Evaluating the greenhouse gas emissions of a municipal wastewater treatment plant with sludge incineration

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Abstract

This study addresses the assessment of greenhouse gas emissions (GHG) produced by a large municipal wastewater treatment plant (WWTP), which includes the management of sludge by incineration. For the scope, a WWTP, processing mainly domestic wastewater with a treatment capacity of 358,448 PE (population equivalent), was considered. The assessment of GHG emissions considered both the plant in its current configuration, which involves the co-management of primary and secondary sludge, anaerobic digestion and disposal of mechanically dewatered sludge in landfills, and the plant in the configuration based on sludge incineration (which involves the fluidized bed technology) with energy recovery. The quantification of GHG emissions was carried out through the holistic approach implemented with ECAM 2.0 (Energy Performance and Carbon Emissions Assessment and Monitoring), a tool developed within the WaCClim project. The obtained results showed how the thermal scenario produces higher GHG emissions than the reference scenario and the largest GHG contribution was made by the additional fuel (methane) used for starting up and supporting the combustion process. It is therefore advisable to reduce the consumption of additional fuel. In this regard, it was estimated that by adopting an integrated thermal sludge treatment (drying + incineration), instead of conventional incineration, would result in a 98% GHG emissions reduction due to auxiliary fuels alone.

1. Introduction

The issue of the treatment and disposal of sludge from municipal wastewater treatment processes has become increasingly important in recent years. One of the most important aspects in industrialized countries is the land scarcity for waste disposal (De Feo and De Gisi, 2014).

Among the many available technologies, thermal processes have the advantage of significantly reducing the amount of sludge to be disposed of. On the other hand, many disadvantages such as the opposition of the communities make it difficult to realize and authorize them in practice (De Feo and Williams, 2013).

The main argument is that incinerators cause pollution; hazardous compounds such as dioxins (PCDD/PCDF) are released into the environment. The combination of "incinerator and greenhouse gas production" is also very frequent. Therefore, in this context, it is important to disseminate correct information in order to reduce the so-called NIMBY (*Not-In-My-Back-Yard*) syndrome. In addition, it is important to demonstrate how the best solution for a specific case study can also be based on thermal processes, in terms of both technical and environmental performances.

Currently, there are several methodologies developed for an adequate quantification of the greenhouse gas emissions (GHG) produced in a company working into the water and wastewater field (Table 1). However, their application, including for the identification of the best sludge management alternatives, is not consolidated.

The aim of the study was to evaluate the GHG emissions of a thermal sludge-based municipal wastewater treatment plant (WWTP).

For the scope, a large municipal WWTP was considered; two different sludge management scenarios were identified. The first, considered as reference scenario, provided for the anaerobic digestion of mixed sludge (primary and secondary biological sludge) and the disposal of mechanically dewatered sludge in landfills; the second, in addition, provided for the thermal treatment of the sludge in a fluidised bed combustor.

2. Methodological approach

The study of the performance of the WWTP under investigation in terms of the main contaminants removed was considered initially. Subsequently, the alternative sludge management scenario, which included sludge incineration, was studied.

The final step concerned the GHG emissions evaluation considering the reference scenario (*status quo*) and the thermal treatment-based scenario. The evaluation of GHG emissions was carried out using the ECAM 2.0 tool, as herein described.

Table 1. Overview on GHG emission estimation methods.

N.	Reference	Name	Features
1	IPCC	IPCC Inventory Software version. 2.54	Implementation of Tier 2 methods for the “energy”, “IPPU” and “waste” sectors
2	US EPA	MOVES – Moto Vehicle Emission Simulator	Model for estimating emissions from moving sources, containing a wide range of pollutants and possibilities for multi-scale analysis
3	Wolters Kluwer company	Enablom Greenhouse Gas Emissions Software	Detailed management of the inventory of GHG emissions (direct and indirect) of a company
4	US EPA	ICR version 2.1 (RWETv2.1) – Refinery wastewater emissions tool spreadsheet	Calculation of GHG emissions for waste water treatment companies. Estimation of GHG emissions from landfills for municipal solid waste
5	US EPA	LandGEM – Landfill Gas Emission Model	Estimation of GHG emissions from landfills for municipal solid waste
6	US EPA	Water9	Model for the estimation of aeriform emissions of each treatment unit of a water treatment plant
7	WaCClim	ECAM 1.0	Estimation of GHG and energy efficiency for each utility operating in the water sector
8	WaCClim	ECAM 2.0	As in the previous case, but with more sludge management options (BEAM model)
9	GHG Protocol	Tools collection	For companies and cities, the protocols enable the development of complete and reliable emission inventories.
10	UNFCCC/CCNUCC	A/R tool 2.0	Estimation of fossil fuel combustion emissions

2.1 WWTP under investigation

The WWTP considered as a case study is located in Italy (Trentino Alto Adige region); it has a capacity of 358,448 population equivalent (PE, corresponding to a five-day biodegradable organic load of 60 g BOD_5/d) and an average flow-rate of 89,612 m^3 per day. The inlet wastewater consists mainly of a domestic component, which is treated according to the treatment scheme of Figure 1.

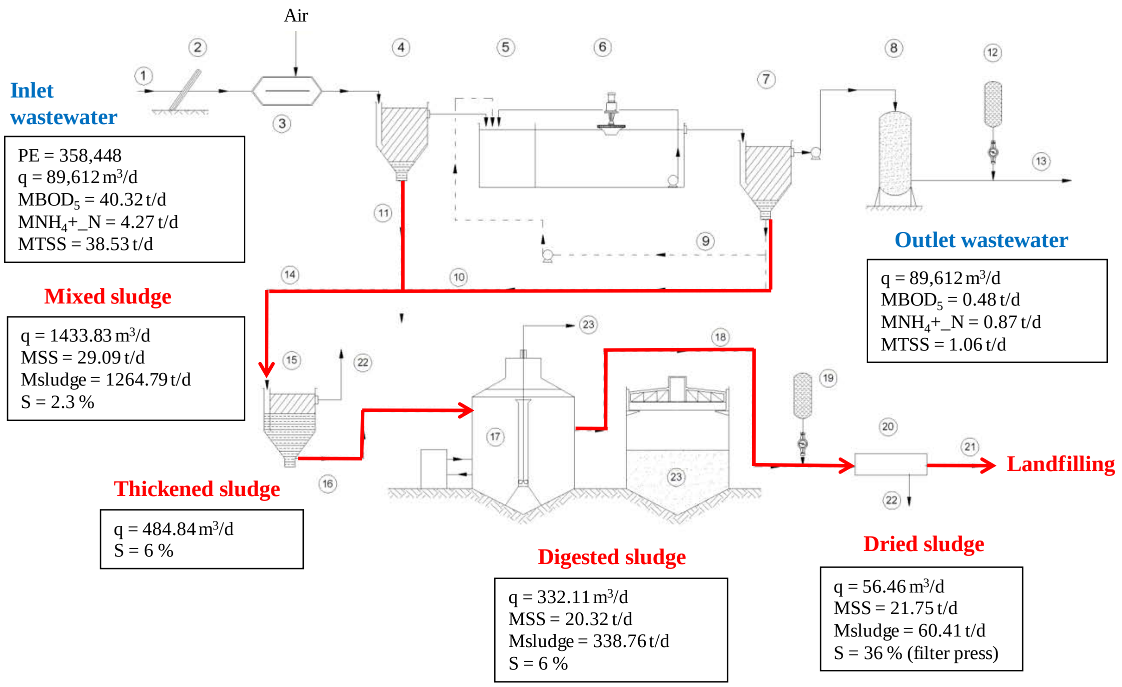

Figure 1. Flow chart of the reference scenario. In this figure: 1 = inlet wastewater; 2 = screening; 3 = sand and oils removal; 4 = primary sedimentation; 5 = denitrification; 6 = nitrification/oxidation; 7 = secondary sedimentation; 8 = sand filtration; 9 = return activated sludge; 10 = secondary (biological) sludge; 11 = primary sludge; 12 = disinfection; 13 = effluent to the discharge; 14 = mixed sludge; 15 = thickening; 16 = thickened sludge; 17 = anaerobic (mesophilic) digestion; 18 = digested sludge; 19 = chemical conditioning; 20 = mechanical dewatering with filter press; 21 = dried/dewatered sludge for landfilling; 22 = supernatant; 23 = biogas flow for energy recovery.

The water line includes pre-treatments (screening, sand and oils removal), primary sedimentation, activated sludge-based biological treatment for biodegradable BOD removal and for nitrogen compounds control, secondary sedimentation, sand filtration and disinfection. The sludge line, on the other hand, includes thickening, anaerobic digestion (with recovery of biogas and consequently electricity), sludge chemical conditioning and mechanical dewatering. The latter is carried out with a press filter, which is able to assure a dry sludge content of 36%.

The WWTP is loaded with mainly domestic wastewater, the characteristics of which are shown in Table 2.

The system is able to comply with the limit values set by Legislative Decree 152/2006 for the discharge of water into the receiving body (D. Lgs 152, 2006).

Table 2. Data from the WWTP under investigation.

General characteristics	**Wastewater characteristics**			
	Parameter	**Inlet [mg/l]**	**Effluent [mg/l]**	**Removal efficiency [%]**
Design population equivalent = 364,000 PE	BOD	450	5,4	98.8
Effective population equivalent = 358,448 PE	COD	766	37.7	95.1
Average inlet flow-rate = 89,612 m^3/d	Total nitrogen	47.7	9.6	79.9
Nature of influential wastewater = predominantly domestic	Total phosphorous	9.6	1.0	89.6
	TSS	430	11.8	97.3

The removal efficiencies are high on average, with values of 98.8%, 95.1%, 79.9%, 89.6% and 97.6% for BOD_5 (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), Total Nitrogen, Total Phosphorous and TSS (Total Suspended Solids), respectively.

2.2 Sludge management scenario based on thermal treatment

The alternative sludge management scheme to the reference one involves that the dewatered sludge is sent to the incineration system (Fig. 2).

After anaerobic digestion, the mixed sludge (composed of primary and secondary-biological sludge) is chemically conditioned with a polyelectrolyte and then sent to mechanical dewatering based on belt presses; the dry content achieved, differently from the reference scenario, is slightly lower and equal to 25%.

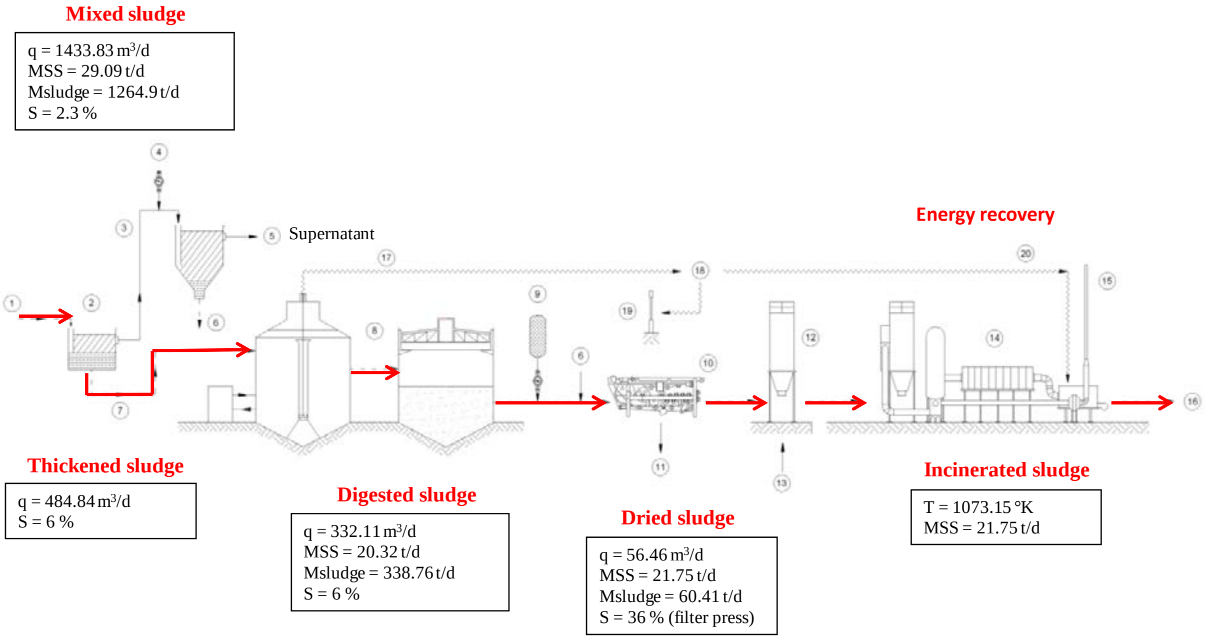

Figure 2. Flow chart of the thermal-sludge based scenario. In this figure: 1 = mixed sludge produced in the water line reported in Fig. 1; 2 = thickening; 3 = supernatant; 4 = chemical addition for phosphorous removal; 5 = supernatant; 6 = chemical sludge rich in phosphorous; 7 = thickened sludge; 8 = anaerobic (mesophilic) digestion; 9 = sludge conditioning; 10 = mechanical (belt press) dewatering; 11 = supernatant; 12 = sludge storage; 13 = external sludge; 14 = incineration; 15 = chimney emissions; 16 = incinerated sludge.

The sludge so dehydrated is sent to the incineration unit based on the fluidised bed technology (Notarnicola *et al.*, 2017).

According to ECAM 2.0 options, the dried sludge (dry, 36%) is incinerated in the fluidized bed combustor at the temperature in the range 800-950°C. The combustion reaction generates fumes, unburned ash and fly ash, which are then treated in order to protect the environment.

2.3 ECAM 2.0 tool

The holistic approach of ECAM first requires an initial assessment (called *Tier A*), which gives a comprehensive overview of GHG emissions and energy consumption. ECAM then carries out a detailed assessment (called *Tier B*) regarding the three main sections of a WWTP: (1) Collection; (2) Treatment; and (3) Discharge/Reuse.

In the first section, it was necessary to define the volume of wastewater treated in the plant, the energy consumed for the initial pumping, the initial BOD_5 load o and the consumption of annual proteins. This part of analysis provides for the definition of the site-specific characteristics of the country where the WWTP is located.

In the second section, it was necessary to provide information on the inlet and outlet polluting load (i.e., in terms of BOD), the value of BOD_5 removed as sludge, the production and use of biogas as well as sludge management modalities.

In the third section, the energy consumed in the discharge, the concentration of nitrogen in the discharge and, where appropriate, the volume of water reused shall be specified.

ECAM 2.0 allows to evaluate the GHG emissions for each WWTP section, expressed in terms of CO_2eq. In particular, three types of emissions are evaluated: direct, indirect emissions from electric energy and other indirect emissions. It is observed that although they exist, ECAM 2.0 is not able to evaluate all the emissions produced in a WWTP (Tab. 3).

Furthermore, for evaluation purposes, the following assumptions were made: Emission factor for grid electricity = 0.41 kgCO_2/kWh; Annual protein consumption per capita = 40.88 kg/person/y. According to the Global Warming Potential source (IPCC5 th AR (2014/2013) CCF) the following assumptions were made: 1 CO_2 = 1 CO_2 equivalents; 1 CH_4 (methane) = 34 CO_2eq; 1 N_2O (Nitrous oxide) = 298 CO_2eq.

Finally, the energy consumption estimation has been performed using the database reported in De Feo *et al.* (2012). Instead, the running costs have been estimated using the database of Italian WWTPs reported in De Gisi *et al.* (2015).

Table 3. GHG emission typologies calculated with ECAM 2.0 with reference to the wastewater field.

GHG emissions typologies	**WWTP sections**		
	Collection	**Treatment**	**Discharge**
Scope 1 – Direct emissions			
Emission from the maintenance trucks	□	□	□
CO_2, CH_4 and NO_2 emissions from on-site stationary fossil fuel combustion	■	■	■
CH_4 from sewer or biological wastewater treatment	□	■	
N_2O from sewers or biological wastewater treatment	□	□	
Scope 2 – Indirect emissions			
Indirect emissions from electric energy	■ ○	■	■ ○
Scope 3 – Other indirect emissions			
Emissions from the manufacturing of chemical used		□	
Emissions from the construction materials used	□	□	□
CH_4 and CO_2 emissions from wastewater discharge without treatment	■		
CO_2, CH_4 and NO_2 emissions from sludge transport off-site		■	
N_2O emissions from effluent discharge in receiving waters			■

Legend: □ = emissions not quantified in the ECAM tool, even though they exist; ■ = emissions quantified in the ECAM tool; ○ = unless wastewater collection/discharge is by gravity.

3. Results and discussion

The application of the ECAM methodology made it possible to quantify the GHG emissions produced by the two sludge management scenarios investigated. The results are layers presented both in absolute terms, on an annual basis, and in terms of GHG emissions per population equivalent (Table 4).

In particular, a significantly lower GHG value was observed for the reference scenario (36,921.8 t CO_2eq/y) than for the sludge thermal treatment-based scenario (6,808,044.4 t CO_2eq/y).

Table 4. GHG emissions results considering the reference scenario and the thermal sludge treatment-based scenario with only incineration, as permitted by ECAM 2.0.

WWTP section	GHG emissions [t CO_2eq/y]		GHG emissions [kg CO_2eq/y/PE]	
	Reference scenario	Thermal sludge treatment-based scenario	Reference scenario	Thermal sludge treatment-based scenario
Collection	1305.7	1305.7	4.0	4.0
Treatment	33,940.1	6,805,062.7	95.0	18,984.8
Discharge/Reuse	1676.0	1676.0	5.0	5.0
Total	36,921.8	6,808,044.4	104.0	18,993.0

The WWTP section that generated the highest value of GHG emissions was basically that relating to treatment. The other two sections, collection and discharge, had significantly lower values than the treatment.

Moreover, since the two investigated scenarios were distinguished only by the introduction, in the thermal scenario, of the incineration of dewatered sludge, the GHG emissions corresponding to the collection and discharge sections resulted as being the same (Fig. 3a, b).

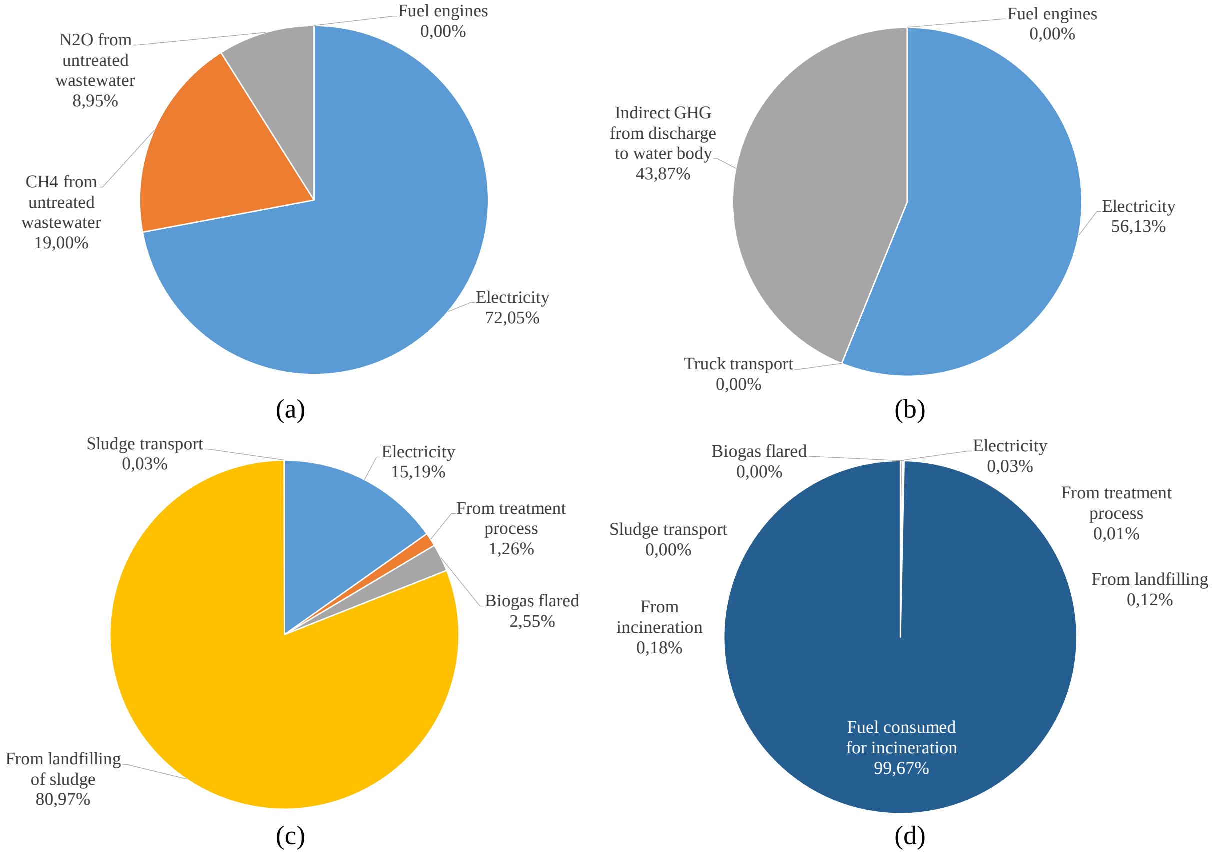

Figure 3. Weight of individual items in the calculation of GHGs emissions: (a) Collection section for both scenarios; (b) Discharge/reuse section for both scenarios; Treatment section for (c) the reference scenario and for (d) the thermal sludge treatment-based scenario with only incineration.

Regarding the collection section, the highest GHG emissions concerned the production of electricity for the initial pumping of wastewater (72.05%). GHG emissions from untreated wastewater were 27.95% (19% of CH_4 and 8.95% of N_2O from untreated wastewater).

The discharge section highlighted how GHG emissions were mainly due to the consumption of electricity for the handling of treated waste (56.13%); indirect GHG emissions from discharge to the water body were equal to 43.87%, also in this case for both scenarios.

The analysis of the treatment section showed that in the case of the reference scenario, GHG emissions were mainly due to the disposal of sludge in landfills (80.97%), to the electricity used for the treatment processes (15.19%), to the thermal destruction, through torch, of the surplus biogas produced in anaerobic digestion (2.55%) and finally to the treatment process (1.26%) (Fig. 3c).

On the other hand, the GHG emissions produced by the sludge thermal treatment scenario were exclusively due to the consumption of additional fuel (methane) used to start-up and sustain combustion (99.6%) (Fig. 3d). In this regard, the consumption of additional fuel was found to be 3,336,254.7 Nm^3/y (9140.4 Nm^3/d), evaluated adopting a specific value of 0.5 Nm^3 per kg of dry dewatered sludge (36%) as well as a production of dry sludge of about 18,200 t/d. Additionally, the specific value of above was assumed on the basis of the information provided by Mininni *et al.* (2004) that suggested such a value for a mechanically dewatered sludge with a dry of 36% and an incineration without drying.

Table 5. GHG emissions results with reference to the only incineration and the “drying + incineration” integrated treatment.

WWTP section	GHG emissions [t CO_2eq/y]		GHG emissions [kg $CO_2eq/y/PE$]	
	Thermal sludge treatment-based scenario (only incineration)	Thermal sludge treatment-based scenario (drying + incineration)	Thermal sludge treatment-based scenario (only incineration)	Thermal sludge treatment-based scenario (drying + incineration)
Collection	1305.7	1305.7	4.0	4.0
Treatment	6,805,062.7	158,394.2	18,984.8	441.8
Discharge/Reuse	1676.0	1676.0	5.0	5.0
Total	6,808,044.4	161,375.9	18,993.0	450.8

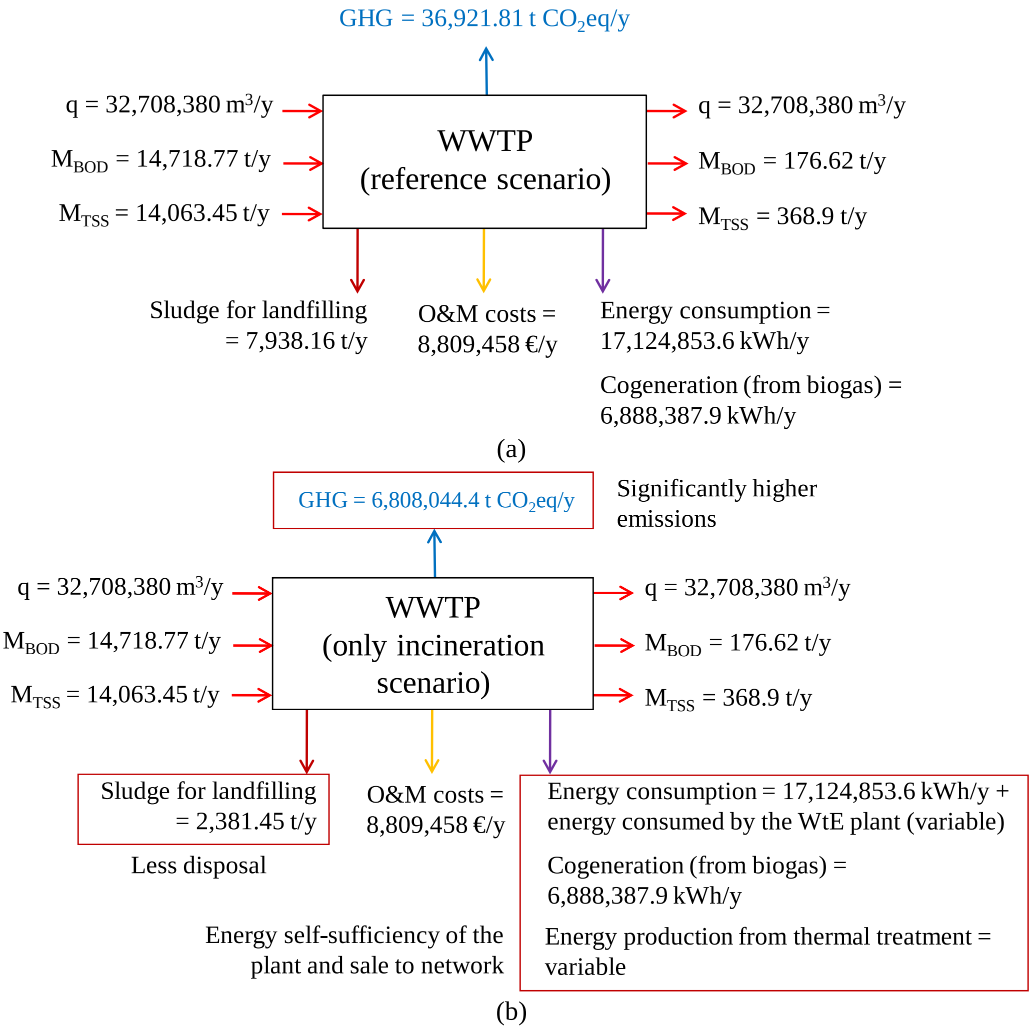

Figure 4. Mass and energy balance results related to the (a) reference scenario and (b) thermal sludge treatment-based scenario with only incineration.

As GHG emissions were linked to fuel consumption, they could have been reduced if fuel consumption had been reduced. Mininni *et al.* (2004) reported how by adopting an integrated treatment such as “drying +

incineration", it led to a strongly reduction in the specific consumption of methane; in our case, it ranged from a value of 0.5 to one of 0.01 Nm^3/kgSS, with a percentage reduction of 98%. The corresponding GHG emissions related to the only additional fuel contribution would have been 135,646.3 t CO_2eq/y.

Therefore, GHG emissions corresponding to a thermal scenario with such an integrated treatment would be 158,394.2 t CO_2eq/y (Table 5).

Despite this, GHG emissions from the improved thermal process (drying + incineration) were higher (450.8 kg CO_2eq/y/PE) than in the reference scenario (104.0 kg CO_2eq/y/PE).

Finally, taking into account the mass and energy balances (Fig. 4), the obtained results showed that the identification of the best scenario was only possible considering further aspects to GHG emissions, such as costs, less space for landfills, etc. For this purpose, a multi-criteria analysis methodology should be adopted (De Feo *et al.*, 2018).

4. Conclusions

The investigation highlighted the suitability of ECAM 2.0 as a holistic approach for estimating the GHG emissions produced in a large municipal WWTP. However, ECAM does not allow thermal technologies other than incineration alone (although based on fluidised bed) to be considered, representing a first limitation.

The main GHG emissions for a plant that provides for the incineration of sludge were linked to fuel consumption (99.67%). As a result of such consumption, GHG emissions in the thermal scenario were significantly higher (18,993 kg CO_2eq/y/PE) than in the reference scenario (104 kg CO_2eq/y/PE).

Despite this, the analysis of the case study has shown how, using an integrated thermal treatment such as "drying + incineration", able to reduce the consumption of methane from 0.5 to 0.01 Nm^3/kg of dry inlet dewatered sludge, it was possible to generate a very significant reduction in GHG emissions of about 98%.

As a result, thermal treatment becomes very competitive for the scenario under investigation (450.8 kg CO_2eq/y/PE), especially considering that the selection of the most suitable scenario for sludge management must necessarily take into account other aspects such as operating costs (including sludge disposal) and energy consumption; as is well known, these aspects are much more positive in the case of thermal treatment.

Acknowledgements

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