

ENVIRONMENTAL COMPARISON OF ALTERNATIVE SCENARIOS FOR SEWAGE SLUDGE MANAGEMENT

Cristina Nocita^a, Lidia Lombardi^b, Elena Bettazzi^c, Donatella Fibbi^c, Ennio Carnevale^a

^a*Industrial Engineering Department, University of Florence, via Santa Marta 3, 50139 Firenze, Italy*

^b*Niccolò Cusano University, via Don Carlo Gnocchi 3, 00166 Rome, Italy,*

^c*G.I.D.A. S.p.A, Via di Baciacavallo 36, 59100 Prato, Italy*

ABSTRACT: The present study is concerned with the application of LCA method to analyse five different scenarios for the management of the sewage sludge produced by G.I.D.A., a company that owns five WWTPs in Prato (Tuscany, IT) with a total design capacity of 1.2 millions per-capita equivalents. The first scenario describes the real situation with reference to 2014: after mechanical dewatering, 76.1%DM of the sludge is sent to the existing multiple-hearth incinerator (without energy recovery) located in one of the WWTPs; the remaining amount is sent to external plants characterized by different disposal/treatment systems. The second scenario assumes that all the DM is treated in a fluidized bed incinerator. As a matter of fact, G.I.D.A. is currently studying the possibility of building a new incinerator with energy recovery, with a treatment capacity suitable to accept the sludge produced by all the five WWTPs. The third scenario assumes that the entire amount of dry matter sludge is treated in a hypothetical wet oxidation reactor, since this process has been proposed in literature as an alternative to incineration. The fourth scenario refers to shutting down the existing multiple-hearth incinerator without building a new plant: in this case all the sludge produced by G.I.D.A. would be sent to external plants. The fifth scenario is about the most recent G.I.D.A. sewage sludge management data, referring to 2015. The inventory for the considered processes was compiled by using different sources, described in details in the paper. According to the results, the possibility of building a new incineration plant, with energy recovery, at one of the G.I.D.A. sites, seems to provide the lowest environmental impacts.

KEYWORDS: *sewage sludge management, life cycle assessment, wastewater, incineration, wet oxidation, composting, land spreading, landfill.*

1. INTRODUCTION

Sewage sludge management is one of the most important issues regarding the management of a wastewater treatment plant (WWTP). The attention paid to the topic has risen in the last

years due to the high number of WWTPs and the increase of water depurative standards in developing countries. The choice of a specific disposal solution is related to many different factors, i.e. the sludge characteristics, the plants availability, the market condition, etc.; there is not a general solution suitable for all the WWTPs.

G.I.D.A. is a company that manages five WWTPs in Prato (Tuscany, IT), with a total design capacity of 1.2 millions per-capita equivalents, that treat both civil and industrial wastewater. In 2014 the all WWTPs produced a total amount of 33,295 ton of dewatered sludge, corresponding to 8,232 ton of dry matter (DM). Currently G.I.D.A. sends the 76.1%DM of sewage sludge produced every year to combustion in a multiple-hearth incinerator, located in one of the WWTPs. The incinerator capacity is insufficient to guarantee the combustion of all the produced sewage sludge, because the thermal treatment plant was built several years ago, when G.I.D.A. managed only one WWTP; furthermore the plant is not equipped with the energy recovery section. The remaining quantity of sludge is transported in external treatment/disposal plants - located in Tuscany and in North Italy - where it is composted, directly used as fertilizer, landfilled or is subjected to a pyrolysis process.

The company is now studying the possibility to change its own sewage sludge management system, in order to reach two purposes: being independent from external plants and using the energy content of the sludge. With this aim, G.I.D.A. proposed a new incineration plant project, based on fluidized bed technology, able to burn all the sludge produced by the five WWTPs and recovering electricity.

However another alternative treatment for sewage sludge was considered, that is the wet oxidation (WO). Large discussion and interest is growing around this technology, especially in Italy, where there is only one operative plant (3V Green Eagle, 2007). WO consists in the oxidation of organic and inorganic pollutants at high temperature (150–360 °C) and pressure (30–250 bar) by means of pure oxygen as oxidizing agent (Bertanza et al., 2015a; Chunga et al., 2009). As a consequence of the enhanced contact with molecular oxygen the organic matter is converted to carbon dioxide, water, and intermediate oxidation products such as low molecular weight organic compounds (Debellefontaine and Foussard, 2000).

The aim of this work was to compare the different described alternative sewage sludge management systems, with reference to G.I.D.A. case, from an environmental point of view. For this purpose, the life cycle assessment (LCA) approach was used. LCA is a framework methodology that analyses the potential environmental impacts of an assigned system and could be used as a basis for decision-making. The analysis was carried out, reported and described according to the LCA phases (EN ISO 14040:2006; EN ISO 14044:2006): goal and scope definition and inventory analysis are presented in the materials and methods section, while impact assessment and interpretation will be discussed in the results section.

2. MATERIALS AND METHODS

2.1 Goal and scope definition

The purpose of the present LCA is to analyse the environmental impacts of five scenarios related to sewage sludge management system. The study is focused on G.I.D.A., the company that treats wastewater in Prato (Italy) with five WWTPs and owns an incinerator plant for sewage sludge. The considered alternative solutions are listed in Table 1. **Compared scenarios.**

Table 1. Compared scenarios.

Scenario	Description	Abbreviation
1	G.I.D.A. management in 2014: 76.1% sludge incinerated, 23.9% send to external plants	SC1-GIDA14
2	Incineration hypothesis: 100% of sludge incinerated in a new bigger plant	SC2-INC
3	WO hypothesis: 100% of sludge treated in a WO plant	SC3-WO
4	Off site management hypothesis: 100% of sludge sent to external plants	SC4-OffSite
5	G.I.D.A. management in 2015: 76.1% sludge incinerated, 23.9% send to external plants (different from 2014)	SC5-GIDA15

The LCA boundaries of the analysed systems include sludge treatment starting from the mechanical dewatering, until final disposal of both sludge and possible residues of the processes. Mechanical dewatering is applied to all the sewage sludge produced in each scenario, except for SC3-WO, where only 61,1% of sludge is dewatered in order to reach the dry matter content required by the wet oxidation process: around 5-7% (Bertanza et al., 2015a). In the other cases sludge has 25% of solid content after this pre-treatment.

In the scenarios 1 to 4 the total treated amount is 8,232 tDM (sludge produced in 2014), in scenario 5 the quantity is 8,210 tDM (sludge produced in 2015).

The first scenario consists in incineration of 76.1% (6,263.8 tDM) of the sludge produced by the five WWTPs and the remaining part (1,968.4 tDM) is sent to external destinations: 12.9% is composted, 8.1% is directly used as fertilizer, 2.4% is disposed in landfill and 0.5% is thermally treated in a pyrolysis plant. In 2015 (SC5-GIDA15) approximately the same quantity of sludge is sent in external destinations and allocated as it follows: 18.5% is composted, 2% is directly used as fertilizer and 3.4% is disposed in landfill. In the fourth scenario hypothetically 60.5% of sludge is sent to landfill and 39.5% is composted and then used as fertilizer.

The abovementioned options are compared, assuming the functional unit equal to 1 t of dry matter (tDM). The impact results are evaluated taking into consideration the avoided effects caused by the substitution of process products and co-products:

- fertilizer use avoidance by sludge land spreading (SC1-GIDA14, SC4-OffSite and SC1-GIDA15);
- electric energy avoided by energy recovery from the combustion of biogas produced in landfill and in the anaerobic digester present in the WWTP where the leachate is treated (SC1-GIDA14, SC4-OffSite and SC1-GIDA15);
- inert materials avoided by the recovery of incineration residues (SC1-GIDA14, SC2-INC and SC5-GIDA15);
- sodium chloride avoided by the recovery of residual sodium in incineration residues (SC2-INC);
- electric energy avoided by the energy recovery in the incineration process (SC2-INC).

Environmental impacts of plants activity, air/water/soil emissions, production of electric energy, methane and chemicals are taken into consideration. Pyrolysis is not included in the inventory

analysis because its contribution is negligible. Impacts caused by the construction of the plants are not inserted in the system.

The inventory of all materials and energy flows is performed utilizing ecoinvent 3.0 database. The impact assessment is carried out with the use of CML-IA baseline method, composed of eleven impact categories: abiotic depletion, abiotic depletion (fossil fuels), global warming (GWP100a), ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. The marine aquatic ecotoxicity is excluded by the analysis because its results are too high compared to the others categories.

The contribution analysis of the different processes present in the scenarios was carried out. Finally, the sensitivity and uncertainty analysis of the results is presented.

2.2 Life cycle inventory analysis

The inventory analysis is developed according to the ISO 14040 and it includes the required energy and materials (inputs) flows as well as products, co-products, emissions and wastes (outputs) emitted to the environment during all the considered processes.

Mechanical dewatering is the only treatment common to all scenarios: it comes preliminarily all the considered treatment/disposal processes. Sludge entering the dewatering phase has a dry matter content of 3%, the outlet flow has an average level of 25%DM. G.I.D.A. data are used for the inventory analysis (Table 2. Inventory of mechanical dewatering.).

Table 2. Inventory of mechanical dewatering.

Element	Value	Unit (/tDM)
<u>Inputs</u>		
Polyelectrolyte	18	kg
Electricity	3.9	kWh
Water for polyelectrolyte solution	6	m ³
<u>Output</u>		
Wastewater	29.3	m ³

In the following paragraphs the detailed inventory of the five scenarios are reported. For this purpose chemical composition of sludge illustrated in Table 3. Chemical composition of G.I.D.A. sludge. is used.

Table 3. Chemical composition of G.I.D.A. sludge.

Element	Value	Unit
Carbon	21.3	% DM
Hydrogen	5.1	% DM
Nitrogen	1.7	% DM
Sulphur	1.5	% DM
Oxygen	22.3	% DM
Chloride	0.1	% DM
Phosphorous	0.5	% DM
Potassium	0.1	% DM
Chromium	96	mg/kgDM
Mercury	<1	mg/kgDM
Zinc	668	mg/kgDM
Lead	86	mg/kgDM
Cadmium	<1	mg/kgDM
Nickel	26	mg/kgDM
Copper	394	mg/kgDM
Arsenic	2	mg/kg
Barium	121.9	mg/kg
Cobalt	1	mg/kg
Molybdenum	2	mg/kg
Antimony	4.9	mg/kg
Selenium	1	mg/kg
Tin	1.7	mg/kg
Vanadium	5	mg/kg
Beryllium	1	mg/kg
Thallium	1	mg/kg

2.2.1 SC1-GIDA14

The inventory for multiple-hearth incinerator present in the first scenario - and also in SC5-GIDA15 - is gathered on the basis of the report that annually G.I.D.A. presents to the regional supervisory authority. Destination of incineration residues is considered according to the real case, but literature data are used for the inventory of disposal process.

Table 4. Inventory of multiple-hearth incinerator (G.I.D.A. S.p.A., 2015a).

Element	Value	Unit (/tDM)
<u>Inputs</u>		
Electricity	267.8	kWh
Natural gas	456.4	Nm ³
Urea	0.07	kg
Water for urea solution	0.00021	m ³
Sodium hydroxide	0.09	kg
Water for sodium hydroxide	0.0003	m ³
Water for bottom ash cooling	0.06	m ³
<u>Outputs to air</u>		
CO	58,500.1	mg
Particulates	41,785.8	mg
NO _x	672,751.3	mg
SO ₂	286,232.7	mg
TOC	31,339.3	mg
Cd+Tl	12.5	mg
Mercury	213.1	mg
Metals	585	mg
PCDD+PCDF	32.4	ng
IPA	0.65	mg
HF	16,714.3	mg
HCL	87,750.2	mg
<u>Other outputs</u>		
Wastewater (flue gas treatment)	471.5	m ³
Bottom ash	366.1	kg
Fly ash	1.95	kg

Table 5. Inventory of incineration residues disposal.

Element	Value	Unit (/kg _{residues})	Reference
<u>Bottom ash</u>			
Electricity	0.004	kWh	CiAI, 2010
Sand (recovered)	0.6	kg	—
Gravel (recovered)	0.4	kg	—
<u>Fly ash</u>			
Transport to final disposal	0.3	tkm	G.I.D.A. data

The other processes present in this scenario (land spreading, composting and landfill) are inventoried using data from previous LCA studies, Integrated Pollution and Prevention Control (IPPC) authorization documents of the plants where sludge was sent and an Ecoinvent model (Doka, 2009).

For land spreading 0.73 kg/tDM of diesel and 58.5 kWh/tDM of electricity use are assumed (Hospido et al., 2005). Other data used for this sludge treatment are presented in the following

tables.

Table 6. Heavy metals transfer coefficients in land spreading (Lederer and Rechberger, 2010).

Coefficient	Run-off [%]	Land accumulation [%]
Cadmium	20	80
Chromium	20	80
Copper	20	80
Mercury	20	80
Nickel	20	79
Lead	20	80
Zinc	20	76

Table 7. Coefficients for fertilizer recovery in land spreading (Houillon and Jolliet, 2005).

Coefficient	Value	Unit
Nitrogen	0.6	kg/kgN
Phosphorus	0.7	kg/kgP
Potassium	0.8	kg/kgK

Table 8. Coefficients for air emissions in land spreading (Doka, 2009).

Coefficient	Value	Unit
NH ₃	25.8	% N
N ₂ O	1.2	% N

The inventory data are calculated multiplying these coefficients by sludge composition, as shown in the following equation:

$$Emission_i = coefficient_i \cdot element_i$$

It was assumed that sludge combustion CO₂ emissions are of biogenic origin.

In composting process the substrates must have input humidity content lower than 55% (Masotti, 2011). Sewage sludge after dewatering has 75% of humidity, thus green waste addition is needed and considered in the inventory.

Table 9. Inventory of land spreading.

Element	Value	Unit (/tDM)
<u>Inputs</u>		
Electricity	58.5	kWh
Diesel	0.7	kg
Ammonium nitrate (recovered)	10.4	kg
Single superphosphate (recovered)	3.5	kg
Potassium chloride (recovered)	0.9	kg
<u>Outputs to air</u>		
N ₂ O	0.2	kg
NH ₃	4.4	kg
<u>Outputs to soil</u>		
Cadmium	0.001	kg
Chromium	0.08	kg
Copper	0.3	kg
Mercury	0.001	kg
Nickel	0.02	kg
Lead	0.07	kg
Zinc	0.51	kg
<u>Outputs to water</u>		
Cadmium	0.0002	kg
Chromium	0.02	kg
Copper	0.08	kg
Mercury	0.0002	kg
Nickel	0.005	kg
Lead	0.02	kg
Zinc	0.1	kg
Phosphorus	1	kg

Table 10. Input data for composting inventory.

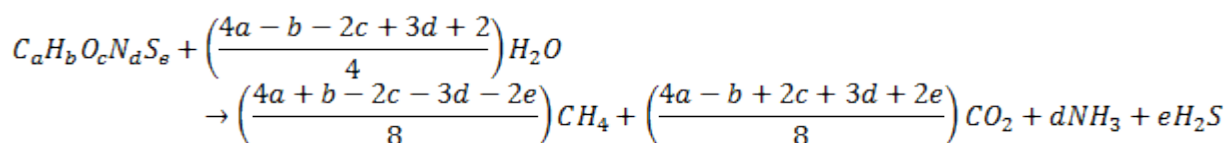
Data	Sludge	Green waste	Reference
Humidity	75	60.9	G.I.D.A. data
Total solids (TS)	25	39.1	G.I.D.A. data
Total volatile solids (% TS)	64.3	85	G.I.D.A. data
Biodegradable TVS (%TVS)	80	72	G.I.D.A. data
Biodegradability coef. (% bio-TV S)	35	70	IPCC Allevi Srl, 2006

Table 11. Green waste composition.

Element	Dry basis composition [%]
Carbon	42.3
Hydrogen	5
Oxygen	39.2
Nitrogen	1.3
Sulphur	0.2
Ashes	11.9

Calculations show that after composting a mass loss of 38% applies. Composted sludge has a humidity level of 60.6%. Energy required for composting is an average of five values used found in literature (Garrido-Baserba et al., 2015; Murray et al., 2008; Hong et al., 2009; Suh and Rousseaux, 2002; Brown et al., 2010): it is equal to 65.9 kWh/tDM. After composting, sludge is used as fertilizer: for this phase data presented in Table 8 are used.

In order to draw up inventory for landfill, biogas and leachate production is considered. Biogas production and composition is calculated with the approach proposed by Lombardi et al. (2006), utilizing the following reaction (Tchobanoglous et al., 1993):



Not all the produced biogas is captured, 47% is in fact directly emitted to the air (Doka, 2009). The captured gas is used as it follows: 52% is flared and 48% is used to cogenerate electricity and heat (Ecofor Srl, 2014). Electricity produced (calculated as 126.2 kWh/tDM) is used to cover landfill energy requirement.

Table 12. Biogas composition [volume %].

Compound	Value
CH ₄	45.5
CO ₂	43.8
NH ₃	7.9
H ₂ S	2.8

To calculate leachate production, an Ecoinvent model is used, where input data is sludge composition disposed into landfill. The following equation is used to calculate leachate volume (Doka, 2009):

$$V_m = I_m / (h \cdot \rho)$$

Where:

- V_m: average annual leachate volume [mm/kgwaste·year];

- I_m : average annual rate of infiltration in landfill, equal to 392.5 mm/m²year (Pecorini, 2005);
- h : landfill height, equal to 20 m (Ecofor Srl, 2014);
- ρ : average waste density 1,004.6 kgwaste/m³ (G.I.D.A. data).

Considering that 1 mm of rain is equal to about 1 liter per m² of surface, V_m can be converted to l/kgwaste·m²·year: it is obtained a value of 0.02 l/kgwaste·m²·year.

According to the model, leachate is collected for the first 100 years after the placement of the waste in landfill and transferred in a wastewater treatment plant: emissions to air, cleaned wastewater and sludge are considered. Sludge produced by leachate treatment undergoes an anaerobic digestion (AD) and then it is used as fertilizer.

Table 13. Inventory of landfill.

Element	Value	Unit (/tDM)
<u>Input</u>		
Electricity	126.2	kWh
<u>Output</u>		
Electricity (recovered from biogas)	126.2	kWh
<u>Outputs to air</u>		
CH ₄	42.4	kg
H ₂ S	2.6	kg
NH ₃	7.3	kg

Table 14. Inventory of wastewater treatment plant.

Element	Value	Unit (/tDM)	Reference
<u>Inputs</u>			
Electricity	87.7	kWh	Doka, 2009
Natural gas			—
<u>Output to air</u>			
N ₂ O	0.04	kg	Model results
<u>Outputs to water</u>			
COD	3.82	kg	Model results
Solphate	17.1	kg	—
Phosphate	0.27	kg	—
Ammonia	12.5	kg	—
Nitrate	52.06	kg	—
Nitrite	0.58	kg	—
Chloride	2.53	kg	—
Arsenic	0.0001	kg	—
Barium	0.025	kg	—
Cadmium	0.0003	kg	—
Cobalt	0.0006	kg	—
Chromium	0.012	kg	—
Copper	0.0003	kg	—
Mercury	0.00007	kg	—
Molybdenum	0.0004	kg	—
Nickel	0.001	kg	—
Lead	0.00001	kg	—
Antimony	0.0009	kg	—
Selenium	0.0002	kg	—
Tin	0.00001	kg	—
Vanadium	0.0009	kg	—
Zinc	0.042	kg	—
Beryllium	0.0001	kg	—
Thallium	0.0001	kg	—
<u>Others output</u>			
Electricity (rec. from AD)	13,5	kWh	Model results

Land spreading of sludge produced from leachate treatment is not a very likely option, but in this case it was assumed in order to easily close the sludge life cycle. As it will be shown in the results paragraph, this choice does not influence the outcomes for SC1-GIDA14 and SC2-GIDA15, but it does for SC4-OffSite. In Table 15. Inventory of land spreading of sludge produced by leachate treatment. information from Table 8 are adapted to this case.

Table 15. Inventory of land spreading of sludge produced by leachate treatment.

Element	Value	Unit (/tDM)
<u>Inputs</u>		
Electricity	0.51	kWh
Diesel	0.006	kWh
Ammonium nitrate (recovered)	1.62	kg
Single superphosphate (recovered)	0.12	kg
<u>Outputs to air</u>		
N ₂ O	0.031	kg
NH ₃	0.681	kg
<u>Outputs to soil</u>		
Cadmium	0.0002	kg
Chromium	0.01	kg
Copper	0.0008	kg
Mercury	0.0001	kg
Nickel	0.0005	kg
Lead	1.62E-05	kg
Zinc	0.075	kg
<u>Outputs to water</u>		
Cadmium	6.37E-05	kg
Chromium	0.002	kg
Copper	0.0002	kg
Mercury	3.48E-05	kg
Nickel	3.48E-05	kg
Lead	2.17E-05	kg
Zinc	0.02	kg
Phosphorus	0.035	kg

2.2.2 SC2-INC

Information needed to inventory the incineration process based on fluidized bed technology is taken from the project reports published by G.I.D.A. for the authorizations request and they are illustrated in the following table.

Table 16. Inventory of fluidized bed incinerator (G.I.D.A. S.p.A., 2015b).

Element	Value	Unit (/tDM)
<u>Inputs</u>		
Electricity	231.6	kWh
Natural gas	128,7	Nm ³
Urea	3,5	kg
Water for urea solution	0,01	m ³
Sodium hydroxide	9,8	kg
Water for sodium hydroxide	0,03	m ³
Lime	60,2	kg
Activated carbon	1,4	kg
Sodium hydrogen carbonate	30,8	kg
Sand (furnace replenishment)	6,9	kg
Sulphuric acid*	5,5	kg
Sodium hydroxide*	9,9	kg
Sodium hypochlorite*	15,2	kg
<u>Outputs to air</u>		
CO	27,272.7	mg
Particulates	18,181.8	mg
NOx	318,181.8	mg
SO2	18,181.8	mg
TOC	9,090.9	mg
NH3	18,181.8	mg
HF	909.1	mg
HCL	18,181.8	mg
Metals	227,272.7	r g
Mercury	72,727.3	r g
Cd+Tl	4,545.5	r g
IPA	90.9	r g
PCDD+PCDF	36,363.6	pg
<u>Other outputs</u>		
Wastewater (flue gas treatment)	1,99	m ³
Fly ash	402,8	kg
Residual sodium chemicals	132,87	kg
Wastewater from air deodorization	0,10	m ³
Electricity produced by ORC cycle	230,77	kWh

* Chemicals used for air deodorization

It is assumed that ashes are recovered as inert material and residual sodium products – as produced by the flue gas treatment - are sent to a landfill for hazardous waste after sodium chloride recovering.

Table 17. Inventory of incineration residues disposal.

Element	Value	Unit (/kgscrap)	Reference
<u>Residual sodium chemicals</u>			
Electricity	0.03	kWh	Turconi et al., 2011
Sodium chloride (recovered)	0.743	kg	—
Sand (inertization)	0.07	kg	—
Remains to landfill	0.146	kg	—
<u>Fly ash</u>			
Electricity	0.004	kWh	CiAI, 2010
Sand (recovered)	0.6	kg	—
Gravel (recovered)	0.4	kg	—

2.2.3 SC3-WO

Wet oxidation process is studied through some models, which assume as starting point the equation that describes the WO reaction kinetic (Debelletfontaine and Foussard, 2000):

$$\frac{dC}{dt} = k' \cdot e^{\frac{-E}{R \cdot T}} \cdot C^{\alpha} \cdot (O_2)^{\beta}$$

Where

- C: organic matter concentration;
- k': pre-exponential factor;
- E: activation energy;
- R: gas constant;
- T: temperature action;
- α: reaction order with respect to organic matter concentration;
- O₂: oxygen concentration;
- β: reaction order with respect to oxygen concentration.

According to Bertanza et al. (2015a), particulate organic compounds (S) are transformed into liquid intermediate products (L₁), a fraction of the dissolved organic substance is mineralized to gaseous compounds (G), while the other one is transformed into low molecular weight organic liquid residues (L₂).

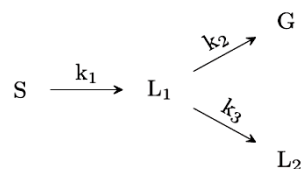


Figure 1. Kinetic model used to describe the reaction mechanisms (ki=rate constants) during WO process (Bertanza et al., 2015a).

Table 18. Input data used to apply the WO model.

Input	Value	Unit	Reference
VSS	38.32	g/l	G.I.D.A. data
VSS/VSS	0.75	-	Bertanza et al., 2015a
COD	55.14	g/l	G.I.D.A. data
k1	0.00662	min ⁻¹	Bertanza et al., 2015a
k2	0.00128	min ⁻¹	—
k3	0.00057	min ⁻¹	—
O2	41.36	g/l	—
q	60	min	—
k	1	-	—
α	0.82	-	—
T	250	°C	IPCC 3V Green Eagle, 2007
P	50	bar	—

Table 19. Results obtained from WO model.

Parameter	Value	Unit
S(u)	5.86	g/l
L ₁ (u)	14.71	g/l
L ₂ (u)	10.65	g/l
G(u)	23.92	g/l
sCOD	25.36	g/l
pCOD	5.86	g/l
COD	31.23	g/l
VSS	4.13	g/l
COD removal	43.37	%
VSS removal	89.26	%

To calculate nitrogen removal the model proposed by Zanobi et al. (2008) is used.

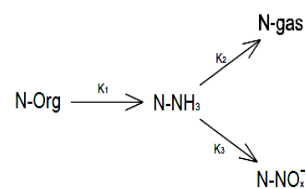


Figure 2. Kinetic model used to describe the nitrogen reaction mechanisms (ki=rate constants) during WO process (Zanobi et al., 2008).

Table 20. Input data used to apply the nitrogen removal model.

Input	Value	Unit	Reference
Norg	3.36	g/l	G.I.D.A. data
N-NH ₃	0.53	g/l	G.I.D.A. data
Ngas	0	g/l	Hypothesis
N-NO _x	0.0004	g/l	G.I.D.A. data
TN	3.89	g/l	G.I.D.A. data
q	60	min	Bertanza et al., 2015a
K ₁	0.0081	min ⁻¹	Zanobi et al., 2008
K ₂	0.0010	min ⁻¹	—
K ₃	0.0010	min ⁻¹	—

Table 21. Results obtained for the nitrogen removal model.

Parameter	Value	Unit
Norg	2.07	g/l
N-NH ₃	1.68	g/l
Ngas	0.07	g/l
N-NO _x	0.071	g/l
TN	3.82	g/l
TN removal	1.8	%

Outputs of wet oxidation are gas (mainly CO₂, N₂, water vapor, and excess oxygen), liquid and solid fractions. In order to obtain the solid fraction is necessary to apply a dewatering or filtration stage to separate liquid from solids. Allocation of liquid and solid fluxes is shown in the following table.

Table 22. Percentage of liquid and solid effluent from WO process (Bertanza et al., 2015b).

Parameter	Liquid	Solid
TSS	2	98
VSS	2	98
COD	93.8	6.2
TN	96.3	3.7
Flow rate	98.4	1.6

Liquid flux is supposed to be treated in a G.I.D.A. WWTP and solid fraction is hypothetically sent to a non-hazardous wastes landfill (Bertanza et al., 2015b). The solid residues chemical composition is the same of incineration residues.

Information about energy demand of a WO plant is extracted from the authorization documentation of the only Italian plant performing this process. It requires 3 kWh/t and 1.8 kWh/t per 1 t of treated sludge (3V Green Eagle, 2007).

Table 23. Inventory of wet oxidation process.

Element	Value	Unit (/tDM)
Inputs		
Electricity	28.6	kWh
Natural gas	5.3	Nm ³
Liquid oxygen	619.7	kg
Outputs to air		
N ₂	60.1	kg
CO ₂ (biogenic)	1.4	kg
Water vapor	30.8	kg
Inputs for dewatering		
Polyelectrolyte	2.6	kg
Electricity	0.5	kWh
Water for polyelectrolyte solution	0.8	m ³
Outputs		
Liquid effluent	14.6	m ³
Solid effluent	237.1	kg

2.2.4 SC4-OffSite

In this scenario 60.5% of sludge is sent to landfill and 39.5% is sent to composting plants and then used as fertilizer. The destination was assumed on the basis of G.I.D.A. sludge chemical composition and on the characteristics of Italian plants that could accept it. Landfill and composting processes are inventoried as previously shown in paragraph 2.2.1.

2.2.5 SC5-GIDA15

In this scenario 76.1% of sludge is incinerated, 18.5% is composted, 2% is directly used as fertilizer and 3.4% is disposed in landfill. All these processes are inventoried as previously shown in paragraph 2.2.1.

2.2.6 Transports

All considered transports are road transport.

In SC1-GIDA14 23.9% of sludge is transported to external plant located in Tuscany and in North Italy; transports of chemicals and incineration residues are also considered. Real distances were considered.

Table 24. Transports inventory of SC1-GIDA14.

Element transported	Value (tkm/tDM)
Sludge	216.5
Polyelectrolyte	3.6
Urea	0.01
Sodium hydroxide	0.01
Bottom ash	66.1
Fly ash	0.2

In SC2-INC sludge is transported from three G.I.D.A. WWTPs to one of the five G.I.D.A. WWTPs (in one case sludge is transferred by pipes). Transportation distances for chemicals and residues are real ones.

Table 25. Transports inventory of SC2-INC.

Element transported	Value (tkm/tDM)
Sludge	4.6
Polyelectrolyte	3.6
Urea	0.7
Sodium hydroxide	2.4
Lime	12
Activated carbon	0.3
Sodium hydrogen carbonate	6.2
Sand	1.4
Sulphuric acid	1.1
Sodium hydroxide	3.0
Fly ash	32.6
Residual sodium chemicals	16.1

In SC3-WO sludge transport is the same as in the previous scenario. Transportation distances for chemicals and residues are real ones.

Table 26. Transports inventory of SC3-WO.

Element transported	Value (tkm/tDM)
Sludge	4.6
Polyelectrolyte	4.1
Oxygen	189
Solid effluent	19.2

In SC4-OffSite all sludge is transported in Tuscany or North Italy: distances are assumed according to the distance of real plants that could accept G.I.D.A. sludge.

Table 27. Transports inventory of SC4-OffSite.

Element transported	Value (tkm/tDM)
Sludge	766.7
Polyelectrolyte	3.6

In the last scenario 23.9% of sludge is transported in Tuscany and North Italy.

Table 28. Transports inventory of SC5-GIDA15.

Element transported	Value (tkm/tDM)
Sludge	212.0
Polyelectrolyte	3.6
Urea	0.01
Sodium hydroxide	0.01
Bottom ash	66.1
Fly ash	0.2

2.2.7 Ecoinvent datasets

Table 29. reports Ecoinvent records used for the inventory of streams present in the different scenarios.

Dataset
Electricity, medium voltage {IT} market for
Natural gas, high pressure {IT} market for
Diesel {Europe without Switzerland} market for
Transport, freight, lorry >32 metric ton, EURO5 {RER}
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}
Liquid manure spreading, by vacuum tanker {CH} processing
Polyacrylamide {GLO} production
Urea, as N {RER} production
Soda ash, light, crystalline, heptahydrate {RER} soda production, solvayprocess
Sand {CH} gravel and quarry operation
Charcoal {GLO} production
Sulfuric acid {RER} production
Lime, hydrated, packed {CH} production
Sodium hypochlorite, without water, in 15% solution state {RER}
Water, decarbonised, at user {RER} water production and supply, decarbonized
Oxygen, liquid {RER} air separation, cryogenic
Ammonium nitrate, as N {RER} ammonium nitrate production
Phosphate fertiliser, as P2O5 {RER} single superphosphate production
Potassium chloride, as K2O {RER} potassium chloride production
Sodium chloride, powder {RER} production
Gravel, crushed {CH} production
Hazardous waste, for underground deposit {RoW}

3. RESULTS AND DISCUSSION

In order to evaluate the environmental impacts, the CML impact assessment method is applied. The present acronyms are assumed: AD (Abiotic Depletion), ADff (Abiotic Depletion fossil fuels), GW (Global Warming), OLD (Ozone Layer Depletion), HT (Human Toxicity), FWA (Fresh Water Aquatic Ecotoxicity), TE (Terrestrial Ecotoxicity), PO (Photochemical Oxidation), AC (Acidification), EU (Eutrophication).

In the following paragraphs results for each scenario are illustrated in term of contribution analysis. In order to compare the impact categories, normalization factors are used (EU25). The discussion is carried on through the comparison of environmental impacts of the different options analysed and a sensitivity analysis.

3.1 Impacts of each scenario

In SC1-GIDA14 incineration is the process, between the six analysed, that has the highest impact level of all scenario (Figure 3. Impacts of SC1-GIDA14 referred to 1 tDM.). The category Terrestrial Ecotoxicity has the highest contribution caused by land spreading and composting, in particular because of metals transfer from sludge to the soil (especially chromium); these two processes give small impacts to the others categories. Landfills, involving a small amount of sludge, and transports have small impact values too. Although all sludge is subjected to dewatering, this pre-treatment generates a low impact contribution.

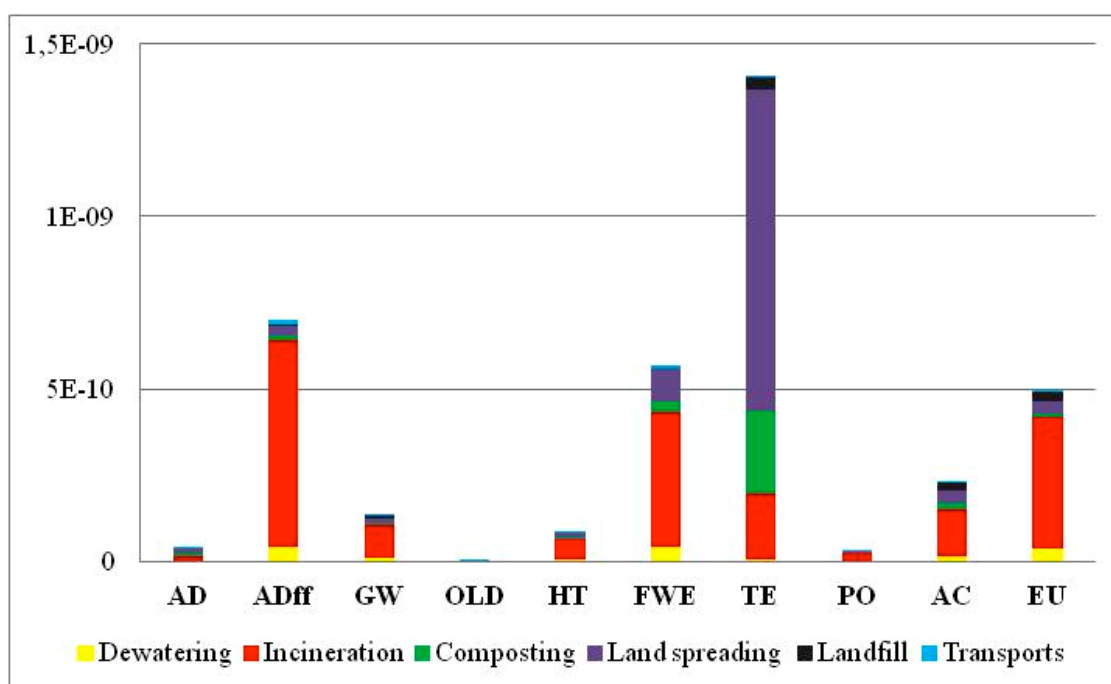


Figure 3. Impacts of SC1-GIDA14 referred to 1 tDM.

Figure 4 shows the process percentage contribution for the first scenario, considering the more significant impact categories: GW, HT, AC and EU. For example, the sub-processes that cause more than 60% of the Global Warming value of the entire scenario are the production of both natural gas and electricity used by the incinerator and the treatment of wastewater deriving from flue gas treatment.

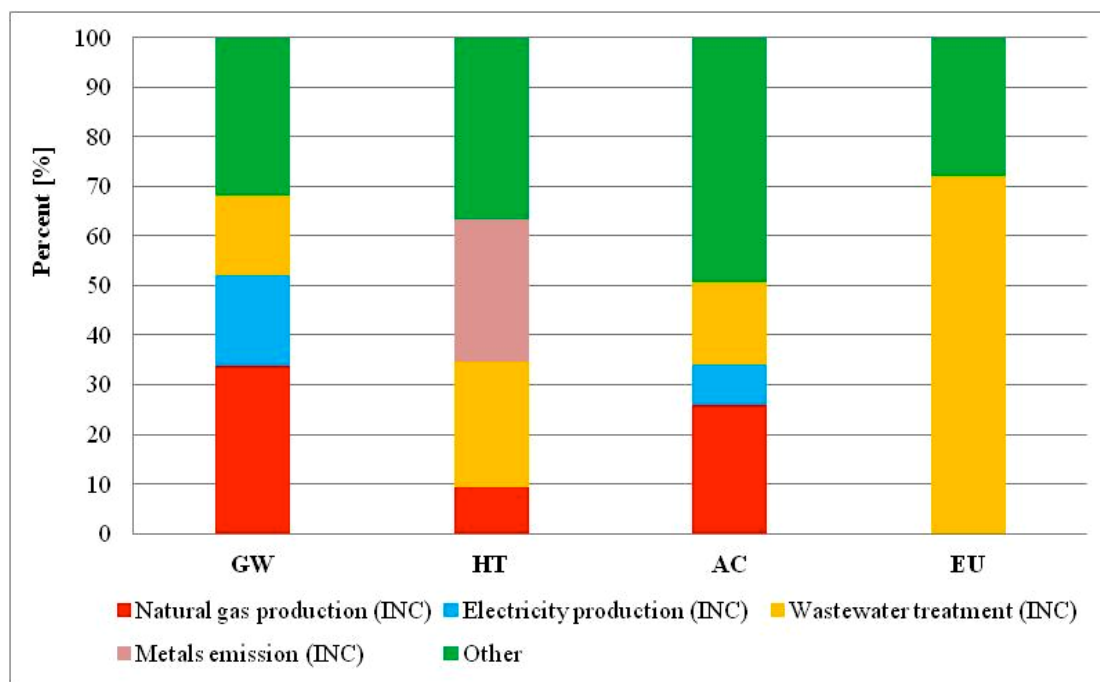


Figure 4. Contribution of the main processes to the four selected impact categories in SC1-GIDA14.

In SC2-INC the incineration causes the highest values of impact for almost all categories. Dewatering generates the same impacts of the previous scenarios because it involves the same amount of sludge. It can be noticed (Figure 5. **Impacts of SC2-INC referred to 1 tDM.**) that the recovery of incineration residues produced negative impacts: this means that the impacts for the production of materials that are replaced are avoided. The category Abiotic Depletion (fossil fuel) is mostly influenced by natural gas production for incineration process.

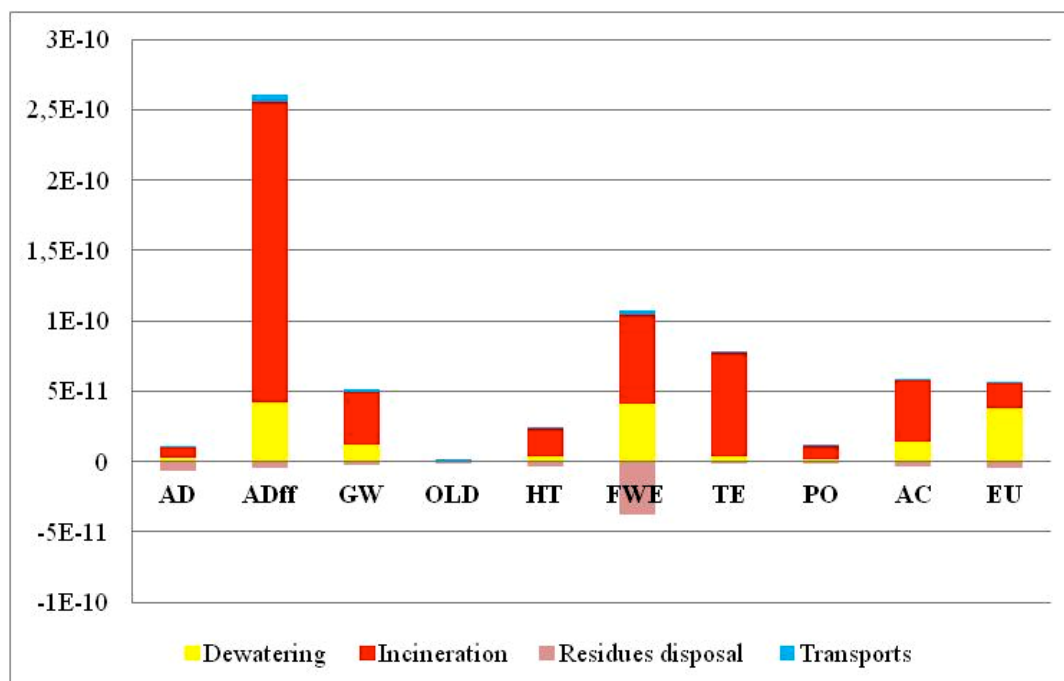


Figure 5. Impacts of SC2-INC referred to 1 tDM.

Looking at Figure 6. Contribution of the main processes to the four selected impact categories in SC2-INC. it can be underlined that in this case wastewater treatment deriving from flue gas

treatment is not one of the most impact processes (less water is used), and treatment of wastewater deriving from dewatering phase is now relevant.

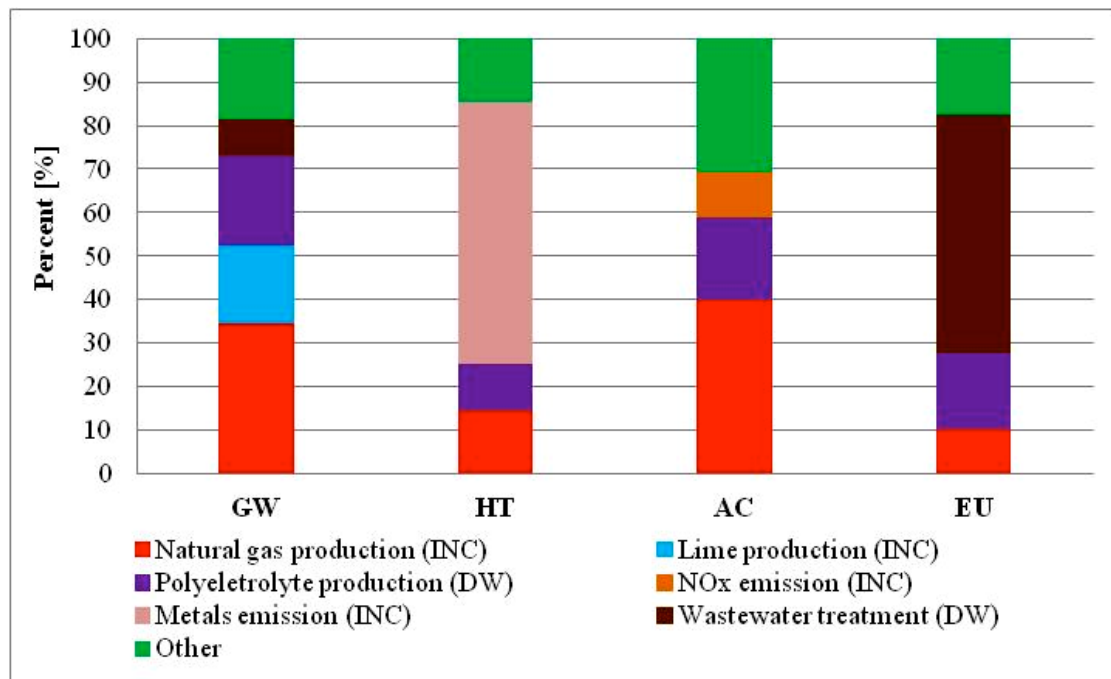


Figure 6. Contribution of the main processes to the four selected impact categories in SC2-INC.

In SC3-WO all impact categories in this scenario are mostly influenced by residues disposal and wet oxidation process. Fresh Water Ecotoxicity category has the highest value because of the disposal of solid residues in landfill. This time dewatering involves 61.1% of sludge, so its impacts are lower than in the other cases.

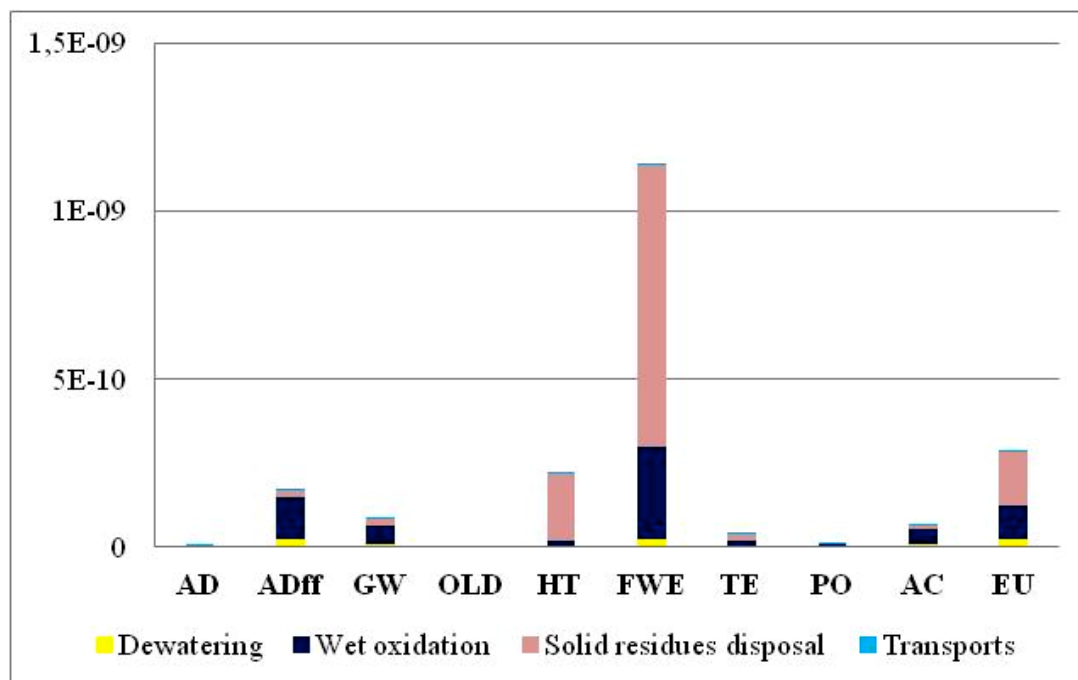


Figure 7. Impacts of SC3-WO referred to 1 tDM.

The sub-process linked to wet oxidation that generates the most important impacts is the

production of oxygen (Figure 8. **Contribution of the main processes to the four selected impact categories in SC3-WO.**).

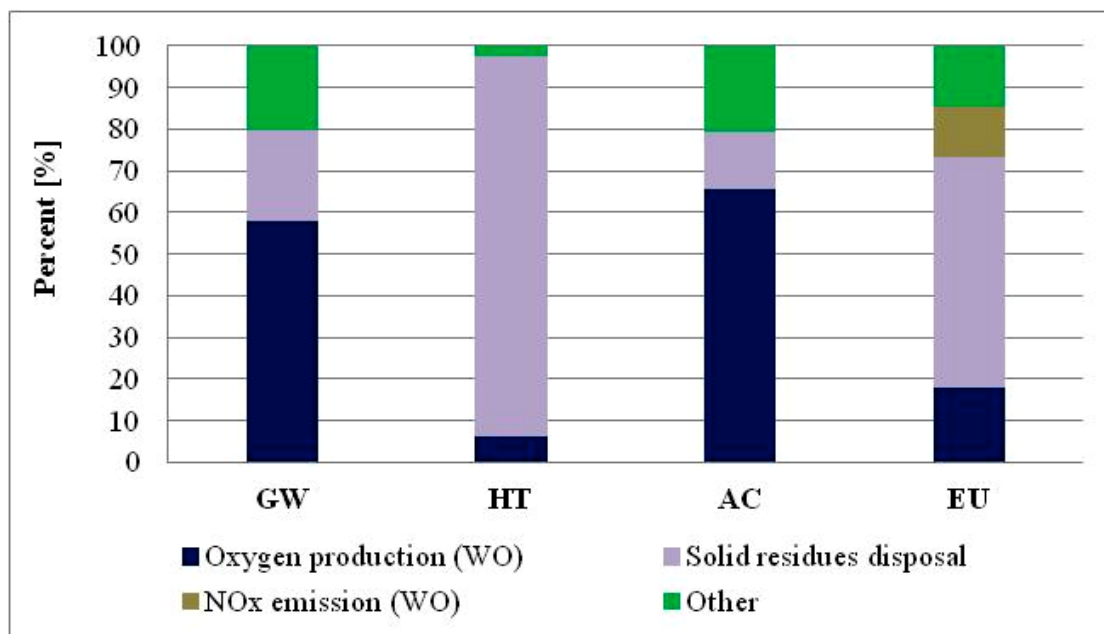


Figure 8. Contribution of the main processes to the four selected impact categories in SC3-WO.

In SC4-OffSite the highest contribute to all the considered indicators comes from landfill (Figure 9. Impacts of SC4-OffSite referred to 1 tDM.): Terrestrial Ecotoxicity is the category most influenced by this disposal process, especially because of the land spreading of the sludge produced by the leachate treatment.

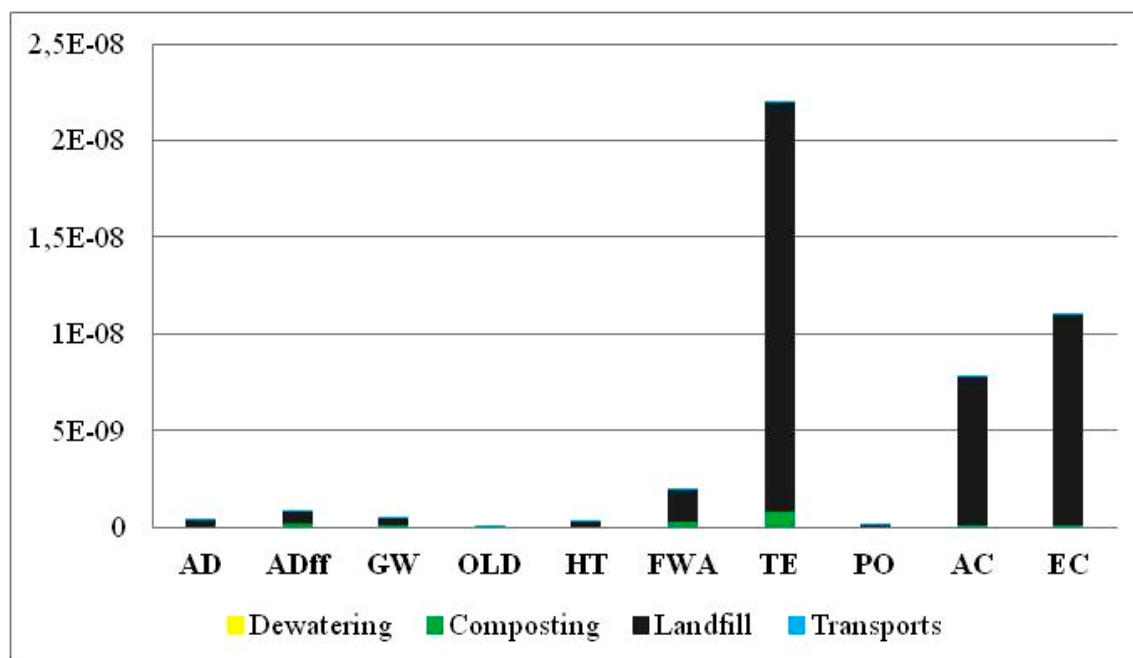


Figure 9. Impacts of SC4-OffSite referred to 1 tDM.

The sub-processes that mainly influenced the four selected categories are different (Figure 10. **Contribution of the main processes to the four selected impact categories in SC4-OffSite.**). In

Global Warming CH_4 and N_2O emission from landfill, electricity production for WWTP and N_2O emission from leachate treatment are considerable. In Human Toxicity land spreading of sludge produced from leachate treatment is significant, especially for chromium emission in soil and use of farming vehicles. Emission in water of SO_4 from leachate treatment is the main process contributing to Acidification. For Eutrophication, emission to water of both NH_4 and NO_3 are relevant.

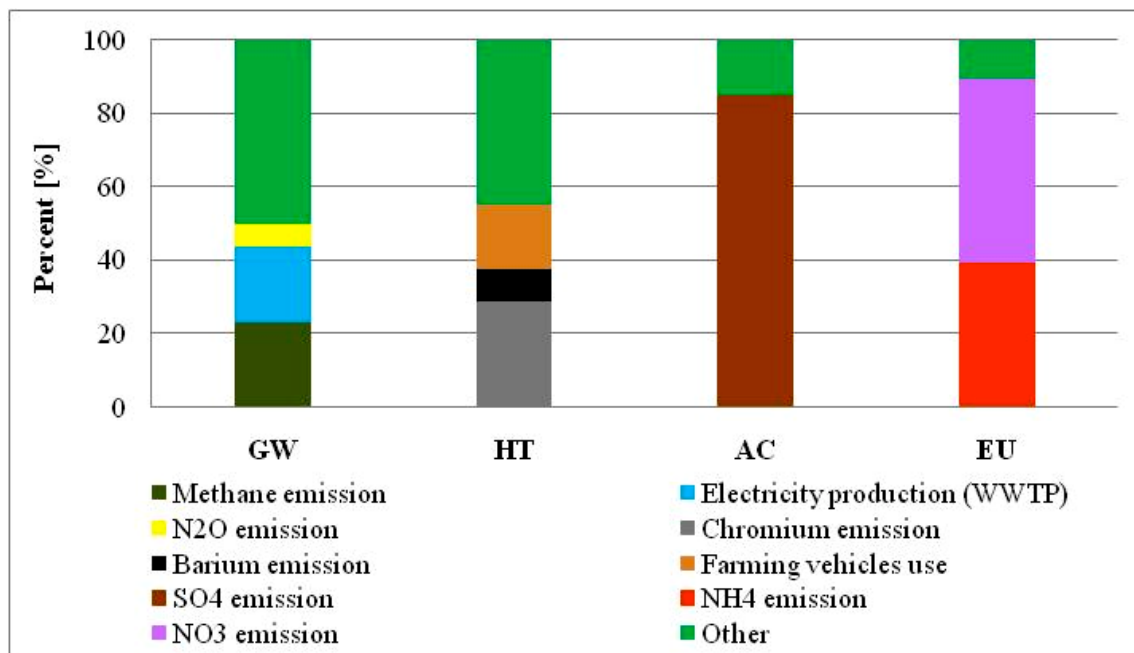


Figure 10. Contribution of the main processes to the four selected impact categories in SC4-OffSite.

In SC5-GIDA15 the situation is similar to SC1-GIDA14: there are six processes and incineration is the one that impacts the most (Figure 11. **Impacts of SC5-GIDA15 referred to 1 tDM.**), due to the high percentage of sludge processed in this way. This time the category Terrestrial Ecotoxicity is less influenced by land spreading because in 2015 G.I.D.A. sent a smaller amount of sludge to this destination and a greater amount to composting.

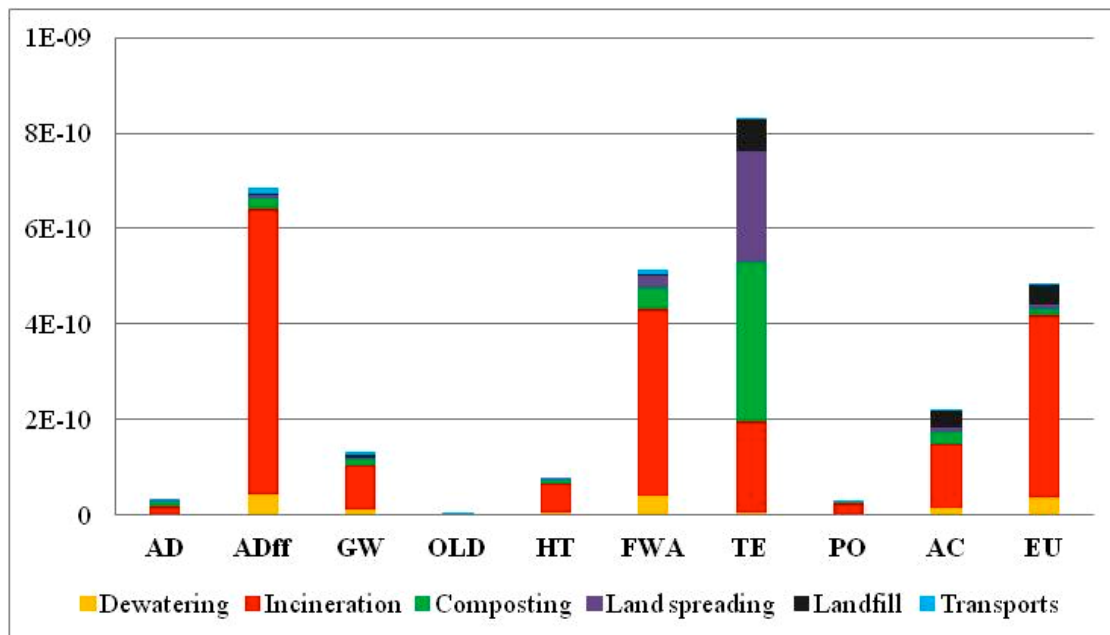


Figure 11. Impacts of SC5-GIDA15 referred to 1 tDM.

The sub-processes that give the most important contributions to the four selected categories of SC1-GIDA15 are similar to the ones of the first scenario (Figure 12. Contribution of the main processes to the four selected impact categories in SC5-GIDA15.).

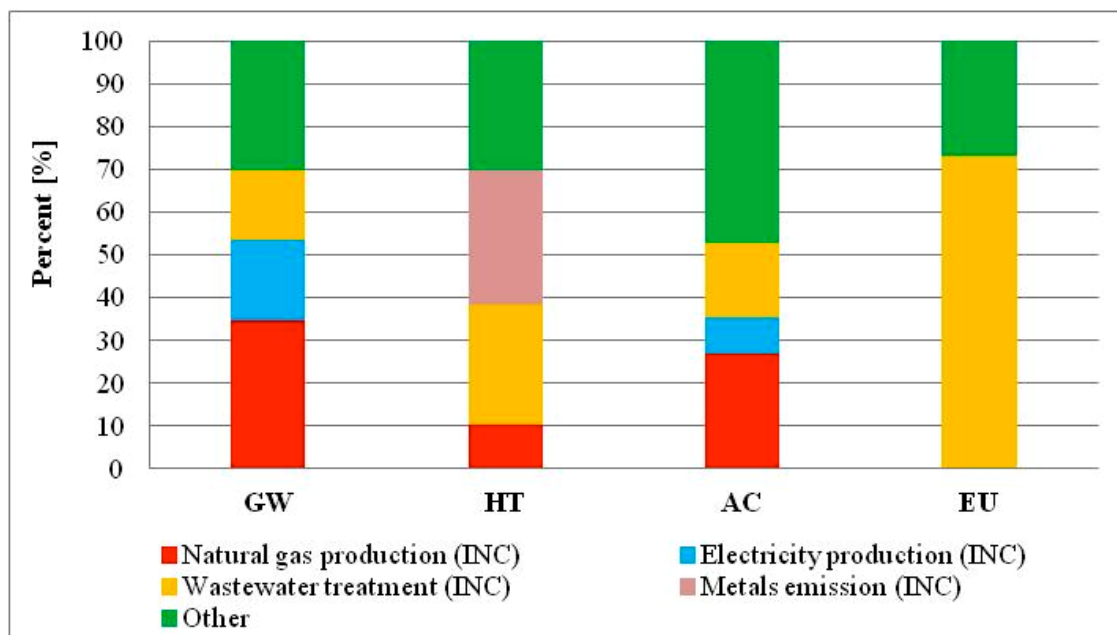


Figure 12. Contribution of the main processes to the four selected impact categories in SC5-GIDA15.

3.2 Scenarios comparison

Indicators calculated for the five scenarios are here directly compared.

Figure 13 shows the impacts of the single processes present in each scenario - related to Global Warming only. The values shown are referred to the functional unit. The present

acronyms are assumed: DW (dewatering), INC (incineration), LSP (land spreading), COM (composting), LF (landfill), WO (wet oxidation), RD (residues disposal), TR (transports).

Figure 13 shows that DW has the same impacts for all scenarios, except for SC3-WO where it is applied only to 61.1% of sludge. The incineration of 76.1% of sludge with the current G.I.D.A. plant impacts more than incineration of 100% of sludge with the new plant. This is mainly due the absence of the energy recovery system and the high amount of water used for the flue gas treatment in the current incinerator. Wet oxidation has an impact higher than the incineration of the second scenario. The difference between impacts of LSP, COM and LF are due to the different percentages of sludge send to these processes in the scenarios: landfill has the greatest Global Warming impact in SC4-Offsite where 60.5% of sludge is disposed. The recovery of incineration residues in SC2-INC is the only process that has a negative value. The impacts of residues disposal in SC1-GIDA14 and SC5-GIDA15 are the same (and very low), and the one in SC3-WO has high value because the entire solid effluent is sent to landfill. Transports in SC4-OffSite are the most elevated because involving all sludge produced by G.I.D.A. WWTPs in one year. Although in SC2-INC and SC3-WO the same quantity of sludge is transported, in the third scenario impacts are higher because a great amount of oxygen must be transported in a year for wet oxidation process.

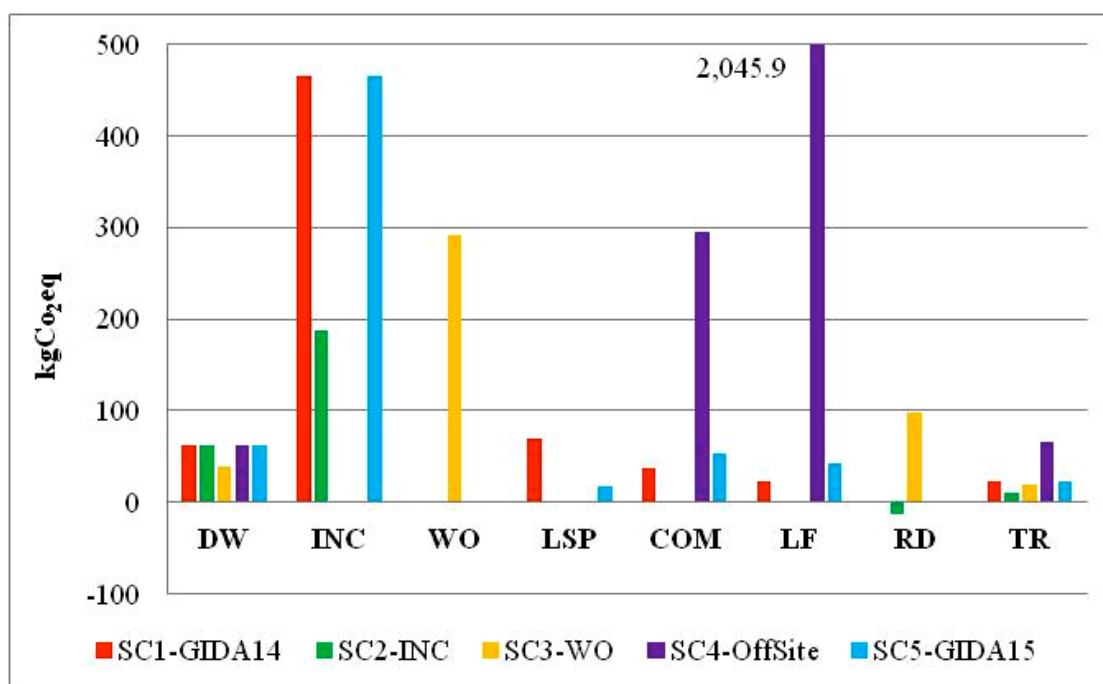


Figure 13. Comparison between Global Warming impacts of processes included in the five scenarios.

In order to assess which of the five scenarios is the best alternative for G.I.D.A., the values of the ten impact categories are compared and shown in the following table: for each category the lowest values is highlighted in green and the highest in red. In Figure 14 the results are illustrated using the normalization factors.

Table 30. Global impacts of the five scenarios referred to 1 tDM.

Impact categories	SC1-GIDA14	SC2-INC	SC3-WO	SC4-OffSite	SC5-GIDA15	Unit
AD	0.003	0.00036	0.00043	0.035	0.003	kgSb _{eq}
ADff	22,119.5	8,066.1	5,539.8	25,374.2	21,530.9	MJ
GW	683.2	248.7	445.6	2,469.9	663.4	kgCO _{2eq}
OLD	0.00021	0.00008	0.00004	0.00023	0.0002	kgCFC-11 _{eq}
HT	652.6	158.0	1,704.1	2,508.3	591.9	kg1,4-DB _{eq}
FWA	295.1	36.5	591.3	1,024.5	264.9	kg1,4-DB _{eq}
TE	68.2	3.68	1.90	1,064.1	40.3	kg1,4-DB _{eq}
PO	0.3	0.09	0.08	0.7	0.2	kgC ₂ H _{4eq}
AC	6.5	1.6	1.9	218.7	6.2	kgSO _{2eq}
EU	6.5	0.7	3.7	145.4	6.4	kgPO _{4eq}

The current G.I.D.A. sludge management in the two analysed years causes similar impacts, mainly because the same quantity of sludge is burnt in the multiple-hearth incinerator. The differences are due to the different allocation of sludge in the external plants (in 2015 there is more composting and landfill and less land spreading with respect to 2014).

Sending all sludge to external plants is clearly the choice that causes the highest environmental impacts: in fact, all categories of SC4-OffSite have the highest values compared to other scenarios. Scenarios that have lowest impacts are SC2-INC and SC3-WO. SC3-WO collects the best values in four out of ten. SC2-INC has six best values out of ten (including the selected four categories).

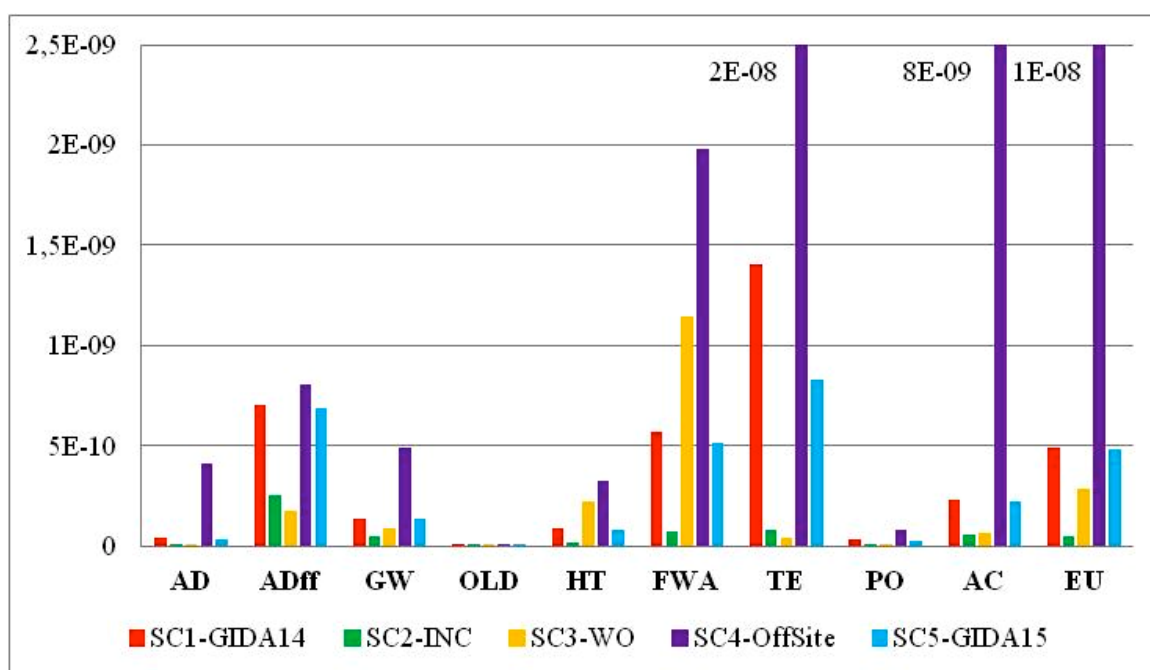


Figure 14. Comparison between environmental impacts of the five scenarios (values referred to 1tDM).

Therefore, the scenario characterized by the lower environmental impact is SC2-INC: the construction of a new incineration plant with energy recovery in one of G.I.D.A. WWTPs is the best option.

3.3 Sensitivity analysis

The sensitivity analysis investigates how the variation of some assumptions made in the inventory affects the obtained results. The examined assumptions are:

- final disposal of incineration residues in SC2-INC;
- final disposal of wet oxidation solid residues in SC3-WO.

3.3.1 Final disposal of incineration residues (SC2-INC)

The new hypothesis consists in substituting the assumption of ashes and residual sodium products recovering by their landfilling: ashes are sent to inert waste landfill and residual sodium products are sent to hazardous waste landfill after inertization. The new ecoinvent records used are:

- Hazardous waste, for underground deposit {RoW};
- Inert waste, for final disposal {RoW}.

The lack of recovery processes involves significant changes in the impacts: from a positive contribution to the environment (negative values of categories) to a negative one (positive values of categories).

The impacts of the SC2-INC scenario increase by 32% on average. Comparing the new impact values with the ones of SC3-WO original scenario, it can be noticed that the two scenarios collect the same number of best values in the comparison. If only the four selected categories are considered, SC2-IN modified is the best scenario.

Table 31. Global impacts of the SC2-INC modified and SC3-WO original, referred to 1 tDM.

Impact categories	SC2-INCmod	SC3-WO	Unit
AD	0.0009	0.00043	kgSb _{eq}
ADff	8,640.3	5,539.8	MJ
GW	295.2	445.6	kgCO ₂ _{eq}
OLD	0.0001	0.00004	kgCFC-11 _{eq}
HT	201.9	1,704.1	kg1,4-DB _{eq}
FWA	65.6	591.3	kg1,4-DB _{eq}
TE	3.8	1.90	kg1,4-DB _{eq}
PO	0.1	0.08	kgC ₂ H ₄ _{eq}
AC	1.8	1.9	kgSO ₂ _{eq}
EU	0.8	3.7	kgPO ₄ _{eq}

3.3.2 Final disposal of wet oxidation solid residues (SC3-WO)

Final disposal of solid residues of wet oxidation is currently a common issue concerning this technology: here it is assumed to send the solid WO residues to landfill. If we assume that the WO solid residues behave similarly to municipal solid waste (MSW) or similarly to inert waste when landfilled, impacts may change with respect to the basic assumption of ashes-like behaviour. The Ecoinvent record used in these two cases are:

- Municipal solid waste {CH} treatment of, sanitary landfill;

- Inert waste, for final disposal {CH}.

When WO residues are considered as MSW, the impacts of the entire scenario decrease of 16.3% on average. In this case, SC2-INC is still the scenario with the greater number of categories characterize by the lowest values.

Table 32. Global impacts of the SC2-INC and SC3-WO modified (MSW), referred to 1 tDM.

Impact categories	SC2-INC	SC3-WOmod	Unit
AD	0.00036	0.0004	kgSb _{eq}
ADff	8,066.1	5,049.4	MJ
GW	248.7	467.0	kgCO _{2eq}
OLD	0.00008	0.00004	kgCFC-11 _{eq}
HT	158.0	188.8	kg1,4-DB _{eq}
FWA	36.5	620.1	kg1,4-DB _{eq}
TE	3.68	1.2	kg1,4-DB _{eq}
PO	0.09	0.10	kgC ₂ H _{4eq}
AC	1.57	1.65	kgSO _{2eq}
EU	0.7	2.3	kgPO _{4eq}

Consider WO residues as inert waste makes impacts values decreasing by 34.1% on average. With this new hypothesis, the two scenarios - SC2-INC and SC3-WO - have the same number of categories with the best value (Table 33).

Table 33. Global impacts of the SC2-INC and SC3-WO modified (inert), referred to 1 tDM.

Impact categories	SC2-INC	SC3-WOmod	Unit
AD	0.00036	0.0004	kgSb _{eq}
ADff	8,066.1	5,019.9	MJ
GW	248.7	349.3	kgCO _{2eq}
OLD	0.00008	0.00004	kgCFC-11 _{eq}
HT	158.0	143.4	kg1,4-DB _{eq}
FWA	36.5	159.2	kg1,4-DB _{eq}
TE	3.68	0.9	kg1,4-DB _{eq}
PO	0.09	0.07	kgC ₂ H _{4eq}
AC	1.57	1.63	kgSO _{2eq}
EU	0.7	1.7	kgPO _{4eq}

4. CONCLUSIONS

Purpose of this Life Cycle Assessment study was to analyse and compare the environmental impacts due to different alternatives of sewage sludge management systems applied to a real case: G.I.D.A. Company, located in Prato (Italy), which manages five WWTPs.

Five scenarios were defined and compared. Scenario 1 described G.I.D.A. sludge management in 2014: 76.1% of sludge is sent to an incinerator (without energy recovery)

located in one of the G.I.D.A. WWTPs and 23.9% is transported to external plants. In Scenario 2 the possibility to build a new incinerator able to treat all G.I.D.A. sludge and to produce electricity is studied. In Scenario 3 the wet oxidation of sludge is analysed and in Scenario 4 it is assumed to send all the produced sludge to external plants. In Scenario 5, G.I.D.A. sludge management in 2015 is studied. All scenarios were inventoried using G.I.D.A. data, previous literature studies or Ecoinvent models.

The impact assessment was carried out adopting the CML-IA baseline method. The impacts were calculated including the avoided effects caused by the substitution of final products in marginal production processes.

Results showed that the greater impacts of the current sludge management are caused by the production of natural gas and electricity used by the G.I.D.A. incinerator, the wastewater treatment of the water used in the flue gas treatment, and by the metals emissions at the stack. The most important impact of the SC2-INC are the production of natural gas for incineration and polyelectrolyte for dewatering, treatment of wastewater produced by dewatering, and metals emissions at the stack. Wet oxidation generates environmental impacts especially by oxygen production used by the process and the disposal of solid residues in landfill. The incineration of 76.1% of sludge with the current G.I.D.A. plant produces higher level of impact than the incineration of 100% of sludge with the new plant.

The alternative of sending all the produced sludge to external destinations, mainly landfill, would generate the highest impacts compared to the other cases. Therefore, SC4-OffSite is the worst option from an environmental point of view. SC2-INC is instead the alternative that guarantees the lowest impacts.

The sensitivity analysis was carried out considering alternative possibilities for the final disposal of incineration residues in SC2-INC and solid residues of wet oxidation. In the first case, the disposal of residues in landfill in place of material recovery worsens the impacts of the second scenario, making them similar to the impacts of the third scenario. In the second case, solid residues of WO are sent to landfill assuming two different hypotheses on their chemical composition. If they are considered to behave similarly to MSW, no significative changes in the results are highlighted, while if they are assumed to behave similarly to inert waste, SC3-WO collects the lowest impacts, very similar to the ones of SC2-INC.

REFERENCES

- G. Bertanza, R. Galessi, L. Menoni, R. Salvetti, E. Slavik, S. Zanaboni (2015a). Wet oxidation of sewage sludge: full-scale experience and process modeling. *Environmental Science and Pollution Research*, Volume 22 (10), pp 7306-7316.
- G. Bertanza, M. Canato, S. Heimmerson, G. Laera, R. Salvetti, E. Slavik, M. Svanström (2015b). Techno- economic and environmental assessment of sewage sludge wet oxidation. *Environmental Science and Pollution Research*, Volume 22 (10), pp 7327-7338.
- S. Brown, N. Beecher, A. Carpenter (2010). Calculator tool for determining greenhouse gas emissions for biosolids processing and end use. *Environmental Science & Technologies*, Volume 44 (24), pp 9509–9515.
- J.Chunga, M. Leeb, J. Ahnc,W. Baed, Y.Leea, H. Shime (2009). Effects of operational conditions on sludge degradation and organic acids formation in low-critical wet air oxidation. *Journal of Hazardous Materials*, Volume 162, pp 10-16.

CiAI (2010). Separazione e recupero dei metalli e valorizzazione delle scorie di combustione dei rifiuti urbani. Politecnico di Milano, Dipartimento DIIAR.

H. Debellefontaine and J. N. Foussard (2000). Wet air oxidation for the treatment of industrial wastes. Chemical aspects, reactor design and industrial applications in Europe. Waste Management, Volume 10, pp 15-25.

G. Doka (2009). Life Cycle Inventories of Waste Treatment Services. ecoinvent report n. 13. Swiss Centre for Life Cycle Inventories, Dübendorf.

EN ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework.

EN ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines.

M. Garrido-Baserba, M. Molinos-Senante, J.M. Abelleira-Pereira, L.A. Fdez-Güelfo, M. Poch, F. Hernandez-Sancho (2015). Selecting sewage sludge treatment alternatives in modern wastewater treatment plants using environmental decision support systems. Journal of Cleaner Production, Volume 107, pp 410-419.

G.I.D.A. S.p.A. (2015a). Relazione annuale relativa al funzionamento ed alla sorveglianza dell'impianto di incenerimento di Baciacavallo.

G.I.D.A. S.p.A. (2015b). Progetto definitivo di sostituzione dell'impianto di incenerimento fanghi di Baciacavallo. Valutazione di impatto ambientale.

J. Hong, J. Hong, M. Otaki, O. Jolliet (2009). Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. Waste Management, Volume 29, pp 696-703.

A. Hospido, M.T. Moreira, M. Martin, M. Rigola, G. Feijoo (2005). Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes. The International Journal of Life Cycle Assessment, Volume 10 (5), pp 336-345.

G. Houillon, O. Jolliet (2005). Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. Journal of Cleaner Production, Volume 13 (3), pp 287-299.

3V Green Eagle S.p.A. Integrated Pollution and Prevention Control authorization released by Lombardia Region with Deed n. 328/2007.

Azienda Agricola Allevi Srl Integrated Pollution and Prevention Control authorization released by Pavia District with Deed n. 43/2006.

Ecofor Srl, Integrated Pollution and Prevention Control authorization released by Pisa District with Deed n. 1809/2014.

J. Lederer, H. Rechberger (2010). Comparative goal-oriented assessment of conventional and alternative sewage sludge treatment options. Waste Management, Volume 30 (6), pp 1043-1056.

L. Lombardi, E. Carnevale, A. Corti (2006). Greenhouse effect reduction and energy recovery from waste landfill. Energy, Volume 31 (15), pp 3208-3219.

- L. Masotti (2011). *Depurazione delle acque, Tecniche ed impianti per il trattamento delle acque di rifiuto*. Edizione Calderini.
- A. Murray, A. Horvath, K.L. Nelson (2008). Hybrid Life-Cycle Environmental and Cost Inventory of Sewage Sludge Treatment and End-Use Scenarios: A Case Study from China. *Environmental Science & Technologies*, Volume 42 (9), pp 3163–3169.
- I. Pecorini (2005). Master Degree thesis: Applicazione di modelli di produzione di percolato di discarica.
- Y.J. Suh, P. Rousseaux (2002). An LCA of alternative wastewater sludge treatment scenarios. *Resources, Conservation and Recycling*, Volume 35, Issue 3, pp 191–200.
- G. Tchobanoglous, H. Theisen, S. Vigil (1993). *Integrated solid waste management. Engineering, principles and management issues*. NewYork: McGraw-Hill.
- R. Turconi, S. Butera, A. Boldrin, M. Grosso, L. Rigamonti, T. Astrup (2011). Life cycle assessment of waste incineration in Denmark and Italy using two LCA models.
- S. Zanaboni, G. Bertanza, R. Galessi, M.C. Collivignarelli (2008). Cinetiche di rimozione della sostanza organica e dell'azoto nel trattamento di rifiuti liquidi con ossidazione ad umido. SIDISA, Firenze 24-27 Giugno.