), and those of solids retention time showed unsatisfactory performance (Figure 9c), corresponding to θ_c below the minimum acceptable for extended aeration, i.e., 16–18 d vs. 20–40 d, typically. Nevertheless, 16–18 d are in the nitrification range, which provides the conditions for high-water quality and subsequently a high α-value, one of the two variables with the highest positive impact on energy consumption. Actually, these retention times corresponded to good–excellent performance of the treated wastewater quality and to >0.90 reliability for BOD_5, COD, TSS, and N-total.

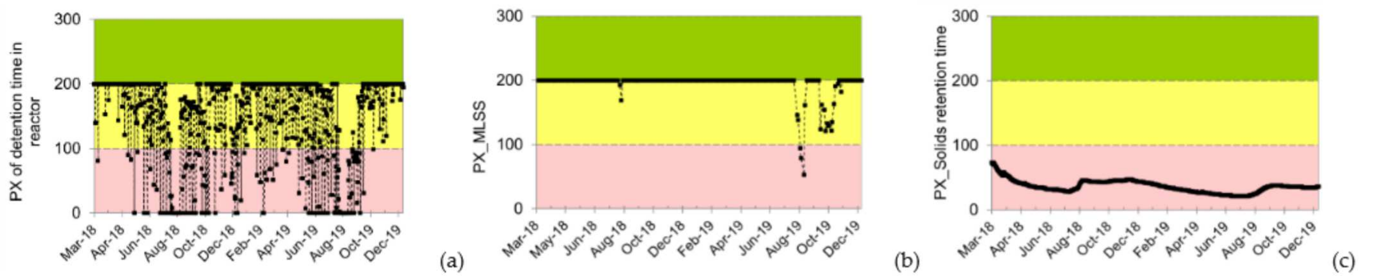

Figure 9. The performance indices of detention time (**a**), MLSS (**b**), and solids retention time (**c**), in the AS reactor of WWTP K.

The reference values derived for aeration accounted for these conditions and their daily variation (Figure 10), and the results obtained during this 1.8-year period varied (i) for excellent performance (R_{300}), from 37 Wh/m^3 to 615 Wh/m^3 (the upper limit of the light green zone in Figure 10); (ii) for good performance, from 376 Wh/m^3 to 1220 Wh/m^3 (the upper limit of the green zone); and (iii) for the minimum acceptable performance, from 603 Wh/m^3 to 2087 Wh/m^3 (the upper limit of the yellow zone). The reference values for acceptable performance (R_{100}) also consider the energy required for mixing, which depends on the detention time, as explained in Table 1.

The reference values for excellent performance (R_{300}) showed a linear relation with F/M ratio; the higher the F/M, the higher the oxygen requirements (Figure 11). Using the k-means method for the clustering analysis of the relation between R_{300} and F/M (with standardized values since R_{300} and F/M scales were very different), the turning point of F/M identified was 0.09 d^{-1}. The ANOVA p-value and the homogeneity of variance of the two clusters of F/M were computed— the p-value was 6.2E^{-13} (<0.05) and the F values < F critical values—and the statistical differences were verified. Thus, if the water utility decreases the F/M from 0.11 d^{-1} to 0.07 d^{-1}, the energy requirement will decrease from 416 Wh/m^3 to 252 Wh/m^3, which, considering the average treated wastewater of 12,312 m^3/d, represents a potential saving of 2019 kWh/d or 505 kg CO_{2e}/d of indirect carbon emission, using the Portuguese energy emission factor of 2019 (0.25 kg CO_{2e}/(kWh)). The F/M ratio is therefore a key variable of energy performance that is easy to monitor and control.

By analyzing the aeration energy index throughout the 1.8-year WWTP operation, the performance varies between good and excellent (Figure 12a), associated with energy consumption varying from 164 Wh/m^3 in the winter months to 560 Wh/m^3 in the summer months. Nevertheless, it may be further improved during the summer, when the detention time increases due to lower influent flowrates (low season, Figure 12a) and the reactor is being over-aerated. The gains from better adjusting the energy consumed to the energy required, i.e., levering all days to energy PX 300, translate into a potential energy savings of, on average, 141 Wh/m^3. Yu et al. [54], using Bayesian semi-parametric quantile regression, identified the temperature and the total nitrogen-rich wastewater as the factors associated with the higher level of energy consumption.

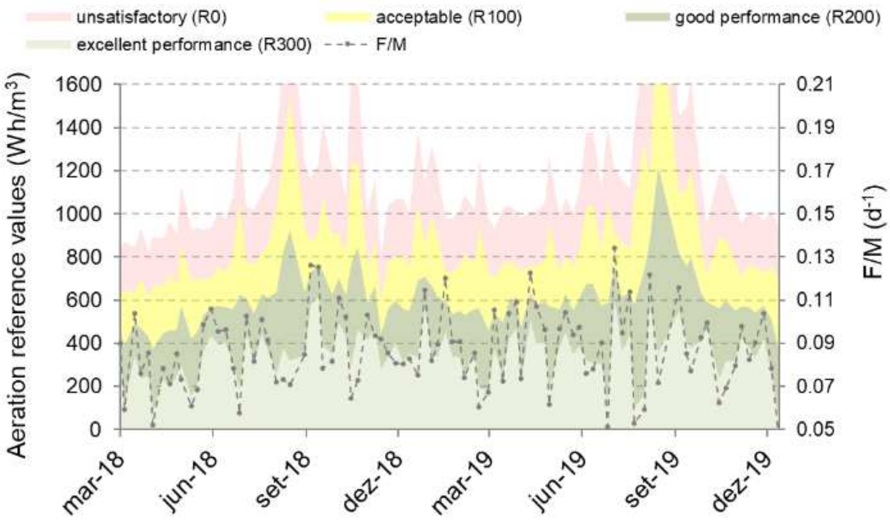

Figure 10. The reference values for energy consumption in aeration over the 1.8-year period analyzed in WWTP K.

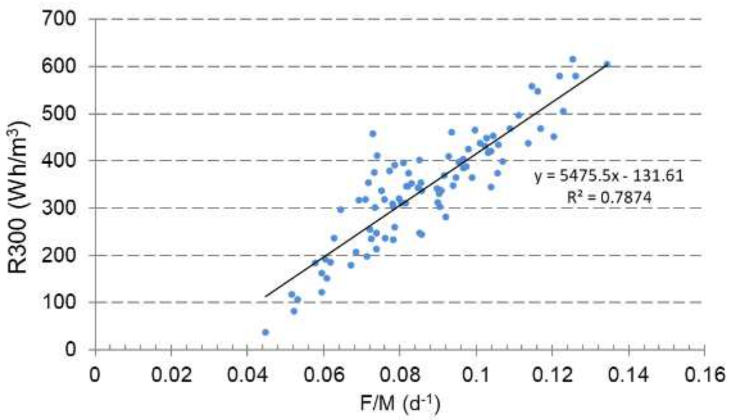

Figure 11. The reference values for R_{300} vs. F/M ratio in WWTP K (θ_c within 16–18 days).

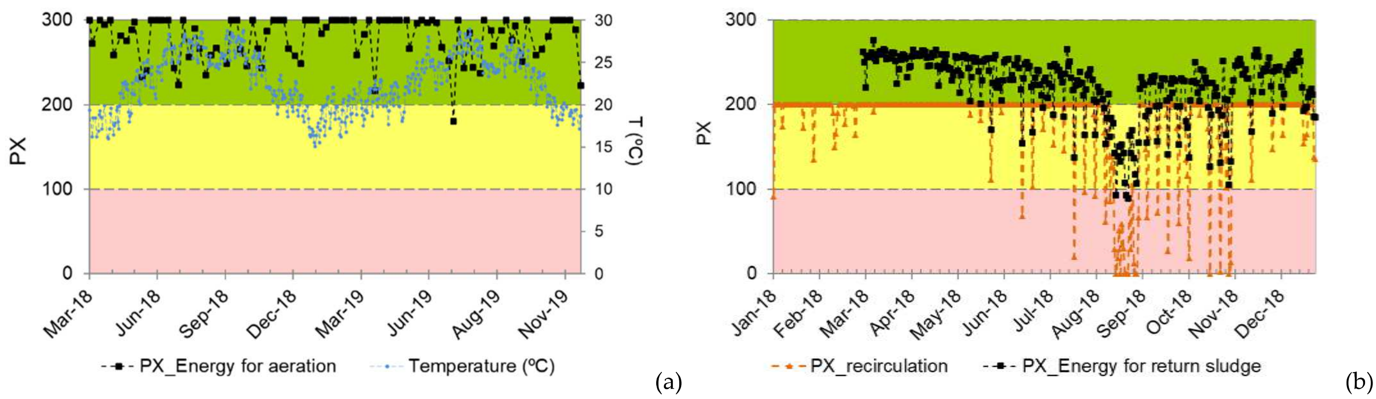

Figure 12. The performance indices of energy for aeration and temperature (**a**), and the performance indices of the return sludge and of the associated unit energy (**b**), over the period analyzed in WWTP K.

The return sludge was responsible for 3.1% of the total energy consumption in WWTP K. As explained in Section 2.3.3, the reference values for energy consumption in recirculation are based on the typical return sludge ratio (0.5–2 for extended aeration; Table 7) and on the pump recirculation efficiency, which was 55%. The indices of energy consumption in recirculation vs. return sludge flowrate demonstrate that the energy performance decreased when the return sludge ratio exceeded the typical values, during the summer months (Figure 12b). In this period conditions, if one decreases the return sludge ratio from above 2 to 1.5, the energy needed will decrease from >40 Wh/m^3 to 30 Wh/m^3.

This assessment allowed for the identification of energy improvement measures in the WWTP daily operation or in equipment inefficiencies, namely,

- Decreasing the F/M range from 0.04–0.13 d^{-1} to 0.04–0.09 d^{-1}, to decrease the energy requirements;
- Better adjusting (decreasing) aeration during the summer period when the flowrate decreases, to avoid excessive aeration and better modulate the energy consumed to the energy required; this could be done by submergence adjustment, speed adjustment, and on-off operation [9];
- Reducing the return sludge ratio in the summer period (e.g., from above 2 to 1.5);
- Further studying the feasibility and benefits of reducing the number of treatment lines operating in parallel in the summer (low season), when the detention time increases due to lower influent flowrates.

5. Conclusions

This paper presents a comprehensive set of performance indices for water practitioners to assess and improve the energy performance of widely used activated sludge systems, and the reference values for judging it, which consider the aspects affecting the energy consumption expressed by the operating conditions that are regularly monitored.

Furthermore, this paper shows the importance of measuring the energy consumption of each specific use, instead of the overall WWTP, to allow for the adjustment of the energy consumed to the energy required, which may be computed by the reference values herein derived. Thus, the energy consumption should be adjusted to the plant design (tank volumes, pump heads) and/or the daily fluctuations in the influent flow and oxygen biochemical demand, since

- The uses related to flow pumping, namely, the return sludge and the sludge wasting, depend on the pumping head, and the AS sludge wasting also depends on the detention time. For instance, the energy for return sludge in extended aeration systems, considering a pumping head of 10 m and an efficiency of 50%, varies from 28 Wh/m^3 when the recirculation is the minimum value of the typical range (0.5) to 112 Wh/m^3 for the maximum R of the typical range (2);
- The mixing depends on the detention time in the aerated, anoxic, and anaerobic reactors. For instance, the increase of θ in the A2O anaerobic zone, from 0.5 h to 1.5 h, increases the maximum energy requirement for mixing (R_{100}) from 7 Wh/m^3 to 20 Wh/m^3;
- The aeration depends on the influent BOD_5 and ammonia, the biomass wasted (determined by MLSS, θ_c, and θ), and the amount of oxygen transferred under field conditions. The oxygen transfer varies according to the mechanical aerator type (N_0), the diffuser type (SOTE), the compressor efficiency, and many field parameters (temperature; dissolved oxygen; altitude; the oxygen transfer correction factor for waste (α); and, for air diffusers, also the fouling factor (F) and the outlet pressure).

A sensitivity analysis was conducted to understand to what extent each parameter affects the oxygen transfer by air diffuser systems and by mechanical aerators. The parameters with lower impact are β and temperature, and those with higher impact are α, F, and SOTE for air diffusers, and α and N_0 for mechanical aerators. These are therefore the key variables the improvement measures should address, as exemplified. For instance, for WWTP G, if α increases from 0.52 to 0.65, the energy requirements decrease by 20%, from 385 Wh/m^3 to 306 Wh/m^3.

Fourteen Portuguese urban WWTPs, which are very diverse in size and inflows, were analyzed, and aeration (0.08–1.03 kWh/m^3) represented 25–80% of the total energy consumption (0.23–1.30 kWh/m^3). The reference values for excellent performance were

0.23–0.39 kWh/m^3 (P25–P75) for the AS systems with air diffusers and 0.33–0.80 kWh/m^3 for those with mechanical aerators.

A comprehensive application in one WWTP illustrated the PX system's ability for identifying which operating condition to adjust to improve the energy performance and savings while keeping the treatment effectiveness and reliability. For this WWTP, operating with 16–18 d solids retention time, F/M, a parameter that is easy to monitor and control, was the key variable; the lower the F/M, the lower the oxygen and the energy requirements.

Finally, the comprehensive derivation of the reference values allows the users to customize the assumptions herein made.

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