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Energy recovery and efficiency improvement for an activated sludge, agro-food WWTP upgrade

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Abstract

Wastewater treatment's primary purpose is to protect surface water quality, aquatic life, beneficial and recreational uses of waterways, and primarily comply with local water emission standards. Lately, additional requirements were added for these facilities, concerning minimization of a series of sidestream environmental impacts (i.e., odours, generated waste by-products, etc.), air emissions, including CO_2, methane and nitrogen greenhouse gases (GHGs), and mitigation of various other likely impacts resulting from energy and chemical use in treatment processes. This paper describes a case study in Northern Europe, where critical analysis of an industrial wastewater treatment plant's present conditions, during an evaluation of upgrade possibilities to improve regulatory compliance, led to a sustainable intervention proposal. According to the formulated proposal, process improvement, energy recovery, and overall savings and GHG emissions reduction could be simultaneously achieved with a series of relatively simple interventions.

Key words: carbon footprint, energy recovery, GHG emissions, process efficiency, sustainability, upgrade, WWTP

INTRODUCTION

Wastewater treatment's primary purpose is to protect surface water quality, aquatic life, beneficial and recreational uses of waterways, and compliance with local water emission standards. Hence, in addition to appropriate monitoring of liquid discharge streams from such facilities (Capodaglio *et al.* 2016a; Capodaglio 2017a), minimization of the overall environmental impact should be included in their planning, in view of achieving overall sustainability of this type of facility (Capodaglio *et al.* 2016b; Capodaglio *et al.* 2017). Odours and other air emissions (such as CO_2, methane and nitrogen greenhouse gases (GHGs)) (Capodaglio *et al.* 2002; Torretta *et al.* 2016), emerging pollutant-containing flows (Cecconet *et al.* 2017a; Trojanowski *et al.* 2017), secondary waste streams, and other impacts resulting from energy and chemical (mis)use in treatment processes should also be taken into account.

In comparison to other engineering disciplines, focused mainly on products or production processes, wastewater treatment, whose primary purpose is the protection of the water environment, has surprisingly made probably less progress in the specific development and application of sustainable design concepts in its field. Recent advancements in the application of sustainable thinking have explored the possibility of resource recovery from wastewater (Daigger 2009; Verstraete *et al.* 2009; Capodaglio *et al.* 2013; Capodaglio *et al.* 2016c; Cecconet *et al.* 2017b), and the consideration of broader impacts in process or infrastructure selection (including public acceptance, global warming potential, etc.) (Keller & Hartley 2003; Capodaglio 2017b).

Literature has tried to elucidate sustainability of a specific wastewater treatment plant (WWTP) through the use of various criteria, including life cycle impact assessment (LCA) (Lundin *et al.* 2000; Pasqualino *et al.* 2009), or the comparison of alternative designs (Lim & Park 2009; Callegari & Capodaglio 2017; Molognoni *et al.* 2018) or control strategies (Novotny *et al.* 1991; Novotny & Capodaglio 1992; Raduly *et al.* 2007; Arnell *et al.* 2017; Barbu *et al.* 2017) with the objective of either a minimization of effluent pollutants, or costs.

In this paper, a case study for an industrial WWTP is considered, in which an initial issue 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 by exploiting the facility's specific design characteristics and shortcomings, in order to plan an integrated intervention to enhance treatment efficiency and long-term energetic sustainability, while reducing the overall carbon footprint.

CASE FORMULATION AND ANALYSIS

The facility under consideration is a tertiary, industrial WWTP facility in Northern Europe, in which nitrogen (N) and phosphorus (P) removal is achieved by a bio-P process, followed by a simultaneous nitrification/dentrification activated sludge process and a (reserve) P chemical precipitation unit (Sedlak 1991; Capodaglio *et al.* 2015; Capodaglio *et al.* 2016d). The facility serves an agro-food industrial district (with negligible municipal discharge contribution) and treats an average flow of 10,000 m^3/d, with high loads of organic matter (biological oxygen demand ($BOD_{5,ave}$) = 1,500 mg/L, chemical oxygen demand (COD_{ave}) = 2,400 mg/L) and nutrients (total nitrogen (TN) ~ 160 mg/L, total phosphorus (TP) ~ 50 mg/L). Bio-P removal occurs in an anaerobic tank prior to the simultaneous nitrification/denitrification process. A subsequent flocculation finishing step is activated in the clarifiers for additional P removal, when needed. Table 1 describes the main dimensional characteristics of the facility, while Figure 1 shows its schematic flowsheet.

Table 2 reports the main average design operating parameters. The organic load removal efficiency of the plant is usually more than satisfactory (COD_{eff} = 15–21 mg/L, $BOD_{5,eff}$ = 1–2 mg/L, against discharge limits of 50 and 30 mg/L, 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 vs. 4 mg/L 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 vs. a limit of 0.3 mg/L). Due to the specific nature of the industrial processes generating the wastewater, however, inflow to the plant is usually in a high temperature range (20–28 °C – lower in the winter, higher in the summer), with registered summer effluent peaks up to 30 °C (Figure 2). This is not only in violation of the maximum absolute value for discharge into the receiving waters (T_{lim} = 24 °C), but is also much higher than the optimal temperature determined for local biota in the receiving water, determined by the local environmental agency as 14 °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,

Table 1 | WWTP design characteristics

Unit	Volume (m^3)	HRT (1/d)
Bio-P removal	10,000	1.33
Aerobic (nitrification)	18,000	2.4
Anoxic (denitrification)	9,000	1.2
Total biologic	37,000	5

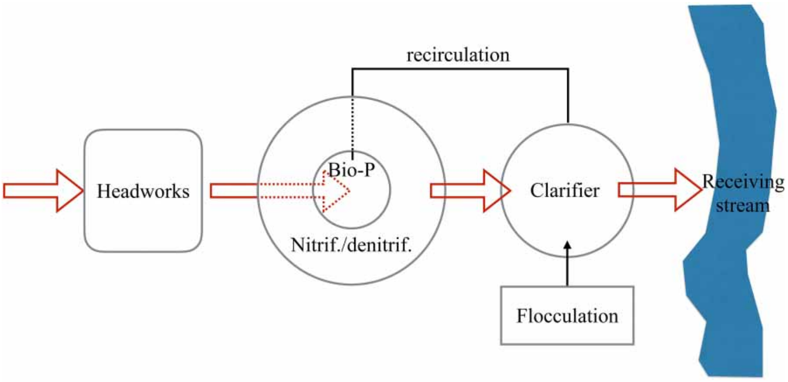


Figure 1 | WWTP schematic flowsheet.

Table 2 | WWTP main operating parameters

Parameter	Value	Units
$BOD_{5,infl}$	1,500	mg/L
COD_{infl}	2,400	mg/L
TN	160	mg/L
TP	50	mg/L
O_2 conc	0.2–3	mg/L
MLSS	4.5	mg/L
$X_w = X_r$	10	mg/L
Aerobic sludge age (nitrification)	9.4	Days
Anoxic sludge age (denitrif.)	4.6	Days
Overall sludge age	14	Days
Q_{in}	7,500	m^3/d
Q_r	0.8–1.0	Q_{in}

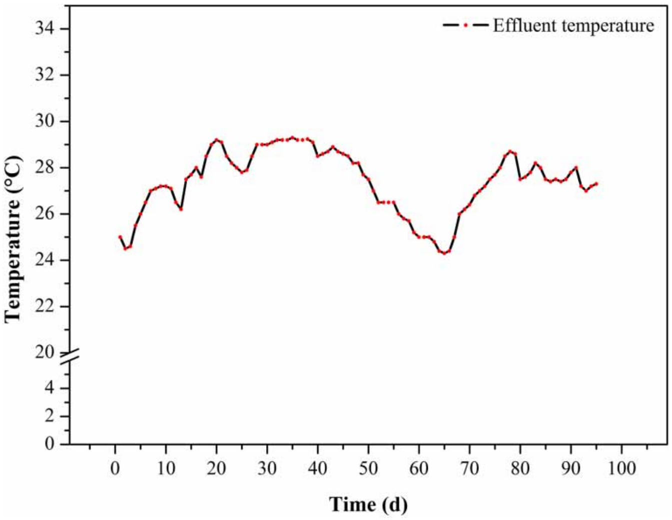


Figure 2 | Summer influent flow temperature trend.

that translates in higher than necessary overall carbon emissions from the plant, the unnecessary discharge into the environment of a potentially recoverable resource, and increasing in an unacceptable way the carbon footprint of the system.

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 the characteristics of the wastewater and the additional process units required for this purpose (resulting in possible fouling of any installed heat exchangers), as well as possible interferences with in-sewer and in-plant phenomena (Baetens *et al.* 1999; Qteishat *et al.* 2011; Kretschmer *et al.* 2016), 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 in the industrial discharge had to be evaluated jointly with an analysis of the WWTP's performance itself.

An 'early' (pre-biological process) heat recovery point would necessarily lower process operating temperatures, modifying their efficiency. In this case, nitrification would be the most affected treatment step, due to its higher sensitivity to process temperature (Wanner *et al.* 2005). 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 during the process. A careful evaluation of the entire biological process train is therefore required.

ASSESSMENT OF INITIAL 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 activity, a verification of present plant efficiency was carried out, analyzing all the recent occurrences in which discharge standards were actually violated, under current 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 the violation. For those days, aerobic, anoxic (not shown in the table) and overall sludge ages were calculated. It is critical, for a correct efficiency analysis, to correlate actual sludge ages with the observed events. In particular, the observed aerobic sludge ages corresponding to effluent violation events are plotted against temperature in Figure 3.

These values are then compared with the theoretical aerobic sludge age values necessary to achieve 80–90% nitrification/denitrification efficiency, determined at different concentrations of dissolved O_2 according to Sedlak (1991):

$$\vartheta_{theor} = \frac{1}{\mu_n - K_{nd}} \tag{1}$$

where K_{nd} can be neglected, due to its small values, and

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

Figures 4 and 5, therefore, show sludge age values in correspondence to the observed violation events (as in Table 3), compared with the theoretical sludge retention time (SRT) limits defined by Equations (1) and (2) above, in the hypotheses of high (3 mg/L) and low (0.2 mg/L) DO concentrations, respectively. In both figures, the minimum sludge age, for which nitrification capacity is

Table 3 | Plant's effluent violations (parameters over limits in boldface)

NH4-N [mg/l]	N03-N [mg/l]	TN [mg/l]	C/N [kgBOD/kgN]	XMLSS [kgSS/m3]	Temp [°C]	ϑx,tot [d]
0.063	**4.5**	**7.14**	6.74	6.65	26.40	18.64
0.066	**7.81**	**11.30**	9.04	6.49	26.13	12.05
0.12	**10.1**	**7.70**	11.01	6.29	26.43	12.79
0.15	**10.4**	**14.5**	8.44	6.22	27.20	16.14
0.38	**10**	**12.6**	6.94	6.14	27.33	18.99
2.81	**9.09**	**14.5**	8.35	5.90	27.37	15.05
4.76	**7.42**	**14.7**	8.92	5.63	27.20	11.78
5.24	**6.47**	**11.1**	7.48	5.48	27.23	15.18
6.08	**4.31**	**12.5**	16.80	5.25	27.17	12.55
3.64	2.32	**6.33**	8.99	5.04	27.43	15.34
3.29	**4.5**	**8.02**	17.87	4.67	31.23	6.74
5.68	**4.19**	**11.7**	8.49	4.10	27.50	9.88
4.29	3.11	**9.74**	6.83	4.17	27.57	10.99
0.71	1.74	**5.27**	8.01	4.41	27.67	12.01
2.26	0.33	**9.09**	18.03	4.16	27.73	4.44
4.09	2.88	**10.2**	8.04	4.13	27.83	12.49
1.75	0.33	**5.45**	9.21	4.29	27.77	12.79
3.03	3.28	**8.6**	7.39	4.20	28.00	12.67
5.47	2.77	1.93	26.92	4.23	28.43	9.79
4.27	1.85	**6.44**	6.88	4.35	27.33	17.43
1.99	1.46	**5.46**	8.25	4.38	27.20	15.76
1.69	0.92	**4.36**	7.16	4.38	26.07	13.08
3.58	0.62	**5.21**	8.01	4.42	28.43	14.59
2.88	0.4	**4.23**	8.69	4.05	22.67	15.90
3.48	0.4	**4.69**	22.94	4.08	22.87	6.60
2.57	0.65	**4.66**	8.51	5.95	23.80	19.81
2.84	0.7	**5.07**	7.97	6.25	23.60	16.94
2.71	0.41	**5.31**	9.20	6.70	23.75	20.85

very small, and the amount of nitrified ammonium is close to 0, defined by Sedlak (1991) as:

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

and the design sludge age (determined as the previously calculated theoretical value, multiplied by a safety factor of 2), are also shown.

In the considered facility, DO levels are controlled by an automatic on/off system, limiting concentrations in the biological reactors within the range 0.2–3 mg/L. When DO concentration is high (3 mg/L), almost all observed 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 (the two points below the design SRT curve are still above the theoretical one).

Considering DO concentration at 0.2 mg/L (Figure 5), the situation for nitrification is, instead, critical: nearly all of the observed points lie below the theoretical sludge age (representing a nitrification efficiency <80–90%) and the lower points are very close to the minimum sludge age curve. That means that nitrification efficiency in such instances is overall very low (between 50 and 10%), and a huge amount of ammonium could therefore still be present in the effluent. Furthermore, due to

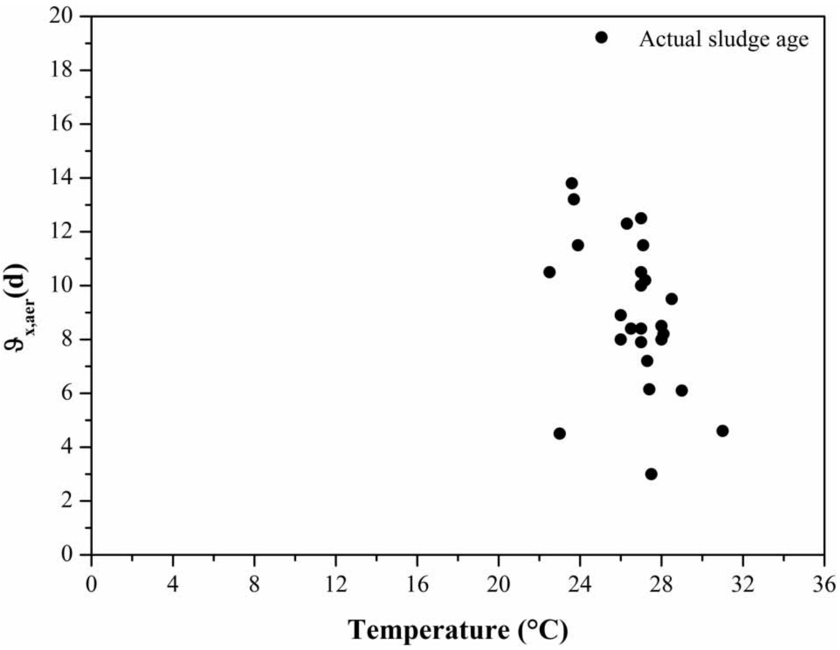


Figure 3 | Calculated aerobic SRT vs. temperature.

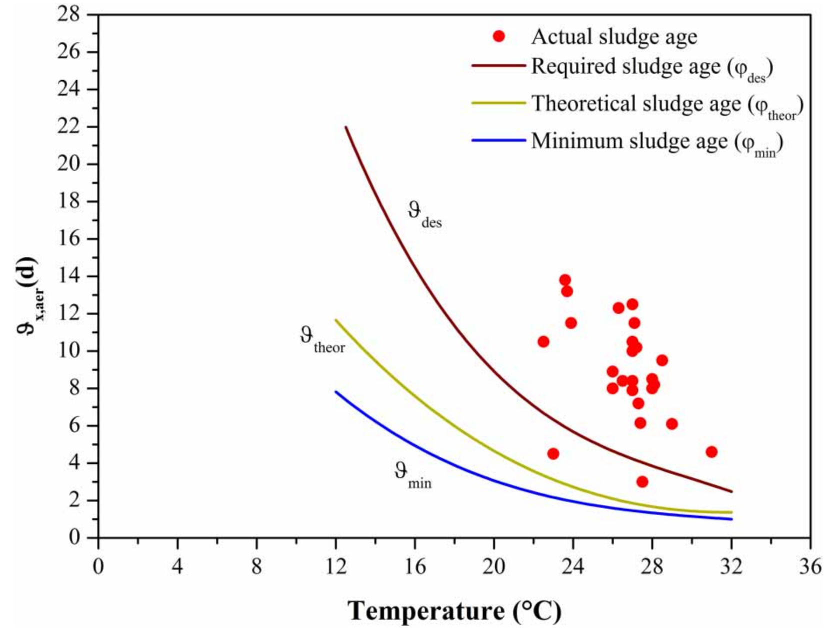


Figure 4 | Comparison of sludge ages, dissolved $O_2 = 3$ mg/L.

the simultaneous nitrification/denitrification process, instantaneous outlet ammonium concentrations depend on two factors, namely the concomitance of periods in which the aerobic reactor is operating at a low oxygen concentration, and the instantaneous ammonium load in the influent. As conditions in a dynamic, simultaneous process are constantly transient, a temporarily unbalanced operational state could therefore generate overload situations, and violations may ensue.

To better qualitatively illustrate possible outcomes of this variability, Figure 6 summarizes the 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

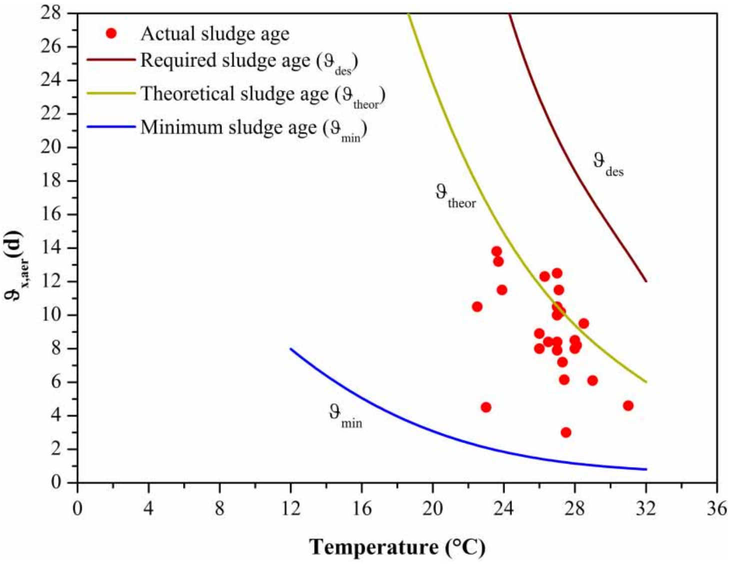


Figure 5 | Comparison of sludge ages, dissolved $O_2 = 0.2$ mg/L.

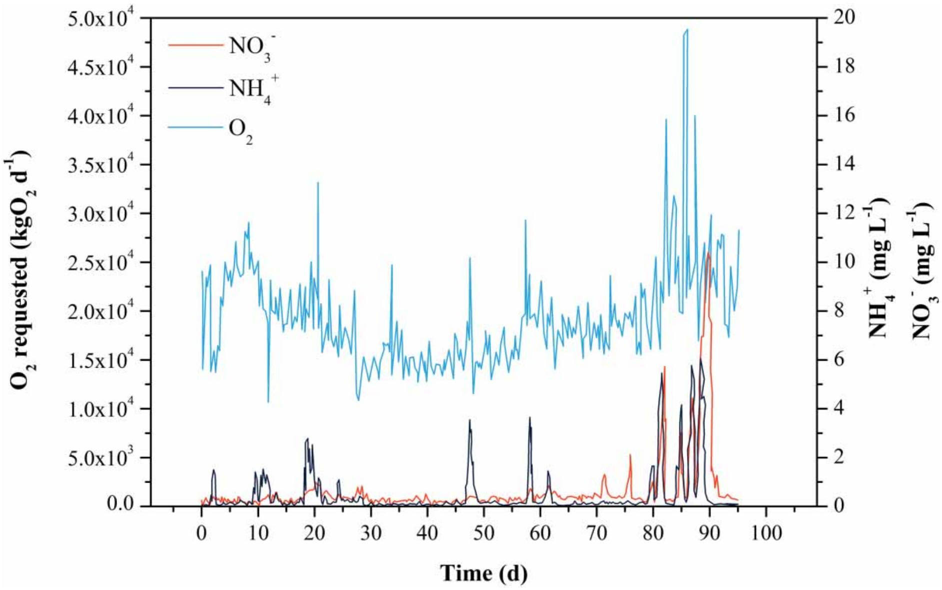


Figure 6 | O_2 requirement and effluent NO_3/NH_4.

concentrations are closely correlated to high oxygen requirement values. In practice, the system, loaded with a high amount of oxygen-consuming matter, cannot fulfill this request at the achievable SRTs determined in oxygen deficit (low DO concentrations), resulting in poor ammonia removal capacity. The resulting sudden oxygen demand then triggers the DO control system, reducing also the nitrification/denitrification efficiency.

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

INTEGRATED UPGRADE APPROACH

From the above analysis 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 only occasionally becomes evident however, under critical organic and/or ammonia loads, and in the presence of 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 (Novotny & Capodaglio 1992; Dai *et al.* 2016), even though in this specific case the presence of a bio-P removal process could add further complexity to such an approach, or by a 'hardware' upgrade. The latter approach was hence hypothesized, keeping in mind the residual issues related to the excess temperature discharge.

The previous analysis also showed that, in the present situation, energy recovery prior to the biological process could exacerbate the effects of the under-design: process kinetics would further degrade, increasing the chances of effluent violations due to slower processes (Wanner *et al.* 2005). Energy recovery downstream of the biological section is therefore confirmed as the only effective solution.

As highlighted by the previous analysis, stressing the need for higher SRTs in order to improve the efficiency of the biological section, an additional amount of process volume is required. Considering the present plant layout (Table 1), unifying the bio-P and nitrification/denitrification sections, currently positioned in concentric tanks, would generate a new, larger nitrification/denitrification dedicated volume. At the same time a separate, new anaerobic P removal tank upstream would cause the least amount of structural disruption, at the lowest additional cost to the existing plant. A new plant configuration was therefore suggested, as shown in Table 4 and Figure 7. The proposal of adding an additional volume of +27% 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 DO concentrations, as shown in Figure 8, virtually eliminating any chance of future violations.

Table 4 | New plant configuration

Unit	Volume (m^3)	HRT (1/d)
Bio-P removal	10,000	1.33
Aerobic (nitrification)	28,000	3.73
Anoxic (denitrification)	9,000	1.2
Total biologic	47,000	6.26

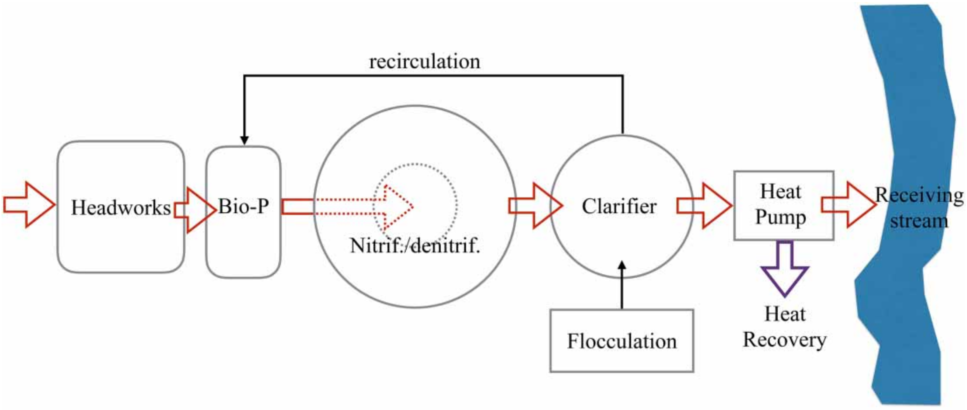


Figure 7 | Proposed WWTP new schematic flowsheet after upgrade.

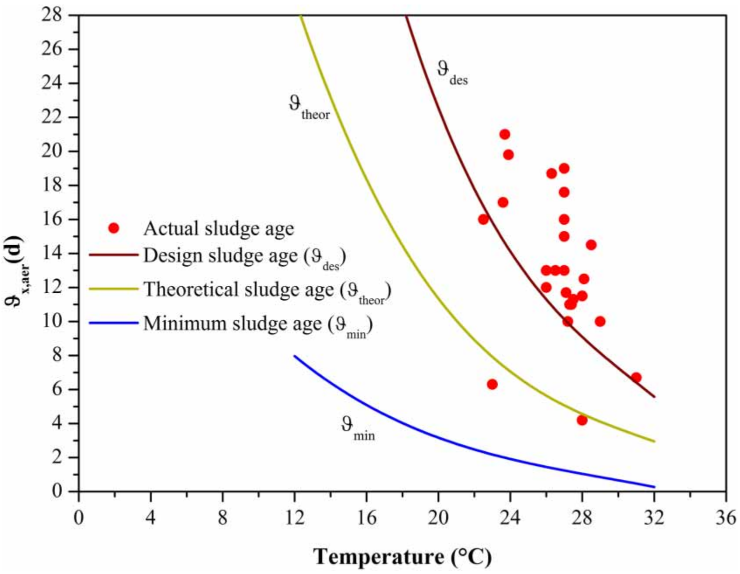


Figure 8 | Process verification diagram under new plant configuration, at low DO (DO = 0.5 mg/L).

Clearly, detailed dynamic modelling of operating conditions would better represent the day-to-day situation of the facility, but even this simplified approach should be sufficient to show the soundness of the proposed solution.

ENERGY RECOVERY

After addressing the treatment efficiency issue, energy recovery from the effluent flow can, at this point, be safely tackled, without fear of adverse consequences on process performance, especially on nitrification (Sedlak 1991).

Based on available records, seasonal effluent temperature statistics are summarized in Table 5. Although the yearly average is below the absolute discharge limit (24 °C), its value is well above the maximum temperature determined for preservation of fish life in the receiving stream, indicated, as mentioned, at 14 °C. It is also a well-known fact that the possible, theoretical energy recovery by heat extraction from a liquid stream is 7 kWh/m^3 per 6 °C water temperature drop (Meggers & Leibundgut 2011).

Therefore, taking into account the receiving waters' seasonal temperature variability, the dynamic of the mixing regime, and possible energy recoveries, two general scenarios with different target effluent temperatures were determined: a discharge temperature of maximum 10 °C in the fall/winter season; and maximum 15 °C in the spring/summer. These give recoverable ΔT's in the range of 9 to 15 °C in each period. On these assumptions, recoverable heat energy from the facility flow can be calculated assuming the use of suitably-dimensioned heat pumps (Liu *et al.* 2010). Calculations were performed for two different final hypothesis of heat recovery and reuse:

Table 5 | Seasonal effluent temperatures from plant

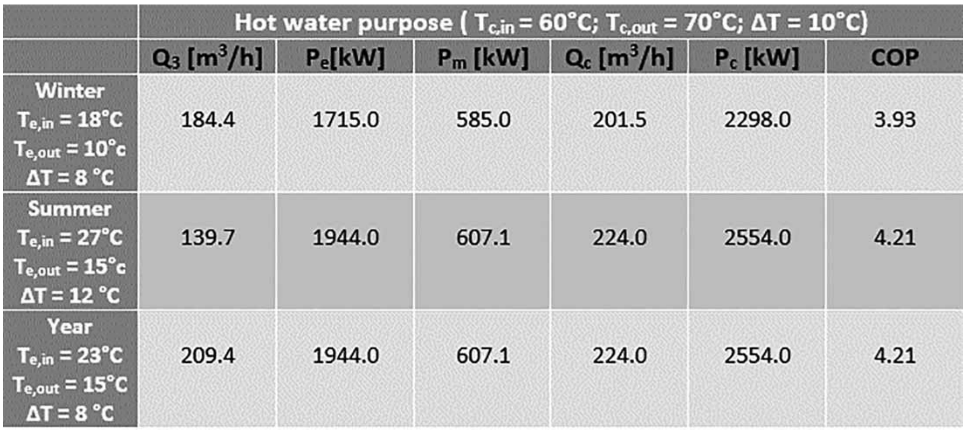
Season	T_{min} °C	T_{max} °C	T_{ave} °C[a]
Spring	20.1	28.9	24.5
Summer	24.5	29.7	27.8
Fall	19.5	25.0	23.6
Winter	16.2	21.1	19.4
Yearly average	=	=	23.7

[a] Calculated on all data.

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

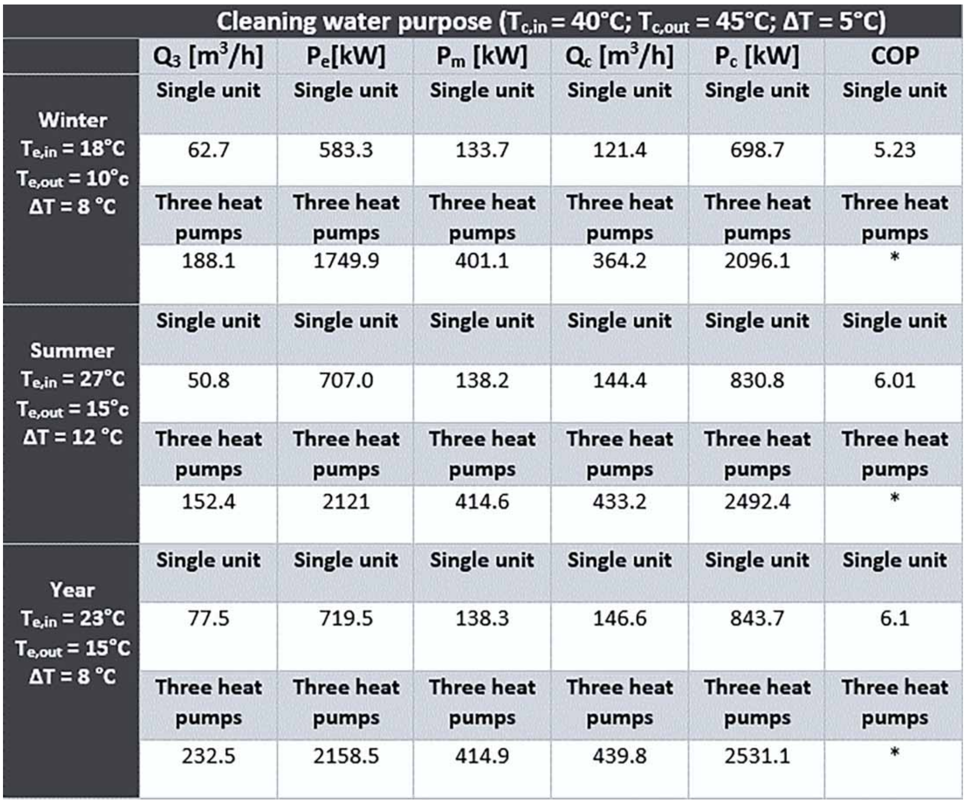
Results of the calculations made under different options are summarized in Tables 6 and 7. It is immediately apparent that a considerable amount of energy can be recovered from the effluent: in the case of district heating (Table 6) it was estimated that the energy recovered could service approximately 1,000 individual apartments, while the energy recoverable for hot water use ranges from 2,000 to 2,500 kW (Table 7), assuming the installation of three heat pumps and depending on external environmental conditions.

Table 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]	P_e[kW]	P_m [kW]	Q_c [m^3/h]	P_c [kW]	COP
Winter $T_{e,in}$ = 18°C $T_{e,out}$ = 10°c ΔT = 8 °C	184.4	1715.0	585.0	201.5	2298.0	3.93
Summer $T_{e,in}$ = 27°C $T_{e,out}$ = 15°c ΔT = 12 °C	139.7	1944.0	607.1	224.0	2554.0	4.21
Year $T_{e,in}$ = 23°C $T_{e,out}$ = 15°C ΔT = 8 °C	209.4	1944.0	607.1	224.0	2554.0	4.21

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



	Cleaning water purpose ($T_{c,in}$ = 40°C; $T_{c,out}$ = 45°C; ΔT = 5°C)					
	Q_3 [m^3/h]	P_e[kW]	P_m [kW]	Q_c [m^3/h]	P_c [kW]	COP
Winter $T_{e,in}$ = 18°C $T_{e,out}$ = 10°c ΔT = 8 °C	Single unit	Single unit	Single unit	Single unit	Single unit	Single unit
	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 pumps	Three heat pumps
	188.1	1749.9	401.1	364.2	2096.1	*
Summer $T_{e,in}$ = 27°C $T_{e,out}$ = 15°c ΔT = 12 °C	Single unit	Single unit	Single unit	Single unit	Single unit	Single unit
	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	414.6	433.2	2492.4	*
Year $T_{e,in}$ = 23°C $T_{e,out}$ = 15°C ΔT = 8 °C	Single unit	Single unit	Single unit	Single unit	Single unit	Single unit
	77.5	719.5	138.3	146.6	843.7	6.1
	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 17,500 to 21,900 MWh/yr, which, in turn, corresponds to an offset of about 12,000 to 15,000 t/yr of avoided CO_2 emissions, assuming alternative production from fossil fuels (USEPA 2014). For comparison purposes, the entire WWTP's CO_2 footprint can be estimated as approximately 75,000 t/yr (USEPA 2010). The emission reduction is therefore equal to about a fifth of the original plant's CO_2 footprint. This constitutes a significant contribution to the reduction of GHG emissions from the facility and a step forward towards maximization of the use of resources present in 'used water', as advocated recently by many (Verstraete *et al.* 2009).

CONCLUSIONS

An industrial, tertiary treatment plant providing COD and bio-P removal, nitrification and denitrification, was the object of an in-depth analysis in order to verify the possibility of recovering excess heat entering the facility through the upstream industrial processes effluents, and preventing it from being discharged into the receiving waters, while improving its overall treatment efficiency during critical events. The plant's effluent, in fact, often exceeded the absolute permit discharge limit of 24 °C, and occasionally also exceeded the TN effluent limit of 4 mg/L. A verification of the process treatment efficiency revealed that the occasional TN limit noncompliance could be related to insufficient SRTs (linked to insufficient available process volume) during critical events. This finding suggested that the biological process train could be revamped with additional process volume and that operating temperature reduction, upstream of the biological section, could have induced a risk of further reduced process performance. Additional plant volume was readily and easily achieved by incorporating the existing bio-P volume in the nitrification/denitrification tank, due to the ease of implementing this intervention, the specific layout, and ability to build a new bio-P reactor. This solution resulted in a 27% volume addition to the critical nitrification section, not by calculation, but by ease and minimal cost of implementation. Excess heat recovery options calculations, downstream of the biological section, were thus conducted, under two possible final use scenarios. Results indicated that between 2,000 and 2,500 kW could be recovered, corresponding to a CO_2 emission reduction (offset) of between 12,000 and 15,000 t/yr, or about a fifth 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 a process efficiency point of view, it improves (reduces) the overall environmental impact from both local (receiving water) and global (carbon footprint) aspects, and improves its economic viability by providing a tradeable commodity (hot water) of substantial economic value. Additional interventions to further 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 upgrading 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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