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Environmental, Safety and Techno-economic Assessment of a Wastewater Treatment Plant at the Early Upgrade Design Stage

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The sustainability concept has become worldwide the leading principle for environmental policy and innovative industrial processes and related technologies. This paper presents a methodology applied at the preliminary plant upgrade phase referring to a wastewater treatment plant (WWTP), a category which is commonly considered with high potential energy saving. Indeed, WWTPs are subjected to regular technical upgrade, either connected to changes in discharge requirements enforced by new European Directive, or to increased regional demands for specific pollutants removal, possibly because of new environmental conditions in the reference area. The concept is applied to an Italian WWTP for evaluating design alternatives and identifying the benefits using an approach at the design stage of a major revamping operation, aimed at enhancing operational efficiency and safety possibly reducing the footprint of the plant itself. Based on a comprehensive methodology, the plant revamping was focused on expanding the biological and sedimentation units, but also on increasing monitoring, energy efficiency, depuration performance and operational reliability of the overall process. The study implied the verification of economic implications and environmental impact by a LCA (Life Cycle Assessment) methodology, through the application of the relevant ISO standards ensuring the objectivity and accuracy of the evaluation results, highlighting the need of an overall vision of the environmental targets and of the sustainability paradigm.

* 1. Introduction

Wastewater treatment plants are essential infrastructures that ensure the safe removal of pollutants from domestic and industrial wastewater, protecting both human health and aquatic ecosystems and are conventionally designed to meet effluent standards enforced by law, with limited focus on energy efficiency optimization (Metcalf et al. 2004). Through a series of physical, chemical, and biological processes, these plants reduce organic matter, nutrients, and pathogens before water is discharged or reused. Despite their fundamental environmental role, WWTPs are also resource-intensive systems. Their operation requires significant amounts of energy (Panepinto et al. 2016) and chemicals, and it generates considerable quantities of sludge and emissions (Chai et al. 2015). Decision-making is not a straightforward process given the complexity of several alternatives and judging criteria, possibly including technical, economic, environmental, safety market, social and policy-related aspects (Benali et al., 2018). In this regard, the implementation of environmentally safer choices at the early stage in the design process can provide advantages and cost optimal operation throughout process life cycle. This challenge can be applied also in upgrading a process plant to meet new legislative requirements by relying on emerging technological solutions. As demonstrated in process plant design, a different, integrated approach is required to implement process, economics and risk analysis aprioristically with Life Cycle Assessment at the conceptualization stage of a process and to compare quantitatively emerging technologies in terms of inherent safety and sustainability (Bassani et al., 2023), translating an inventory of environmental discharges into estimates of impact on health and the environment.

* 1. Theoretical framework

As previously outlined, WWT plants can have a substantial environmental footprint, particularly in terms of energy consumption and greenhouse gas emission. Over the last 50 years, an increased awareness has developed in global society about protecting the environment and particularly water resources (Rashid et al. 2023). Given the high amount of energy demand of WWTPs, the integration of energy-efficient technologies has become increasingly important to reduce their environmental burden. One promising approach is the implementation of anaerobic digestion with combined heat and power systems, which can significantly improve energy efficiency by simultaneously generating electricity and useful thermal energy from a single fuel source. Combined heat and power system (CHP) configurations are commonly adopted in these facilities and are recognized as one of the most cost-effective technologies for energy recovery from biogas: the utilization of biogas in CHP systems can compensate for up to 40% of the plant's total energy demand (Sarpong and Gude, 2021). When considering the sustainability of a WWT system and selecting an appropriate design for a given condition, it is essential quantify and compare the impacts of different technological solutions by adopting comprehensive assessment tools. In this context, Life Cycle Assessment emerges as a particularly suitable and popular methodology for evaluating the overall environmental performance of wastewater treatment processes (Guinée et al. 2011). Life Cycle Assessment is a methodology used to quantify the environmental impacts associated with all stages of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal. The analysis allows for the evaluation of the effects of specific interventions within the plants, while also serving as a practical decision-support tool for comparing alternative operational scenarios (Corominas et al. 2020). As amply known, the structure of LCA can be summarised in 4 steps. The first phase involves the definition of the study goal and scope, including the identification of the objective, functional unit, system boundaries, and any key assumptions or limitations. The second phase is the Life Cycle Inventory (LCI), where all relevant inputs and outputs of the system are collected and quantified in relation to the functional unit chosen (Crawford et al. 2018). According to the third phase, i.e., the Life Cycle Impact Assessment (LCIA), the inventory data, comprising elementary flows, is translated into environmental impact scores using characterization models (Rosenbaum et al. 2018). At last, the interpretation phase provides a critical evaluation of the results from both the LCI and LCIA stages, ensuring that attained conclusions are consistent with the defined goals and scope of the study (Sala et al. 2020).

* 1. Applicative case-study

The study focused on the upgrading of the Sant ’Agostino wastewater treatment plant located in Recanati (MC), Italy, analysing the environmental impact of a pre- and post-upgrading configurations. The plant is currently authorized to treat a load corresponding to 14,000 equivalent inhabitants (PE); it was possible calculating that with these loads, the configuration of biological treatment prior to the revamping was assuring a total sludge age around 6 days, which is insufficient to achieve a complete nitrification in all the meteorological conditions, especially in winter. A target sludge age was established in 12 days, so that the major designed revamping operation involved increasing the volume of the biological tanks and installing two new circular sedimentation tanks. The volume increase of the biological section required also the upgrading of the aeration system and of the basic process control system. Even though the compliance to the legislation in terms of discharge limits implies an obvious benefit to the utility company operating the plant and to the community itself, a deeper analysis of the whole life cycle of the revamping design is considered an essential step to carefully evaluate the overall environmental implications at the early-stage design.

3.1 Life Cycle Assessment

A detailed Life Cycle Assessment was carried out according to enforced standards (ISO 14040, 2006 a,b) to compare the environmental impacts of the two configurations. The impact assessment was performed following the IPCC guidelines, using SimaPro software, with data sourced from the Ecoinvent database. Data for both configurations were collected, modelled, and analysed to evaluate the potential environmental benefits of the revamping process. The aims of the LCA analysis were to evaluate the environmental burdens of wastewater treatment plant and to identify opportunities to improve the environmental performance of the system considering also the implementation of anaerobic digestion and cogeneration processes. It was assumed that 50% of the electricity required for plant operation is supplied by the CHP. The system boundaries covered treatment, system maintenance, sludge management, energy production and consumption, and the options for treated wastewater effluent. The functional unit characterizing the qualitative and quantitative aspects of the service performed by the WWT plant on a normalized basis was selected as 1 cubic meter (m³) of treated water.

* + 1. Life Cycle Inventory

The Life Cycle Inventory analysis (LCI) involved the compilation and quantification of inputs and outputs for the given process throughout its life cycle starting from collecting data and information about the energy and materials used, emissions to air, water, land, and waste generated, suitable to calculate the environmental impacts, including their carbon footprint, water footprint, and other environmental indicators. All the plant raw data collected over one year observation were firstly analyzed and reconciliated, by a proper procedure to detect, identify, and isolate errors in the dataset; subsequently, the reconciled dataset was normalized to the functional unit, i.e., 1 m3 of treated water. According to this approach, it was possible to compare the two scenarios: the current configuration and the designed upgraded configuration. The most relevant data referred to each operational unit of plant analyzed included: Energy consumed [kWh]; Waste produced [kg]; Sand produced [kg]; Sludge produced [kg]; Transport [kg·km]; Chemical reagents [kg]. The overall analysis included the whole operational phase of the wastewater plant, without considering the construction phase of the modified sections. The effluent parameters were considered the same for both configurations, before and after the revamping, since the upgraded one does not involve any operational modification.

* + 1. WWT plant Impact Assessment

The environmental impacts were assessed for each plant unit, to identify the most impactful units and determine which input contributed most significantly to the overall footprint, based on following impact categories.

• Eutrophication [Kg PO4-3 eq.]: it is characterized by an excessive plant and algal growth due to the increased availability of one or more limiting growth factors needed for photosynthesis, such as sunlight, carbon dioxide, and nutrient (N, P).

• Global warming potential (GWP) [CO2 eq.]: it is the heat absorbed by any greenhouse gas in the atmosphere over a time horizon of 100 years.

• Ozone layer depletion [CFC-11 eq.]: ozone is constantly formed and destroyed through sunlight and chemical reactions in the stratosphere. Ozone depletion occurs when the rate of ozone destruction increases due to the release of persistent substances into the atmosphere such as chlorofluorocarbons (Heijungs et al.1992).

• Acidification Potential [SO2 eq.]: it is the reduction in the pH value of the water, lakes, and soil. Atmospheric deposition of inorganic substances, such as sulfates, nitrates, and phosphates are the main responsible.

• Photochemical oxidation - Non-Methane Volatile Organic Compounds [NMVOC]: it is a secondary air pollution component, also known as summer smog. It is formed in the troposphere and mainly by the action of solar ultraviolet radiation on emission pollutants from fossil fuel combustion, e.g. hydrocarbons and oxides of nitrogen.

• Abiotic Depletion [Kg Sb1eq.]: abiotic depletion indicators measure the decreasing availability of (abiotic) resources such as minerals, due to their extraction and scarcity.

• Abiotic Depletion (Fossil Fuels) [MJ]: it measures the decreasing availability of (abiotic) resources such as fossil fuels, due to their extraction and scarcity.

• Water scarcity [m3 eq.]: it quantifies the potential of water deprivation, to either humans or ecosystems, and allows calculating the water scarcity footprint.

* 1. Results and Discussion

This section presents the LCA results of the Life Cycle Assessment analysis for the current configuration, the upgraded designed configuration, and the hypothetical scenario in which anaerobic digestion and a cogeneration unit was implemented to supply 50 % of the plant’s electricity demand. Additionally, some economic considerations are outlined based on simplified CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) analyses.

4.1 Life Cycle Assessment

The attained results on a normalized basis are summarized in Table 1. The last column refers to the evaluation of the percentage of reduction from the upgraded configuration to the cogeneration configuration, which allows an immediate assessment of the categories most affected by the CHP introduction. The above-mentioned results show that the upgrade of the treatment system leads to a slight increase in the environmental impacts across several categories. Comparing the current configuration to the upgraded one, the Global Warming Potential (GWP) increased from 0.309 kg CO₂ eq./m3 to 0.331 kg CO₂ eq./m3, and the Abiotic Depletion of fossil fuels increased from 3.60 MJ/m3 to 3.86 MJ/m3. It should be noted that the introduction of anaerobic digestion and cogeneration implied a notable reduction in the environmental impacts across several categories. The GWP decreased by 13 %, from 0.331 kg CO₂ eq./m3 to 0.287 kg CO₂ eq./m3, while the Abiotic Depletion of fossil fuels dropped by 32 %, from 3.86 MJ/m3 to 2.64 MJ/m3.

Table 1: Life cycle impact assessment per m3 of water treated.

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| **Impact category** | **Original configuration** | **Upgraded configuration** | **Cogeneration configuration** | **Variation****[%]** |
| Acidification (AP) [SO22− eq./m3] | 2.18E-03 | 3.27E-03 | 1.09E-02 | -233% |
| Eutrophication (EP) [Kg PO34− eq./m3] | 6.26E-03 | 6.28E-03 | 7.72E-03 | -23% |
| Global Warming Potential (GWP) [CO2 eq./m3] | 3.09E-01 | 3.31E-01 | 2.87E-01 | 13% |
| Photochemical Oxidation (PO) [NMVOC/m3] | 8.19E-04 | 8.45E-04 | 6.50E-04 | 23% |
| Abiotic Depletion (AD) [Kg Sb1eq./m3] | 6.80E-08 | 6.83E-08 | 7.42E-08 | -9% |
| Abiotic Depletion, fossil fuels (ADF) [MJ/m3] | 3.60 | 3.86 | 2.64 | 32% |
| Water Scarcity (WS) [m3 eq./ m3] | 2.38E-01 | 2.55E-01 | 1.68E-01 | 34% |
| Ozone Layer Depletion (OLD) [CFC-11 eq./m3] | 5.86E-08 | 2.57E-08 | 4.82E-08 | -88% |

Similarly, WS indicator showed a 34% reduction, from 0.255 m3/m3 to 0.168 m3/m3 and the PO improved by 23%. In some categories, however, the environmental performance decreased, e.g., the AP increased by 233% and the OLD increased by 88% mainly due to biogas combustion and digestate management, which can raise the impacts if not properly controlled. Figures 1 and 2 provide a detailed analysis of the two most relevant impact categories, i.e., GWP and WS respectively. In addition to absolute values (a), the percentage contribution (b) of each unit process to the selected indicators is outlined in the above-mentioned Figures 1 and 2, allowing for a detailed assessment of the main drivers behind the overall environmental footprint.

1. ** (b)

 *Figure 1: Global Warming Potential Assessment (a) and Global Warming potential % impact (b)*

1.  (b) 

 *Figure 2: Water scarcity assessment (a) and Water scarcity* % *impact (b).*

The GWP analysis highlights that biological reactor is the dominant contributor across all the explored configurations (74-76% of the total impact), followed by disinfection and dewatering. These units consistently represent the highest emissions due to the high-energy demand of biological reactor and dewatering. At the same time the disinfection has a great impact due to the production und usage of chemical reagent. About the Water Scarcity, since energy production and the manufacturing of chemical reagents require significant water consumption, the biological reactor (75-77%), dewatering (4-6%) and disinfection (9-14%) are the most effective units. Regarding the other units, their impacts are negligible compared to the previous ones (<3%). Results show that while the plant upgrade implies a slight increase of the overall environmental footprint, the integration of anaerobic digestion and CHP leads to substantial improvements. In this regard, the upgrade scores a 13% GWP reduction and a 34% WS reduction, coupled with a significant rise of acidification and eutrophication impacts. These findings can be compared with recent studies proving that anaerobic system can potentially be energy neutral, or energy positive under optimum operative conditions; as a main drawback one must consider that if dissolved methane from anaerobic effluents is not captured and recovered, it causes an extra GWP effect and may also increase toxicity (Yilmaz et al., 2024).

* + 1. Economic considerations and plant optimization

A CAPEX analysis based on actual construction data was performed for the biological section upgrade, highlighting the new aeration and sedimentation tanks as the main cost drivers. Additionally, OPEX historical analysis of the plant in the old configuration was performed relying on the last complete operational year. In a WWT plants energy consumption accounts nearly for 25–40% of operating costs, with values ranging between 0.3-2.1 kW h/m3 of treated wastewater (Liu et al., 2014). As expected, the potential areas for improvement are the working personnel and energy consumption, while sludge management, normally representing a high contribution to OPEX too, was relatively low, owing to the application of sludge beds to curb the disposal costs. Summarizing, the designed configuration may entail a slight increase in the production of sludge, some rise in manpower time, as well as a higher electric power consumption, mainly due to the enlarged aeration system. A further focus was on the addition of a cloth filtration unit to achieve a lower suspended solids content in the water outlet: according to the EU legislation, water at outlet of a tertiary filter followed by a disinfection step would be fit for reuse, especially for irrigation purposes.

WWT plant control system improvement: the new plant configuration foresees continuous control of the aeration flow by dissolved oxygen level monitoring. As amply known, NH3-N is one of the most important indicators of sewage quality, and it is also a strictly regulated sewage pollutant for WWTPs (Guillen-Burrieza et al., 2023). Real-time and average ammonia monitoring can be regarded as a better control strategy of the nitrification process, which is the prevailing demand for dissolved oxygen and therefore for aeration flow. In this regard, it seems well worth considering dynamic O2 and NH4-N control to further reduce nitrification time and connected energy consumptions. As a future upgrade, real-time management of the WWT plant can be developed by applying AI (artificial intelligence) and ML (machine learning) optimization of technology working parameters. As recently demonstrated in different process applications, deep machine learning algorithms offer the opportunity to capture complicated nonlinear mapping relationships and discover event precursors (Vairo et al., 2023), or foresee water quality parameter variations (Magrì et al., 2023). In the explored context, Zhong et al., (2021) successfully applied deep learning algorithms to identify statistically improbable deviations and detect WT plant anomalies, unexpected working conditions, or contamination events.

WWT upgrade for water reuse: water scarcity remains a significant challenge in central and southern Italy, and a continuous flow of cleaned wastewater could be an important resource for agriculture. In this regard, this study considered the possible application of an automatic cloth filter as tertiary treatment as well, to further reduce suspended solids and related organic pollution. This option is in line with the EU regulation 2020/74 (EU, 2020) establishing the minimum requirements for water quality and monitoring and provisions on risk management, for the safe use of reclaimed water in the context of integrated water management. The preliminary marginal cost analysis, under the hypotheses that capital cost investment is an incremental one and fixing the value of the reclaimed irrigation water on the local prices, led to an approximate investment payback of 14 months.

* 1. Conclusions

This paper evidenced the capabilities of combined LCA in enabling decision-makers to chart pathways to improve the environmental performance of an existing WWT plant for operation, optimization, and retroﬁtting. The analysis allowed understanding the anticipated impacts of the revised plant and elucidating environmental hot spots causing a slightly higher environmental impact. In this regard, anaerobic digestion and cogeneration offer clear environmental benefits suitable to compensate for the increased impacts of the upgrade. However, their contribution to higher acidification, eutrophication and ozone layer depletion should be carefully considered. Some plant upgrade challenges are identified, i.e., continuous monitoring of the energetic performances and real-time management of the WWT plant by relying on ad-hoc designed AI and ML tools for working parameters optimization, in view of attaining less wear out of aerator and lower energy consumptions. These findings underline the importance of balancing operational improvements, economic, and safety impacts with environmental trade-offs, while upgrading WWT design processes to improve environmental performances.

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