Optimizing Sewage Sludge Digestion in Wastewater Treatment Plants: a Case Study from the Largest WWTP in Italy

OPTIMIZING SEWAGE SLUDGE DIGESTION IN WASTEWATER TREATMENT PLANTS: A CASE STUDY FROM THE LARGEST WWTP IN ITALY

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ABSTRACT: This study is part of a multi-objective, integrated approach to analyze various possibilities for increasing energy efficiency of the largest Italian wastewater treatment plant (WWTP) at Castiglione Torinese, NW Italy. The final goal of this study was evaluating the optimization interventions on the sludge treatment process in terms of mass, energy and greenhouse gas (GHG) emission balance. An optimization scenario of sludge digestion was simulated and compared the present operating situation. In the optimized scenario, a hybrid thermo-chemical pre-treatment of the waste activated sludge (WAS) entering the digestion process was considered. The biogas produced was upgraded to biomethane with a process working with selective membranes. Full scale simulation of the whole sewage sludge treatment line was performed with the screening model MCBioCH4, developed by the Authors. The results showed that the optimization interventions would provide two important positive impacts. Firstly, a reduction of the sludge volume entering into the digestion process. Secondly, biomethane production would be around 20% higher than the methane fraction contained in the biogas actually produced. The energy saving and the increased specific biomethane production would improve the overall GHG balance of the system.
Keywords: sewage sludge, sewage treatment, methane, biogas, greenhouse gases (GHG), wastewater treatment.

1 INTRODUCTION

WWTPs have hardly ever been designed considering energy efficiency targets [1]. This attitude has been changing in recent years, however, mainly because of the general framework for the achievement of 2030-2050 goals defined for Climate and Energy by the European Union. The most challenging aspect of WWTP energy optimization is finding a viable, economically feasible solution that can address several different objectives (e.g., effluent quality, energy consumption, and environmental aspects).

Sludge management is a critical process in the optimization of WWTPs. Presently, energy recovery through anaerobic digestion (AD) of sewage sludge represents a vital step toward the reduction of energy consumption in WWTPs. Primary sludge and waste activated sludge (WAS) are produced in WWTPs. Primary sludge is made of readily biodegradable substances and produces an average of 0.280 Nm^3 CH_4/kg VS added [2]. Conversely, WAS produces very limited amounts of methane under the hydraulic retention times (HRTs) applied in standard mesophilic processes (18–20 days). Specific methane production (SMP) of WAS rarely goes beyond the values of 0.100 Nm^3/kg VS added. Several treatments (named as pre-treatments, because they are applied before digestion) can be used to make the biodegradable material of WAS more accessible for the anaerobic process and, subsequently, to increase the production of methane [3].

The biogas produced in the AD phase can be used either for valorization in internal combustion engines, to provide electric and thermal energy, or for upgrading biogas to biomethane, for subsequent injection into the gas grid. Biomethane production is continuously increasing in the EU and worldwide, as it represents a more versatile energy vector than biogas. Biomethane can replace natural gas and be sent into the national gas transmission grid. The selection of the best technological solution in terms of energy consumption and environmental impacts requires a preliminary comparative analysis tailored to the case under study [4]. The use of dedicated modeling tools may support such a selection.

In this study, mass, energy, and GHG balances of the sludge treatment section of the WWTP were analyzed, considering the energy optimization options elaborated by our research group in two recent studies [5] [6]. The SMAT plant at Castiglione Torinese, NW Italy, was considered as a case study. This plant is the largest Italian WWTP. The analysis started from considering a combination of thermal and chemical pre-treatments (named hybrid pre-treatments), that was applied to improve the capacity of WAS to producing methane and consequently enhance the energy recovery of the sludge line. The installation of an advanced sludge pre-thickening stage was also considered. The second stage of the study focused on the energy valorization of sewage sludge through anaerobic digestion. In this first stage, biomethane production as an alternative to on-site biogas combustion was evaluated, considering conventional upgrading technologies. The final goal of the study was to provide relevant information toward the definition of the most environmentally friendly and energy-efficient integrated management scheme of WWTPs.

Greenhouse gas flow accounting of the entire sewage sludge treatment line was performed with the screening model MCBioCH4 (acronym of the bio-methane computational model), developed by the authors [7].

2 MATERIALS AND METHODS

2.1 Description of the WWTP

Castiglione Torinese WWTP treats combined municipal and industrial wastewater with a capacity of around 2,000,000 of equivalent inhabitants. It consists of a line for wastewater treatment and one line for sludge treatment. The water line, with an average flow rate of about 25,000 m^3/h, is made up of the following processes: grid screens, grit and grease removal, primary sedimentation, anoxic and aeration basins, secondary sedimentation and final filtration (Fig. 1). The wastewater treatment process generates an average amount of primary and secondary sludge equal to about 300–350 m^3/h (with an average total solids content of 1%) which is sent to the sludge treatment units. In addition to carbon and nitrogen removal, chemical phosphorus removal is achieved by dosing ferric chloride solution ($FeCl_3$) in wastewater treatment line. The sludge treatment line consists of the following units operation: pre-thickening, mesophilic anaerobic digestion, post-thickening and final dewatering (Fig. 2). The pre-thickening process, carried out by means of gravity devices with the addition of polyelectrolyte for the thickening of secondary sludge, reduces the amount of sludge to be treated by AD to about 110m^3/h, with an average TS content of 2.75% for both primary and secondary sludge. The total sludge flow rate is split among five anaerobic digesters, in fact the plant has six reactors, one of which cyclically in maintenance (Fig. 3).

Figure 1: Photo of the WWTP.

2.2 Description of the case study

The case study involved the sludge treatment optimization at Castiglione Torinese WWTP. This scenario was compared with the actual operating configuration, here referred to as Scenario 0. In the present working conditions, two digesters are filled with primary sludge, two with WAS and the last with mixed sludge. Each digester has a volume of 12,000 m^3 (for a total volume useful to the digestion process of 72,000 m^3), a D/H (diameter, height) ratio of 26/30, a filling coefficient of 0.8, a hydraulic retention time (HRT) of about 17 days, a fed sludge amount of 23.5 m^3/h with a TS content of 2.75%, for a mass flow rate of dry substance of 650 kg/h. The digestion process is carried out in mesophilic conditions, at the temperature value of 38 °C. In order to heat the sludge from the average temperature of 15 °C (ambient temperature) to 38 °C and keep the process temperature constant, each digester is coupled with a double-tube heat exchanger fed by the hot water (90 °C) circuit. The heat necessary to the hot water circuit is supplied by four cogeneration engines (GE-Jenbacher JMS 420 GS-B. L.), that produce heat and electricity by burning the biogas generated in the AD process. Each of the cogeneration engines has a power of 1.47 MW; under normal working conditions only two out of the four engines are in operation, for a total power of 2.7 MW. Each cogeneration engine has a thermal efficiency of 42.4% and an electrical efficiency of 41.9%.

Currently, part of the heat to satisfy the plant auto-consumption is recovered from the sludge-drying line. It is estimated that 1 MW of heat can be recovered from this section, with an exchange efficiency of around 85%. The thermal energy produced by the CHP units is also used to the pre-heating of substrates. Electricity is mainly used to satisfy the consumption of the auxiliary systems. The remaining amount is injected into the distribution grid through a high voltage connection. Electricity consumption of the entire section of the process is around 8,000 MWh/y. Total biogas loss from the process is estimated to be 2% (w/w) of the gross biogas production. The digested sludge is transferred to a post-thickening and centrifugation process, with TS content increased up to 25%. An amount of around 20,000 t/y of sludge is transferred to the drying line, where TS content is increased up to 90%. The dried sludge is then transferred to a final use or disposal. The travelling distance depends on the use and may be subject to variation due to regulation and market constraints [8]. In this study, an average traveling distance outside the plant of 20 km was considered.

Figure 2: Photo of the sludge treatment line.

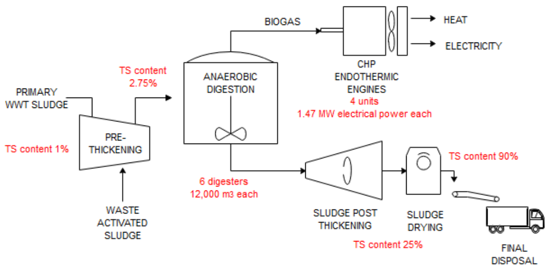

Figure 3: Scheme of the present sludge treatment process.

In the optimized configuration (Scenario 1, Fig. 4), two main innovations were considered. The first is the introduction of a pre-treatment of the waste activated sludge. The second is the installation of a dynamic sludge thickener, with the capacity of increasing the sludge TS content to a value of 6.5%. The pre-treatment process involves a hybrid thermo-alkali treatment. WAS was mixed with NaOH (4% of the TS content) at a temperature of 90°C for 90 minutes. More information on the experimental procedure is reported in [5].

Subsequently, primary sludge and WAS are mixed and pumped into the digesters. In Scenario 1, the production of biomethane was considered. Biomethane was assumed to be obtained with an upgrading process with selective membranes having a specific electricity consumption of the upgrading process is estimated to be 0.3 kWh/m^3. The assumed average efficiency of the process was 98.6%. of biogas treated. It was assumed that the produced biomethane is injected into the national gas distribution grid, replacing an equivalent amount of natural gas. According to this scenario, the sludge-drying line still provides part of the thermal energy needed by the process. For the residual amount, an external energy source is needed. The input parameters and their corresponding values considered in the simulations are reported in Table I.

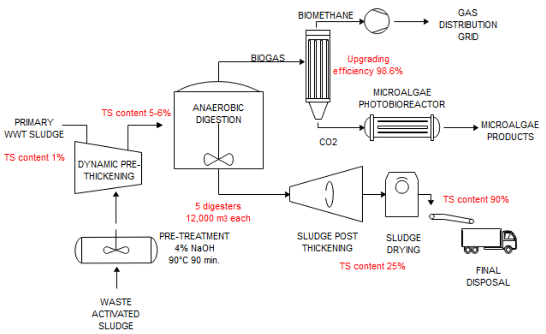

Figure 4: Scheme of the optimized sludge treatment process.

Table I: Input values and parameters used for simulations.

Input parameter/value	Scenario 0	Scenario 1
Primary sludge input flow (t/h)	66.1	30.5
Secondary sludge input flow (t/h)	35.6	16.4
TS input flow (t/h)	3.05	3.05
Primary sludge SMP (Nm^3/kg VS)	0.280	0.280
Secondary sludge SMP (Nm^3/kg VS)	0.090	0.245
Primary sludge TS content after pre-thickening (%)	3	6.5
Secondary sludge TS content after pre-thickening (%)	3	6.5
CH_4 content in biogas (%)	62	62
CH_4 loss from digestion and conversion processes (%)	2	1.33
Thermal energy auto-consumption (MWh/y)	35,650	20,610
Electricity auto-consumption (MWh/y)	8,000	11,770
CHP system efficiency (electric; thermal %)	42.0; 43.0	-
Upgrading system efficiency (%)	-	98.6
Emission factor for natural gas consumption/substitution (gCO_2eq/kWh)	206	206
Emission factor for electricity substitution (Italian national grid) (gCO_2eq/kWh)	337	337

2.3 Full scale plant simulation

Full scale simulation of the process was done with the MCBioCH4 model (acronym of the bio-methane computational model). MCBioCH4 is a standalone application for modeling mass, energy, and environmental balances of biogas/biomethane production plants on a cradle-to-grave basis, i.e., from substrates production to biogas/biomethane end-use. The code was developed with the MATLAB® software, and is provided with a graphical users interface (GUI). MCBioCH4 is structured in three modules for the calculation of mass, energy, and GHG balance, respectively. The model allows the simulation of both biogas combustion or biomethane production. If biogas combustion options are selected, the of thermal energy recovered can be specified. If biomethane scenarios are selected, the user is allowed to specify the typology of upgrading technology, as well as the main features of the upgrading system.

The following technologies are implemented by default: pressurized water scrubbing (PWS), pressure swing absorption (PSA), chemical absorption with amine solutions (MEA) and membrane permeation (MB). Other upgrading technologies may be simulated by introducing customized values of electricity and thermal energy specific consumption. As a starting phase, the user is asked to input the daily mass flow of substrates to be inserted into the digester. Other input parameters can either be provided as default values or be specified by the user. The following sets of output can be obtained from the model:

- the detailed mass and energy balance of the system;
- the net mass flow and energy content of the biogas/biomethane stream;
- the GHG balance of the system, including a comparison with an equivalent system powered by traditional (fossil) fuels. For further details about the developed model, consult [7].

3 RESULTS

3.1 Sludge pre-treatments tests

Fig. 5 shows the curves of SMP (specific methane production) obtained from the lab-scale digestion test for untreated and treated WAS samples. Digestibility tests lasted 20 days; after that time the tests were considered completed since the daily marginal production of biogas or methane was less than 1% of the overall production. It can be observed that the thermo-alkali treatment determined an increase in SBP and SMP of 46.2% and 86.1%, respectively, compared to the untreated samples (data concerning the SBP were not shown).

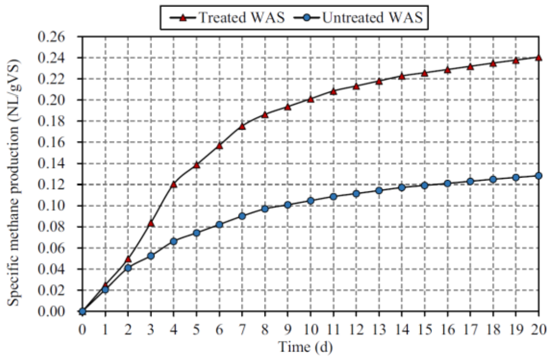

Figure 5: Specific methane production of treated and untreated WAS [5].

The results obtained in the present work can be seen as an improvement over the results of a previous preliminary study [9] carried out with WAS collected from the same WWTP and subjected to the same pre-treatment. In that study increases in SBP in the order of only 16% were observed. A more careful control of the reactors and systems for biogas collection determined more reliable results.

3.2 Full scale simulations

The results obtained by simulating the full scale operation of the process are reported in the following figures and tables. The mass balance of present and optimized configuration is reported in Fig. 6 and Fig. 7 respectively. The energy balance of present and optimized configuration is reported in Fig. 8 and Fig. 9 respectively. A comparison of the results of the two scenarios is reported in Table II.

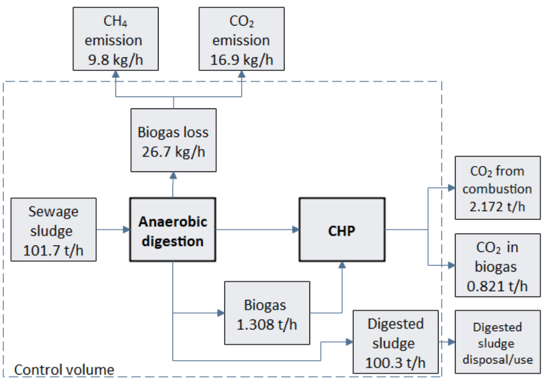

Figure 6: Mass balance of the present situation (Scenario 0).

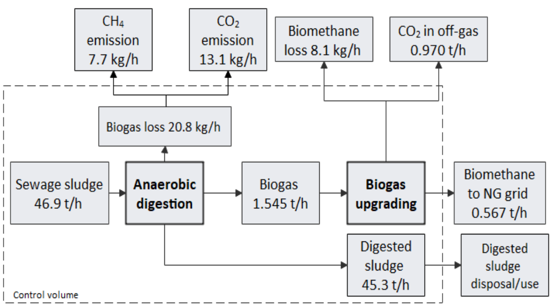

Figure 7: Mass balance of the optimized configuration (Scenario 1).

The results show that the introduction of the optimization interventions brings two critical positive impacts on the overall energy and mass balance of the sludge line of the WWTP. The first is the significant reduction of the sludge volume entering the digesters, due to the installation of a dynamic thickener, in way that the number of digesters could be reduced from 6 to 4. Consequently, to this reduction in volume, three main positive impacts are found:

- A reduction of around 40% of the thermal energy consumed for pre-heating of substrates;
- A reduction of around 20% of the heat dispersion from the digesters;
- A reduction of around 20% of the energy needed to handle and transfer the digested sludge to final disposal and use.

The second positive impact connected to the application of Scenario 1 is the increased specific methane production (SMP) provided by the introduction of hybrid pre-treatment on WAS. Table II shows that, in Scenario 1, biogas energy content is around 18% higher than in the present system. Assuming a conversion efficiency of 90%, the energy content of the biomethane stream is around 63,740 MWh/y. Conversely, the methane released in the upgrading process causes an increase in total methane losses from the overall process (+59%). Also the electricity consumption is higher in Scenario 1, because of the additional energy needed to upgrade biogas to biomethane (+47%). Electricity consumption of the advanced post-thickener is not significant, though, being around 162 MWh/y. The results confirm that an external source of heat is needed to cover the internal demand for thermal energy. For this reason, the installation of a boiler fueled by natural gas was assumed, causing additional energy consumption.

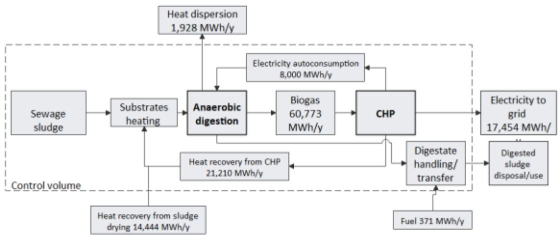

Figure 8: Energy balance of the present situation (Scenario 0).

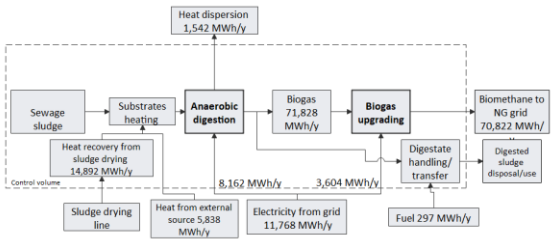

Figure 9: Energy balance of the optimized configuration (Scenario 1).

Table II: Input values and parameters used for simulations.

Input parameter/value	Sc. 0	Sc. 1	Diff.
Biogas production (t/y)	11,456	13,539	+18%
Gross biogas energy content (MWh/y)	60,773	71,828	+18%
Thermal energy internal demand for pre-heating of substrates	33,728	20,236	-41%
Thermal energy internal demand for compensation of digesters dispersion	1,928	1,542	-21%
Internal electricity demand, total	8,000	11,768	+47%
Net thermal energy production (MWh/y)	26,514	63,740	+140%
Net electricity production (MWh/y)	25,454	-	-100%
Thermal energy auto-consumption covered by biogas/biomethane (%)	59	-	-59%
Thermal energy auto-consumption covered by drying line (%)	41	72	+31%
Electricity auto-consumption covered by biogas/biomethane (%)	100	0	-100%
Thermal energy auto-consumption covered by external source (%)	0	28	+28%
Electricity auto-consumption covered by external source (%)	0	100	+100%
Energy consumption for digestate handling/transfer (MWh/y)	371.7	296.6	-20%
Total CH_4 loss from the process (t/y)	87.0	138.7	+59%

The comparison of total greenhouse gas balance resulting from the simulations with the MCBioCH4 model is reported in Table III. In this table, the present and optimized configurations are compared in terms of annual emissions of equivalent CO_2. Both the present and the alternative configurations show a negative GHG balance, meaning that avoided emissions for the substitution of natural gas and electricity are higher than the emissions produced for process maintenance. The optimization interventions are expected to improve the environmental balance of the plant of around 40%. Specific Equivalent CO_2 emission is expected to decrease from -0.278 t CO_{2eq}/t biogas to -0.394 t CO_{2eq}/t biogas (from -3,182 t CO_{2eq}/y to -5,333 t CO_{2eq}/y). These results are comparable to existing studies, although these are largely affected by process configuration [6].

Table III: Results of the GHG balance.

Input parameter/value	Sc. 0 t $CO2_{eq}$/y	Sc. 1 t $CO2_{eq}$/y	Diff.
Total CH_4 loss from the process	2,437	3,883	+34%
Total CO_2 loss from the process	147	115	-39%
Net electricity production	-5,883	-	-
Biomethane replacing natural gas	-	-14,594	-
Thermal energy auto-consumption covered by external source	-	1,203	+100%
Electricity auto-consumption covered by external source	-	3,967	+100%
Energy consumption for digestate handling/transfer	117	93	-30%
Produced GHG emissions	2,701	9,261	+180%
Avoided GHG emissions	-5,883	-14,594	-109%
GHG emission balance	-3,182	-5,333	-41%

4 CONCLUSION

The achievement of a high efficiency in a WWTP requires to deal with issues such as the improvement in pollutant removal and the enhancement of energy utilization. In this study, an integrated experimental and modeling feasibility analysis assessing possible opportunities to minimize the carbon footprint of the largest Italian WWTP was presented. A scenario analysis for improving the biogas production in sludge treatment units was compared with the present situation. The introduction of the optimization interventions would allow optimum exploitation of the energy contained in the sludge. The results also showed that the innovations presented in this study would reduce the GHG emissions of the sludge treatment line of the plant by around 40%. In the next future, the feasibility of the proposed interventions will be analysed in detail, possibly with experimental tests at the full scale. Also the opportunity of using a custom-made planar photobioreactor, for the capture of the CO_2 emitted from the upgrading process will be evaluated.

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