Sustainability concepts integration in the upgrade of an industrial WWTP

A.G. Capodaglio, V. Torretta, and A. Callegari

***Abstract*—**The purpose of wastewater industry is to protect surface water quality, aquatic life, beneficial and recreational uses of waterways, and primarily comply with local water emission standards. Being an industry aimed at the protection of the environment, wastewater's industry should nevertheless also strive to minimize, in addition to water quality impacts, any other possible environmental impacts (i.e. odours, outgoing wastes, etc.), last but not least pernicious air emissions, such as CO_2, methane and nitrogen greenhouse gases, and mitigate other likely impacts resulting from energy and chemical use in treatment processes. This paper describes a case study carried out in Europe, where the critical analysis of an industrial WWTP's present conditions, during the course of an evaluation of its upgrade possibilities to improve regulatory compliance, led to an initially unexpected, but ultimately sustainable, intervention proposal. According to the formulated proposal, process improvement, energy recovery, and overall savings and GHGs emissions reduction could be simultaneously achieved with a relatively simple intervention.

***Keywords*—**carbon footprint, energy recovery, GHG's emissions, process efficiency, sustainability, WWTP upgrade.

I. Introduction

WASTEWATER industry primary purpose is to protect surface water quality, aquatic life, beneficial and recreational uses of waterways, and compliance with local water emission standards. Minimization of the overall environmental impact should nevertheless be included in view of achieving overall sustainability of this type of facilities: odours and other air emissions (such as CO_2, methane and nitrogen greenhouse gases), waste flows and other impacts resulting from energy and chemical (mis)use in treatment processes should also be considered in the planning of WWT facilities. In comparison to other engineering disciplines, focused mainly on products or production processes, Environmental Engineering, whose primary purpose is the protection of the environment, has surprisingly made probably less progress in the specific development and application of sustainable design concepts in its field. In the wastewater field, recent advancements in the application of sustainable-thinking have explored the possibility of resource recovery from wastewater [1]-[4], and the consideration of broader impacts in process or infrastructure selection (incl. public acceptance, global warming potential, etc.) [5]-[8]. Some literature has sought to elucidate sustainability of a specific WWTP through the use of various criteria, among which, life cycle impact assessment (LCA) [7], [9] or the comparison of alternatives post-designs with the objective of either a minimization of effluent pollutant concentrations (e.g., NH_4^+ [10], or metals [11]), and costs. Very recently, some studies have addressed the minimization of environmental impacts [12]-[14], by means of studying specific objective functions in single- or multi-objective optimization problems.

In this paper, a case study is considered in which an initial issue for an industrial WWTP, related to excessive heat discharges into receiving waters, prompted a full evaluation of the efficiency of the facility, and a final upgrade proposal to obtain simultaneously better regulatory compliance, and better biological and chemical processes performance. This was achieved exploiting the facilities' peculiar design characteristics and shortcomings, in order to plan an integrated intervention to enhance treatment efficiency, long-term energetic sustainability, while reducing the overall carbon footprint.

II. Problem formulation and analysis

The facility under consideration is a tertiary, industrial WWTP facility in which N and P removals are achieved by a Bio-P process, followed by a simultaneous nitrification/dentrification activated-sludge process and a (reserve) P chemical precipitation unit. The WWTP serves an agro-food industrial district and treats an average flow of approximately 10000 m^3Md^{-1}, with high loads of organic matter ($BOD_{5,ave}$ = 1500 mg L^{-1}, COD_{ave} =2400 mg L^{-1}) and nutrients (TN ~ 160 mg L^{-1}, TP ~ 50 mg L^{-1}). Bio-P removal (Figure 1) occurs in an anaerobic tank prior to the simultaneous nitrification/ denitrification process. A subsequent finishing P flocculation step is activated in the clarifiers, when needed. Table 1 describes the main dimensional characteristics of the facility.

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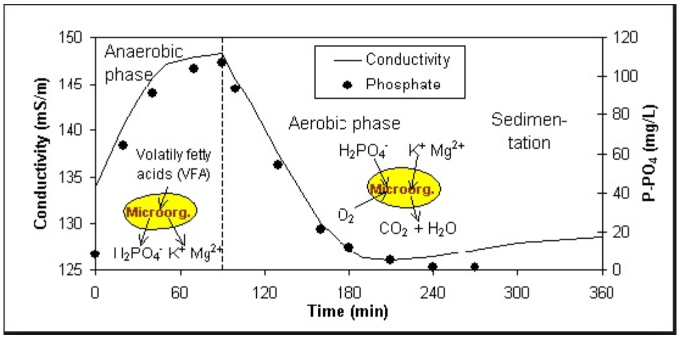

Fig. 1 Bio-P removal process

Tab 1. WWTP design characteristics

Unit	Volume (m^3)	HRT (1/d)
Bio-P removal	10000	1.33
Aerobic (nitrification)	18000	2.4
Anoxic (denitrification)	9000	1.2
Total biologic	37000	5

Table 2 reports the main current design operating parameters. The organic load removal efficiency of the plant is usually more than satisfactory (COD_{eff} = 15-21 mg L^{-1}, $BOD_{5,eff}$ = 1-2 mg L^{-1}, against discharge limits of 50 and 30 mg L^{-1}, respectively). Notwithstanding the high influent nutrient loads, the facility also appears to generally comply with TN discharge limits (TN_{eff} = 1.5-2 mg L^{-1} vs. 4 mg L^{-1} limit), with some frequent exceptions in the summer months. TP emissions, on the other hand, are mostly compliant with the limits (TP_{eff} = 0.2-0.3 mg L^{-1} vs. a limit of 0.3 mg L^{-1}). Due to the specific nature of the industrial processes generating the wastewater, however, inflow to the plant is usually in a high temperatures range (20-26^{o}C, lower in the winter, higher in the summer), with registered summer effluent peaks up to 30^{o}C (Figure 2). This, not only is in violation of the local maximum absolute value for discharge into the receiving waters (T_{lim} = 25^{o}C), but it is also much higher than the optimal temperature determined for local biota in the receiving water, determined by the local environmental agency in 13^{o}C. Thus, the frequent violation of temperature discharge standards is also associated with possible negative effects on the resident biota, and induces a blatant situation of energy waste, that translates in higher-than-necessary overall carbon emissions from the plant, unnecessarily discharging into the environment a potentially recoverable resource, and thus increasing in an unacceptable way the carbon footprint of the system.

Tab 2. WWTP main operating parameters

Parameter	Value	Units
$BOD_{5,infl}$	1500	mg L^{-1}
COD_{infl}	2400	mg L^{-1}
TN	160	mg L^{-1}
TP	50	mg L^{-1}
O_2 conc	0.2-3	mg L^{-1}
MLSS	4.5	mg L^{-1}
X_w=X_r	10	mg L^{-1}
Aerobic sludge age (nitrification)	9.4	days
Anoxic sludge age (denitrification)	4.6	days
Overall sludge age	14	days
Q_{in}	7500	m^3 d^{-1}
Q_r	0.8-1.0	Q_{in}

The apparently simple solution of recovering this excess heat prior to wastewater discharge in the sewer system was not taken into account by the industrial district management, due to potential interferences between characteristics of wastewater and the additional process units required (resulting in possible fouling of any installed heat exchangers), and possible interferences with in-sewer and in-plant phenomena [15] leading to lower biological degradation rates (and higher initial loads). Therefore the design and implementation of a system for the recovery of excess heat wasted from the industrial discharges, had to be evaluated jointly with an analysis of WWTP performance itself.

An "early" (pre-biological process) heat recovery would necessarily lower process operating temperatures, modifying their efficiency. In this case, nitrification would be the most penalized treatment step, due to its higher sensitivity to process temperature.

This may result in additional emission standards violations to add to those currently observed, even though a lower process temperature would enhance oxygen solubility in the mixed liquor, and somewhat decrease overall oxygen supply requirements. A careful evaluation of the entire biological process train is therefore required.

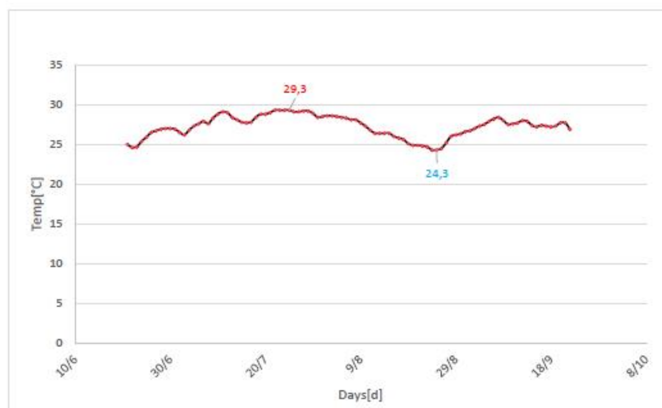

Fig. 2 Summer effluent temperature trend

III. Verification of Plant Efficiency

As mentioned, occasional violation of nitrogen or ammonium effluent standards had been previously and occasionally recorded by plant management. Having hypothesized that lowering influent temperature prior to the biological compartment could cause an increased risk of violation occurrence, due to lower bacterial process kinetic, a verification of plant efficiency was carried out by analyzing all the recent occurrences in which standards were actually violated, under original operating conditions. Table 3 summarizes some of these violations, with one or more of the parameters ammonia, nitrates, and TN recorded above effluent limits, together with observed operating conditions during violation. For those days, aerobic and anoxic (not shown in the table), and overall sludge ages were calculated. It is critical, for a correct efficiency analysis, to relate actual sludge ages with the observed events. In particular, the calculated aerobic sludge ages corresponding to effluent violation events are plotted against temperature in Figure 3.

These values are compared with the theoretical sludge age values (calculated at different concentrations of dissolved O_2) necessary to achieve 80-90% nitrification/denitrification efficiency, determined by Sedlak [16]:

$$\vartheta_{theor} = \frac{1}{\mu_n - K_{nd}} \qquad (1)$$

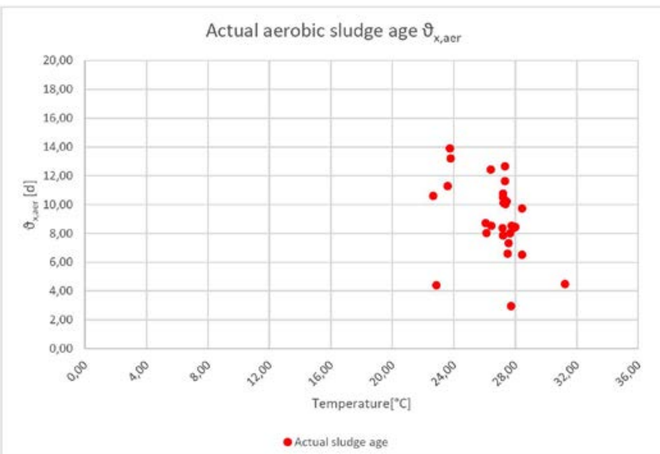

Fig. 3 SRT vs. temperature plot

Table 3. Plant's TN effluent violations (boldface) where K_{nd} can be neglected, due to its small values, and

$$\mu_n = \mu_{n,max}(T) * \left(\frac{NH3-N}{K_n + NH3-N}\right) * \left(\frac{DO}{K_O + DO}\right) \qquad (2)$$

Tab 3. Plant's TN violations (boldface)

NH_4-N [mg L^{-1}]	NO_3-N [mg L^{-1}]	N [mg L^{-1}]	C/N [kgBOD /kgN]	XMLSS [kgSS m^{-3}]	Temp [°C]	ϑx,tot [d]
0.063	**4.50**	**7.14**	6.74	6.65	26.40	18.64
0.066	**7.81**	**11.30**	9.04	6.49	26.13	12.05
0.120	**10.10**	**7.70**	11.01	6.29	26.43	12.79
0.150	**10,40**	**14.50**	8.44	6.22	27.20	16.14
0.380	**10.00**	**12.60**	6.94	6.14	27.33	18.99
2.810	**9.09**	**14.50**	8.35	5.90	27.37	15.05
4.760	**7.42**	**14.70**	8.92	5.63	27.20	11.78
5.240	**6.47**	**11.10**	7.48	5.48	27.23	15.18
6.080	**4.31**	**12.50**	16.80	5.25	27.17	12.55
3.640	2.32	**6.33**	8.99	5.04	27.43	15.34
3.290	**4.50**	**8.02**	17.87	4.67	31.23	6.74
5.680	**4.19**	**11.70**	8.49	4.10	27.50	9,88
4.290	3.11	**9.74**	6.83	4.17	27.57	10.99
0.710	1.74	**5.27**	8.01	4.41	27.67	12.01
2.260	0.33	**9.09**	18.03	4.16	27.73	4.44
4.090	2.88	**10.20**	8.04	4.13	27.83	12.49
1.750	0.33	**5.45**	9.21	4.29	27.77	12.79
3.030	3.28	**8.60**	7.39	4.20	28.00	12.67
5.470	2.77	1.93	26.92	4.23	28.43	9.79
4.270	1.85	**6.44**	6.88	4.35	27.33	17.43
1.990	1.46	**5.46**	8.25	4.38	27.20	15.76
1.690	0.92	**4.36**	7.16	4.38	26.07	13.08
3.580	0.62	**5.21**	8.01	4.42	28.43	14.59
2.880	0.40	**4.23**	8.69	4.05	22.67	15.90
3.480	0.40	**4.69**	22.94	4.08	22.87	6.60
2.570	0.65	**4.66**	8.51	5.95	23.80	19.81
2.840	0.70	**5.07**	7.97	6.25	23.60	16.94
2.710	0.41	**5.31**	9.20	6.70	23.75	20.85

Figures 4 and following, show sludge age values calculated in correspondence to the observed violation events, and compared with the theoretical SRT value defined by eq. (1) and (2) above, the minimum sludge age, for which nitrification capacity is very small, and the amount of nitrified ammonium is close to 0, defined by:

$$\vartheta_{min} = \frac{1}{\mu_{max(T)}} \qquad (3)$$

and the design sludge age (determined as the theoretical value multiplied by a safety factor of 2).

In the plant considered, D.O. levels inside the reactor are controlled by an automatic on/off system, limiting concentrations in the biological tanks within the range 0.2 and 3 mg L^{-1}. When the D.O. concentration is high (3 mg L^{-1}), almost all calculated aerobic sludge age values are situated above the design aerobic sludge age curve (Figure 4). This means that the nitrification process happens in almost "total" efficiency.

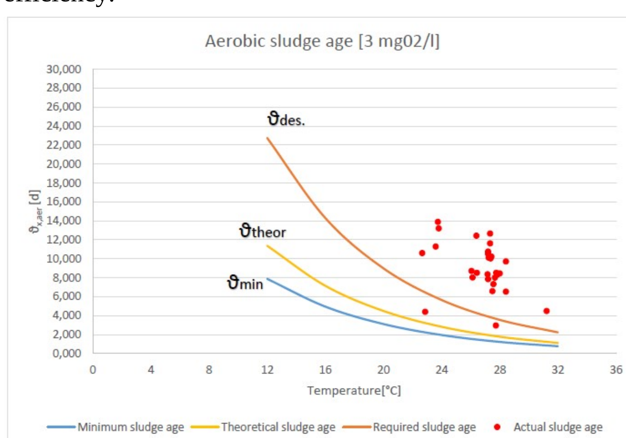

Fig. 4 Sludge ages comparison , O_2= 3 mg L^{-1}

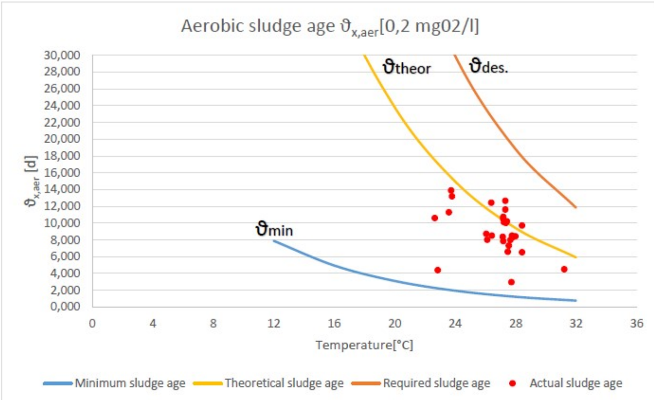

Fig. 5 Sludge ages comparison, O_2=0.2 mg L^{-1}

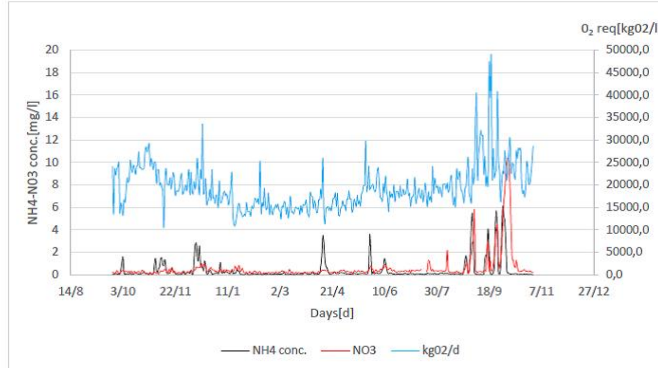

Fig. 6 O_2 requirement and effluent NO_3/NH_4

With oxygen concentration at 0.2 mg L^{-1} (Figure 5), the situation for nitrification is, instead, critical: almost the totality of the points are below theoretical sludge age (nitrification < 80-90%) and the two lower points are very close to the minimum sludge age curve. That means that nitrification efficiency in those instances is very low (≤ 10%) and a huge amount of ammonium could be present in the effluent.

Due to the simultaneous nitrification/denitrification process, outlet ammonium concentrations depend on two factors: the daily time fraction in which the aerobic reactor is operating at low oxygen concentration, and the instantaneous load of ammonium in the influent. In a combined process, conditions are under constant transients, therefore in a temporarily unbalanced overload situation, violations may ensue.

To better qualitatively illustrate possible outcomes, the following graph (Figure 6) was generated, summarizing: total daily oxygen requirement (sum of organic matter and ammonia oxidation, minus denitrification), and effluent ammonium and nitrate concentrations. It can be seen that high effluent ammonium (and nitrate) concentrations closely follow high oxygen requirement values. In practice, the system, loaded with a high amount of oxygen-consuming matter, cannot fulfill this request, with resulting poor nitrification/denitrification efficiency.

Three different possible scenaria can present themselves at any time (Table 3): ammonium concentration above effluent limit; nitrate concentration above limit; both ammonium and nitrate concentrations above effluent limits. From an analysis of Figures 4 and 5, all these three different situations lead to the same result, that is, an insufficient sludge age, implying, under the system's specific layout and conditions, that the performance limitation lies in the insufficient availability of reaction volume under critical circumstances.

IV. Integrated Upgrade Approach

From the analysis above, the following considerations can be drawn: the facility is, in its present layout, mildly under-designed as far as reactor volume is concerned. This condition becomes however evident only occasionally, under critical organic and/or ammonia loads, and high influent temperatures during the summer months. This situation alone could likely be solved with the implementation of an appropriate type of automatic, model-based online control [17], even though in this situation the presence of a Bio-P removal process could further complicate such an approach, or by a "hardware" upgrade. The latter approach was hypothesized keeping in mind the issues related to the original excess temperature discharge issue.

The previous analysis also shows that, in the present situation, energy recovery prior to the biological process would exacerbate the effects of the under-design: process kinetics will further degrade, increasing the chances of effluent violations due to slower processes. Energy recovery downstream of the biological section is therefore confirmed as the optimal solution.

Improving plant efficiency

In order to improve the efficiency of the biological section, an additional amount of process volume is required. Considering the current plant layout, by unifying the bio-P and nitrification/denitrification sections, currently positioned in concentric tanks, thus generating a new, larger N/Den volume, and building a separate, new anaerobic phosphorous removal tank upstream, would cause the least amount of structural disruption, at the lowest additional cost, to the existing plant. A new plant configuration (Table 4) was therefore suggested. The proposal of an additional volume (+27%) added to the nitrification/denitrification section is related primarily to the current plant layout, and is in no way calculated in any optimized fashion. However, a verification of the post-intervention layout with the same methods previously used, proves that this approach will ensure good performance of the process even under low dissolved oxygen concentration (Figure 7), virtually eliminating any chance of future violations.

Tab 4. New plant configuration

Unit	Volume (m^3)	HRT (1/d)
Bio-P removal	10000	1.33
Aerobic (nitrification)	28000	3,73
Anoxic (denitrification)	9000	1.2
Total biologic	47000	6.26

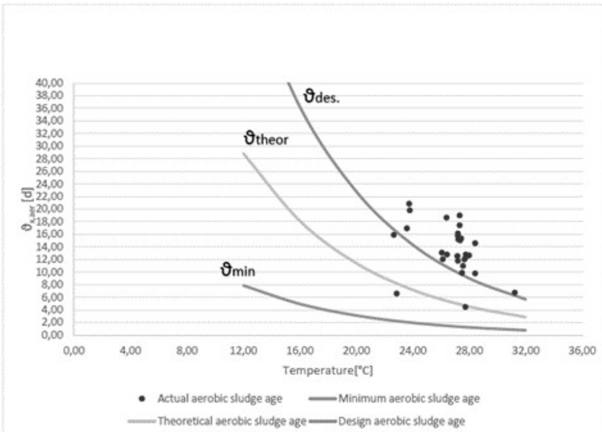

Fig 7. Process verification diagram under new plant configuration, (D.O. = 0.5 mg L^{-1})

Figure 7 shows that under the new configuration, treatment efficiency is mostly > 90%, and remains ≥ 80-90% even under a combination of critical load and low D.O. concentration conditions. Furthermore, the new operational layout may also improve bio-P removal efficiency, limiting the need to activate post-precipitation.

Energy recovery

Energy recovery from the effluent flow can, at this point, be safely addressed, without adverse consequences on process performance. Based on available records, seasonal effluent temperatures are summarized in Table 5. Although the yearly average is below the discharge limit (25°C), its value is well above the maximum temperature determined for preservation of fish life in the receiving stream, indicated by local Authorities in 13°C.

Tab 5. Seasonal effluent temperatures from plant

Season	T_{min} (°C)	T_{max} (°C)	T_{ave} (°C)*
Spring	20.1	28.9	24.5
Summer	24.5	29.7	27.8
Fall	19.5	25.0	23.6
Winter	16.2	21.1	19.4
Yearly average	=	=	23.7

*Calculated on all relevant data

Taking into account the receiving waters' seasonal temperature variability and mixing regime, and the expected energy recovery, two scenaria with different target effluent temperatures were determined: a discharge of maximum 10oC in the fall/winter season and of maximum 15°C in the spring/summer. These give recoverable ΔT's in the range of 9 to 15°C during each period. On these assumptions, recoverable heat energy from the plant flow was calculated assuming the use of suitably-dimensioned heat pumps. Calculations were performed for two different final situations:

- recovery of heat, with product water at 45°C (used for in-plant, and for connected industrial facilities, hot water);
- recovery of heat, with product water at 70°C (used for nearby residential and public buildings heating water).

Results of the calculations made under different options are summarized in Tables 6 and 7. It is apparent that a considerable amount of energy can be recovered from the effluent: in the case of district heating (Table 6) it was estimated that the energy recovered could service about 1000 individual apartments. The energy recoverable for hot water use ranges from 2000 to 2500 kW (Table 7), assuming the installation of three heat pumps, and depending on external environmental conditions.

Tab 6. Recoverable energy, heating water (70°C)

Hot water purpose ($T_{c,in}$ = 60°C; $T_{c,out}$ = 70°C; ΔT = 10°C)						
	Q_3 (m^3 h^{-1})	P_e (kW)	P_m (kW)	Q_c (m^3 h^{-1})	P_c (kW)	COP
Winter $T_{e,in}$=18°C $T_{e,in}$=10°C ΔT = 8°C	184.4	1715.0	585.0	201.5	2298.0	3.93
Summer $T_{e,in}$=27°C $T_{e,in}$=15°C ΔT = 8°C	139.7	1944.0	607.1	224.0	2554.0	4.21
Year $T_{e,in}$=23°C $T_{e,in}$=15°C ΔT = 8°C	209.4	1944.0	607.1	224.0	2554.0	4.21

Table 7. Recoverable energy, hot water use (45°C)

Cleaning water purpose ($T_{c,in}$ = 40°C; $T_{c,out}$ = 45°C; ΔT = 5°C)						
	Q_3 (m^3 h^{-1})	P_e (kW)	P_m (kW)	Q_c (m^3 h^{-1})	P_c (kW)	COP
Winter $T_{e,in}$=18°C	Single unit	Single unit	Single unit	Single unit	Single unit	Single unit
$T_{e,in}$=10°C ΔT= 8°C	62.7	583.3	133.7	121.4	698.7	5.23
	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pump s	Three heat pumps
	188.1	1749.9	401.1	364.2	2096.1	*
Summer $T_{e,in}$=27°C	Single unit	Single unit	Single unit	Single unit	Single unit	Single unit

$T_{e,in}$=15°C ΔT = 8°C	50.8	707.0	138.2	144.4	830.8	6.01
	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps
	152.4	2121.0	414.6	433.2	2492.4	*
Year $T_{e,in}$=23°C	Single unit	Single unit	Single unit	Single unit	Single unit	Single unit
$T_{e,in}$=15°C ΔT = 8°C	77.5	719.5	138.3	146.6	843.7	6.10
	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps	Three heat pumps
	232.5	2158.5	414.9	439.8	2531.1	*

This corresponds to the recovery of roughly 17500 to 21900 MWh y^{-1}, which, in turn, corresponds to an offset of about 12000 to 15000 tonnes y^{-1} of avoided CO_2 emissions, assuming an alternative production with fossil fuels [18]. For comparison purposes, the entire WWTP's CO_2 footprint can be estimated in approximately 75000 tonnes y^{-1} [19]. The emission reduction is therefore equal to about $1/5^{th}$ the original plant CO_2 footprint. This constitutes a significant contribution to the reduction of GHGs emissions.

V. Conclusions

An industrial, tertiary treatment plant, providing COD, bio-P removal and nitrification-denitrification processes was subject to an in-depth analysis, in order to verify the possibility to recover excess heat entering the facility through the upstream industrial processes effluents, and discharged into the receiving waters, while improving its overall treatment efficiency. The plant's effluent, in fact, often exceeded the permit discharge limit of 25°C, and occasionally also exceeded the TN effluent limit of 4 mg L^{-1}. A verification of the process treatment efficiency revealed that the occasional TN limit noncompliance could be related to insufficient available process volumes during critical events, leading to low process sludge ages. This finding suggested that the biological process train of the plant could be revamped with additional available process volume, and that an operating temperature reduction, upstream of the biological section, could have further reduced process performance. Additional plant volume was determined in +27%, not by calculation, but solely based on ease of intervention, related to the specific current plant layout. The non-optimization of this volume should be nevertheless compensated by lower structural costs for plant enlargement.

Excess heat recovery options calculations, downstream of the biological section were, thus, simulated, under two possible final use scenaria.

Simulation results indicated that between 2000 and 2500 kW could be recovered, corresponding to a CO_2 emission reduction (offset) of between 12000 and 15000 tonnes y^{-1}, or about $1/5^{th}$ of the current total estimated emission impact of the facility.

This recovery has multiple impacts on the overall "sustainability score" of the examined facility: it does not impair its performance from the process efficiency point of view, it improves (reduces) the overall environmental impact on both local (receiving water) and global (carbon footprint) aspects, and improves its economic viability by providing a trade-able commodity (hot water) of substantial economic value.

Additional interventions to improve the sustainability of the WWTP under consideration could be the object of future assessments: nutrient (N and P) recovery in the form of struvite mineral could be, in fact, implemented with relative ease (since the facility already operates a bio-P removal process and thus has P-rich sludges).

This case study demonstrates that integrating simple sustainability concepts in WWTP design and upgrade can be done with relative ease and may produce substantial benefits at both local and global levels. Sustainability awareness should become a primary focus for environmental protection facilities designers and managers.

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