Assessing GHG emissions from sludge treatment and disposal routes: the method behind GESTABoues tool

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EXECUTIVE SUMMARY

In 2007, 1 100 000 tons of sewage sludge were produced in France. This figure is constantly increasing and sludges have to be eliminated. Four disposal routes are currently possible: land spreading (directly or after composting), incineration, incineration with household wastes and landfilling. These different disposal routes as well as the sludge treatments produce greenhouse gases (GHG). To help stakeholders to better understand the carbon footprint of sludge treatment and disposal options, we developed a tool called $^{G}E_{S}$TABoues.

This paper aims to present the underlying methodology used to quantify material and energy flows as well as GHG emissions all along the sludge treatment and disposal processes implemented in this tool. GHG emissions generated by our system are quantified for x tons of sludge produced by a wastewater treatment plant of x per-captia-equivalents (PCE) during one year.

The carbon footprint method we developed is adapted to sludge treatment and disposal processes and based on the "Bilan Carbone®" method. The "Bilan Carbone®" method is a general method used to quantify GHG generated from all physical processes which are necessary for any activity or human organization (ADEME, 2009). In our method, three GHG are recorded: carbon dioxide, methane and nitrous oxide. Biogenic carbon was not taken into account but its sequestration was for two types of disposal routes (land spreading and landfilling). For each process involved in the sludge treatment and disposal routes system, three types of emissions are considered: direct, indirect and avoided emissions.

(i) Direct emissions are generated by each process (storage, thickening, anaerobic digestion, composting, land spreading, incineration, incineration with household wastes, landfilling).

(ii) Indirect emissions are due to energy and chemical consumptions (combustible or electricity) to operate each process. Transport emissions (for consumables, sludges and ashes) and civil engineering emissions were taken into account. The first ones were calculated for one ton of goods transported on one kilometre (t.km) and the second ones were the toughest to implement in $^{G}E_{S}$TABoues tool. After a literature review, two main methods were identified. Renou (2006) considers that the most applicable methodology is to consider mass of all civil engineering and electrical/mechanical equipments whereas Doka (2007) considers that civil engineering emissions are defined by wastewater treatment plant for 5 classes of plants. We propose an intermediate methodology to assess these emissions : for each process, components (concrete, cast iron, steel…) of involved machineries and buildings were modelled for 3 sizes of wastewater treatment plants (<10 000 PCE, 10 000 – 100 000 PCE, >100 000 PCE).

(iii) Avoided emissions are generated when products are not used and replaced by recyclable products (heat, electricity, fertilizer…).

GHG data were collected through a literature review for each type of emissions and each process of sludge treatment and disposal routes. All collected data were implemented in $^{G}E_{S}$TABoues, developed with VBA Excel to quantify GHG emissions generated by a wastewater treatment plant of x PCE.

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1 INTRODUCTION

1.1 Background

During the last decades, European institution establishes regulations which aim at protecting the environment from the adverse effects of the collection, treatment and discharge of waste water (Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment) and at maintaining and improving the aquatic environment (Directive 2000/60/EC of 23 October 2000 establishing a framework for community action in the field of water policy). These regulations were transcribed in French laws leading to important constraints on the waste water treatment plants (WWTP).

The environmental cleaning up of water in WWTP inevitably produces sludges that need to be treated and eliminated. Waste water sludge treatment can be an environmental problem as contaminants in water may land up in the sludge. The application of the above-mentioned European and French laws leads to an increase in sludge production (from 580 000 in 2000 to 1 300 000 dry matter tons in 2005; ADEME, 2001) which is eliminated according four main disposal routes: land spreading (directly or after composting), incineration, incineration with household wastes and landfilling.

A recent study (Reverdy and Pradel, 2010) shows an increase in sludge land spreading from 60 to 70% with a significant evolution of composted sludge spreading. As no sludge was composted in 2000, 23 % was spread after composting in 2007 and 46% was directly spread. Incineration slightly increases from 15 to 18% while landfilling significantly decrease from 25 to 12% in 2007.

The environmental assessment of sludge treatment and disposal routes is therefore a big concern as it can be used by stakeholders (WWTP managers, local authorities…) to choose the appropriate alternative in sludge treatments or disposal routes.

1.2 Research objectives

Several authors studied the environmental impacts of WWTP and sludge treatment processes by using Carbon footprint or Life Cycle Assessment methods in order to compare the most favourable alternatives in sludge disposal routes from an environmental or energetic point of view (Houillon and Jolliet, 2005; Lundin et al., 2004; Vandenbossche et al., 2005). These studies are highly instructive but the results greatly depend on the hypotheses and the scenarios analysed. These studies cannot be sometimes compared as the studied system and the functional unit used are different. This leads to the conclusion that the results of these studies cannot be generalized. Moreover, very few studies were conducted to assess the environmental impact regarding each process involved.

This is the underlying reason of the creation of a Carbon footprint calculation tool ($^{G}E_{S}$TABoues) designed to help stakeholders to better understand the impact of sludge treatment and disposal options on Global Warming.

This paper aims to present the underlying methodology used to quantify the material and energy flows and the related greenhouse gases (GHG) for each processes involved in sludge treatment up to those generated by each disposal routes.

The first part of this paper will present the method used (i.e. the system boundaries and the functional unit). The second part of the paper deals with the GHG data collection for each process, a special focus will be done on the transport and the infrastructure data collection. Then, the last part of the paper will show the type of results provided by the tool. Some example of the use of $^{G}E_{S}$TABoues tool will be presented in Reverdy and Pradel (2012).

2 METHODOLOGY

2.1 Carbon footprint method

Carbon footprint general framework

The Carbon footprint is defined as the total amount of greenhouse gases produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO_2). It is a common method to calculate the impacts of human activities on Global Warming (IPCC, 2006). In France, the ADEME (French Environment and Energy Management Agency) developed a carbon footprint framework called "Bilan Carbone®" which allows quantifying and assessing the GHG emissions for human activities or organisations (ADEME, 2009). The fundamental principles of this method lie in equally considering the GHG emissions directly generated by the studied activity and the GHG emissions taken place outside of the studied activity but essential for it. The "Bilan Carbone®" method takes into

account GHG directly emitted in the troposphere by the studied activity but not the gases produced after chemical reactions in the atmosphere.
As the quantification of these gases cannot be directly measured, they are estimated by calculating GHG emissions of each processes involved in the studied activities. The amount of each gas is then converted with an emission factor in CO_2 equivalent (CO_{2eq}) according to their Global Warming Potential (GWP), a relative measure of how much heat a GHG traps in the atmosphere over a specific time interval, commonly 20, 100 or 500 years (IPCC, 2006). The considered gases and their GWP are presented in Table 1.

TABLE 1 **Considered gases in carbon footprint and their Global Warming Potential at 100 years (GWP_{100})**

Common name	Formula	Life span (year)	Radiative efficiency ($W.m^{-2}.ppb^{-1}$)	GWP at 100 years
Carbon Dioxide	CO_2	(note)[a]	$1.4*10^{-5}$	1
Methane	CH_4	12	$3.7*10^{-4}$	25
Nitrous oxide	N_2O	114	$3.03*10^{-3}$	298
CFC compounds	$C_nCl_mF_p$	45 – 1 700	0.18 – 0.32	4 750 – 14 400
HCFC compounds	$C_nH_mCl_pF_q$	1.3 – 17.9	0.14 – 0.22	77 – 2 310
HFC compounds	$C_nH_mF_p$	1.4 - 270	0.09 – 0.28	124 – 14 800
PFC compounds	C_nF_{2n+2}	2 600 – 50 000	0.10 – 0.56	7 390 – 10 300
Sulfur hexafluoride	SF_6	3 200	0.52	22 800
Nitrogen trifluoride	NF_3	740	0.21	17 200

[a] The CO_2 response function used in this table is based on the revised version of the Bern Carbon cycle model used in Chapter 10 of 2006 IPCC report using a background CO_2 concentration value of 378 ppm.

However, "Bilan Carbone®" results can also be expressed in carbon equivalent (C_{eq}). This unit only considers the carbon molecule in the CO_2 compound, i.e. C_{eq} (kg) = 12/44 * CO_{2eq} (kg).

The CO_2 emissions can either been from fossil or biogenic origin. Biogenic CO_2 emissions are belonging to short carbon cycle. They are involved in photosynthesis or thermal or biological ways of oxidation so as the emitted biogenic CO_2 is rapidly incorporated in the carbon cycle. These biogenic emissions are not taken into account in national protocols as they are considered (by convention) as "carbon neutral" (GWP equal to zero). As fossil CO_2 emissions come from the hydrocarbon combustion, stored in the Earth surface from million years, they are belonging to the long carbon cycle. Releasing this fossil carbon by combustion increases the amount of CO_2 in the atmosphere and these emissions need to be accounted in "Bilan Carbone®" method.

Three types of emissions are considered within the "Bilan Carbone®" method: direct, indirect and avoided emissions. The direct emissions are emissions directly produced by the process or the studied activity (ex: CO_2 emissions due to fuel combustion during the activity). The indirect emissions are produced by processes needed by the activity but not directly generated by the activity (ex: CO_2 emissions during transport of goods). Avoided emissions are generated when products are not used and replaced by recyclable products (heat, electricity, fertilizer…).

Adaptation to sludge treatment and disposal routes

The « Bilan Carbone® » method is generally applied in France to assess the GHG emissions of industrial or tertiary activities. The method is not very precise concerning the way to account GHG emissions in WWTP, limiting the GHG emissions only to CH_4 emissions of the waste water released in the environment without treatment. No information is given to the assessment of sludge treatment in WWTP (ADEME, 2010a). Some methodological principles of a carbon footprint assessment in WWTP are given by ASTEE (ASTEE, 2009). The ASTEE method is based on the ADEME's "Bilan Carbone®" but takes into account the entire WWTP, including the sludge disposal as end-of-life of WWTP wastes. No distinction is realized between the water treatment and the sludge treatment so as it is not possible to compare the environmental impact of sludge treatment and the best disposal routes.
To fill in these gaps, we proposed a method to account GHG emissions for sludge treatment and disposal routes. The first step was to propose methodological choice regarding the studied system boundaries and the functional unit used to quantify the GHG emissions.

The system boundaries are limited to the sludge treatment including all the possible disposal routes (Figure 1). Two types of analyses are done to assess GHG emissions: a detailed analysis for all the sludge treatment processes and disposal routes and a global analysis for the consumables, transport and infrastructure involved in the system. The GHG emissions are assessed for the total amount of sludge produced by a WWTP of x Per-Captia Equivalent (PCE).

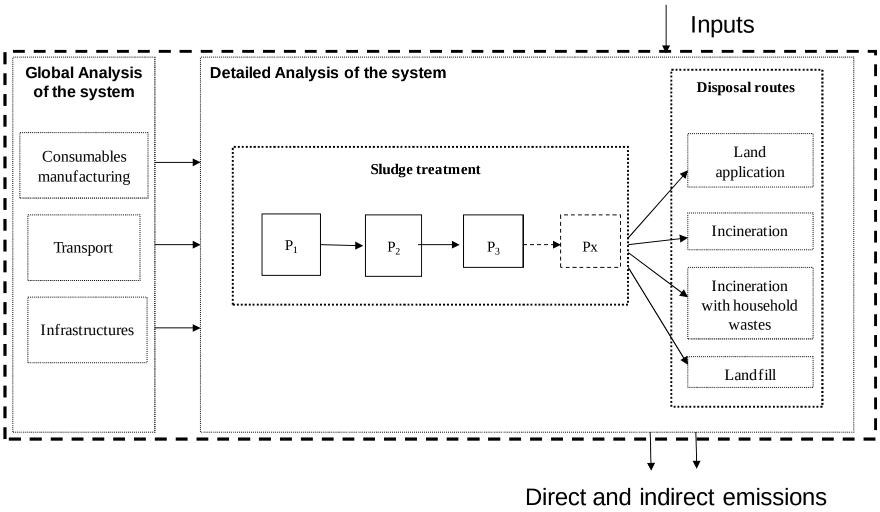

FIGURE 1 **System boundaries**

The factor x is greatly dependent on the WWTP treatment capacity and so of the PCE. We propose to assess the GHG emissions on a whole year as it is a common temporal unit for stakeholders (WWTP manager or local authorities). It can be repeatable and simplify data collection. A temporal allocation will be done if GHG emissions of sludge treatment processes are emitted on more than one year (example of reed drying beds).

The main GHG emissions accounting in WWTP system are fossil CO_2, CH_4 and N_2O. CO_2 emissions are emitted during the organic matter degradation all along the sludge treatment processes. As they are from biogenic origin, they are not taken into account in our method.

As for "Bilan Carbone®", direct, indirect and avoided emissions are taken into account in our method. Direct emissions directly originate from sludge treatment processes or disposal routes. A distinction is done between the GHG emissions due to the sludge (biological degradation…) and the other ones (emissions during fuel combustion or electricity consumption needed to run the different sludge treatment processes or occurring in sludge disposal). Indirect emissions are due to energy and chemical consumptions (combustible or electricity) to operate each process. Transport emissions (for consumables, sludges and ashes) and civil engineering emissions are taken into account. They are discussed in the following section. Avoided emissions are accounted when processes are substituted by other processes. The avoided emissions in sludge treatments and disposal routes can be generated by energy or material substitutions:

- Thermal or electric energy production from biogas: avoided emissions are due to emissions that will have take place for an equivalent non-renewable amount of energy,
- Use of sludge as fertilizers: avoided emissions are those generated by the amount of substitute mineral fertiliser production and its spreading,
- Use of sludge as a combustible or as mineral portion in cement kilns: avoided emissions are due to emissions that will have take place for an equivalent non-renewable amount of energy or the production of the substituted raw materials.

2.2 Sludge treatment processes and disposal routes

Based on OTV (OTV, 1997), 5 types of sludge can be produced in WWTP depending on the type of water treatment.

Sludges from primary treatment are classified in the A class. Sludges from secondary treatment are classified in B1 or B2 classes, the difference lies in the presence of a primary treatment (B2 class) or not (B1 class). The blending of primary and secondary sludges produces sludge that are classified in the C class while a stabilization process provides sludges classified in the D class.

These three types of sludge (primary, secondary and tertiary) are then treated to decrease their water content (by thickening, dewatering and drying processes), stabilized and sanitized before their valorisation through land application, incineration or landfilling.

The different sludge treatment processes and the possible disposal routes are presented in Figure 2. The GHG emissions for each process were quantified and implemented in $^{G}E_{S}$TABoues tool.

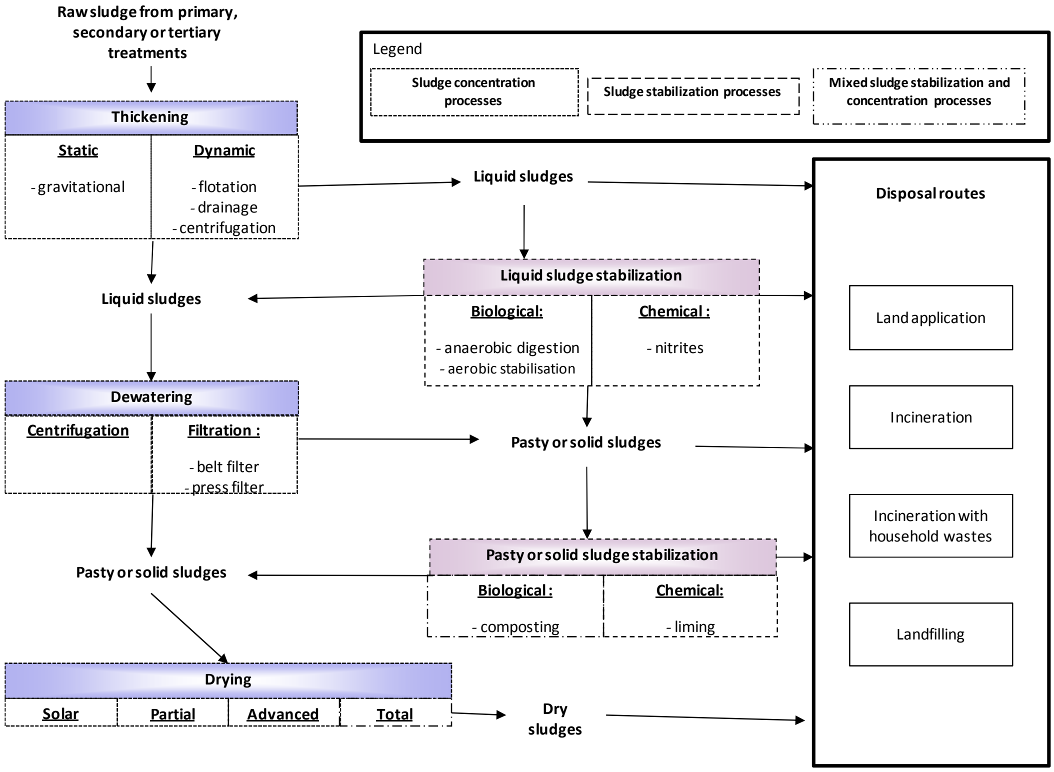

FIGURE 2 **Studied sludge treatment processes and disposal routes**

2.3 GHG data collection

A literature review was conducted to collect required information to assess the carbon footprint of the sludge treatments processes and disposal routes (Reverdy and Pradel, 2011). Data on energetic and polymer consumptions and GHG emissions were collected for each process involved in the studied system. The data analysis shows a great variability for a same type of emission (example: kg CO_2eq/ton of consumed polymer). As we implement a single value in $^{G}E_{S}$TABoues tool, we choose to calculate an average value when values collected from literature are of the same order of magnitude. When the variability is too high, extreme values were excluded and the average value calculated on the remaining data.

Data collection was done regarding two possible uses of $^{G}E_{S}$TABoues tool. On one hand, the user provides own data and collected data may be used as reference values. If the user has no specific data for his WWTP, collected data will be used to assess the carbon footprint of the selected sludge treatments and disposal routes.

GHG emissions for each studied process

Direct GHG emissions were generated for storage, reed drying beds, anaerobic digestion, composting, land application, incineration, incineration with household wastes and landfilling. These emissions are summarized in Table 2.

Indirect GHG emissions, expressed in CO_{2eq}, are generated for each process using inputs such as electricity, gas, light and heavy fuel, lime, soda, polymer, active carbon… These emissions take into account either the GHG emissions released during the input production as well as those occurring during their transport up to the WWTP. The mineral fertiliser production generates indirect GHG emissions ranging from 0.121 to 1.693 kg of CO_{2eq}/kg of nutrient (N, P or K). The variability is explained by the different technologies of manufacturing used and by the form of the produced mineral fertiliser (simple, binary or ternary). The GHG emissions generated by the production of these inputs are shown in Table 3.

TABLE 2 **Direct GHG emissions regarding the sludge treatment and disposal routes studied processes**

Processes	Emissions	Unit	Emission factor	Source
Storage	CH_4	Kg/kg BOD_5	Open silo: 0 < 2 m silo in anaerobic condition: 0.12 < 2 m silo in anaerobic condition: 0.4	Sylvis, 2009 Mallard et al, 2007 Gac et al, 2006 Record, 2008 ADEME, 2005 IPCC, 2006 Citepa, 2010 Pacaud et al, 2009 Gac et al, 2010 EPE, 2006 Shimizu et al, 2007 Doka, 2007
Reed drying beds	N_2O CH_4	Kg/PCE/an	0.0518 0.0453	
Anaerobic digestion	CH_4	Kg/ton	0.18	
Composting	CH_4 N_2O	Kg/ton	2.9 0.4	
Land application	N_2O	Kg/ton	Liquid sludge: 0.0294; Solid limed sludge: 0.05; Composted sludge: 0.05; Dry sludge: 0.2875	
	N_2O	Kg/ha	Other type of sludge and mineral fertilisers: $N_{applied}$ * [0.0157 + 0.3*0.0118 + 0.2*0.0157]	
Incineration	N_2O	Kg/ton	If combustion temperature (t°) is known : [N_{total} * (161.3 – 0.14 * t°)/100]*1.57 If t° is unknown: 1.64	
Incineration with household wastes	CO_2 N_2O	Kg/ton	390 0.092	
Landfilling	CH_4	Kg/ton	If biogas is captured: sludge C * 0.13 If biogas is released: sludge C * 0.43	

TABLE 3 **Indirect GHG emissions regarding the inputs used for each process**

Type of inputs	Type of emissions	Unit	Emission factor	Source
Electricity	CO_{2eq}	Kg/kWh	0.089	IRH, 2009 OTV, 1997 Degremont, 2005 Pradel, 2010 Hospido et al, 2005 Record, 2008 ADEME, 2010b
Gas	CO_{2eq}	Kg/kWh	0.32	
Light fuel	CO_{2eq}	Kg/kWh	0.24	
Heavy fuel	CO_{2eq}	Kg/l	2.662	
Fuel for tractors	CO_{2eq}	Kg/l	3.2	
Polymer	CO_{2eq}	Kg/kg	4.25	
$FeCl_3$	CO_{2eq}	Kg/kg	0.33	
Slaked lime	CO_{2eq}	Kg/kg	0.975	
Quicklime	CO_{2eq}	Kg/kg	1.04	
Caustic soda	CO_{2eq}	Kg/kg	1.17	
Activated carbon	CO_{2eq}	Kg/kg	6	

GHG emissions for transport

The transport process in $^{G}E_{S}$TABoues tool takes into account the transport of inputs from the suppliers storage place to the WWTP and then from the WWTP to the disposal place (either the field, the incinerator or the landfill). The GHG emissions of transport were calculated according the following hypotheses:

- CO_{2eq} emission calculation is done for the ton.km unit, i.e. the emissions generated to transport one ton of product on one kilometre.
- We assume that a single type of transport is done for one type of input. For example, the transport of polymer cannot be done with both a 2.5 ton truck and a 12 ton truck.
- Different inputs cannot be transported at the same time with the same vehicle.
- Transport of energetic consumables such as electricity, fuel or gas is not taken into account as it is already accounted in indirect GHG emissions.

The main transport modelled in $^{G}E_{S}$TABoues is a transport by truck as for "Bilan Carbone®" method (ADEME, 2010c). Sludge transport from the WWTP to the field is done according the method proposed in Pradel (2010). For liquid sludge, transport is done directly from the WWTP to the field with a tractor and a slurry tanker (4 processes are modelled). The other types of sludge are transported from the WWTP to the intermediate storage with a truck (3 processes modelled) and then to the field with a tractor and a spreader (3 processes modelled).

GHG emissions for infrastructure

After a literature review, two main methods were identified. Renou (2006) considers that the most applicable methodology is to consider mass of all civil engineering and electrical/mechanical equipments whereas Doka (2007) considers that civil engineering emissions are defined by wastewater treatment plant for 5 classes of plants. We proposed an intermediate method to take into account infrastructures in $^{G}E_{S}$TABoues tool. We estimate the amount of material needed (such as concrete, steel…) of all civil engineering and electrical/mechanical equipments involved in sludge treatment and disposal routes for 3 classes of WWTP: < 10 000 PCE (small), between 10 000 and 100 000 PCE (medium) and more than 100 000 PCE (big).

GHG emissions were calculated according to the whole life cycle of the infrastructure and the total amount of produced sludge. They are expressed in kg of CO_{2eq} /unit/ton. An example of infrastructure calculation is done in Table 4. Complete infrastructure GHG emissions can be found in Reverdy and Pradel (2011).

TABLE 4 **GHG emissions for sludge treatment and disposal routes infrastructures**

Infrastructure	**Capacity**	**Life span (years)**	**Description**	**Modelled processes**	**Kg CO_{2eq} /unit/ton**
Static thickening	Small	30	Thickener, diameter: 5 m, capacity: 70 m^3	Concrete, Steel, Cast iron, Stainless steel	0.0245
	Medium	30	Thickener, diameter: 12 m, capacity: 450 m^3		0.0109
	Big	30	Thickener, diameter: 20 m, capacity: 1250 m^3		0.0096
Press filter	Small	15	Press filter, 50 plates 500*500 mm, capacity: 290 l, total weight: 3 156 kg	Cast iron, Polypropylene, stainless steel	0.2674
	Medium	15	Press filter, 100 plates 1000*1000 mm, capacity: 2400 l, total weight: 12 385 kg		0.2103
	Big	15	Press filter, 150 plates 1500*2000 mm, capacity: 10000 l, total weight: 59 090 kg		0.4943
Incineration	Medium	40	Fluidized bed incinerator, total weight: 65 970 kg, height: 10 m, diameter: 3.45 m	Refractory steel, refractory fireclay, sand, concrete	0.0188

3 RESULTS PRESENTATION

All collected data presented in the previous section were implemented in $^{G}E_{S}$TABoues, a tool developed with VBA Excel to quantify GHG emissions generated by a wastewater treatment plant of x PCE. An example of results obtained with $^{G}E_{S}$TABoues tool is presented in Reverdy and Pradel (2012).

Two types of results are obtained with $^{G}E_{S}$TABoues tool. The first one is different bar charts (an example is given Figure 3) and a mass/energy balance for the entire studied sludge treatment and disposal route (Figure 4).

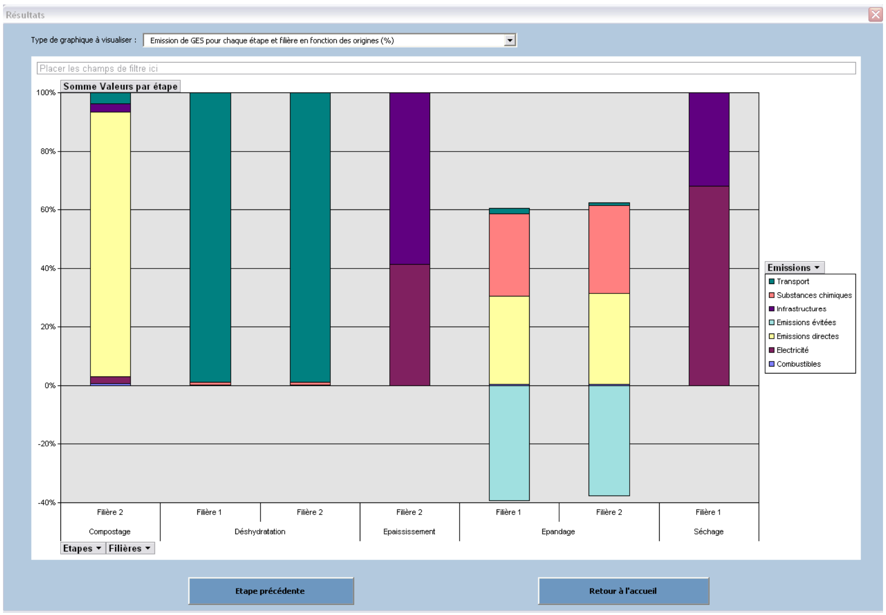

FIGURE 3 **GHG emissions for each process and sludge treatment regarding the GHG origin (in %) ($^{G}E_{S}$TABoues tool screen shot)**

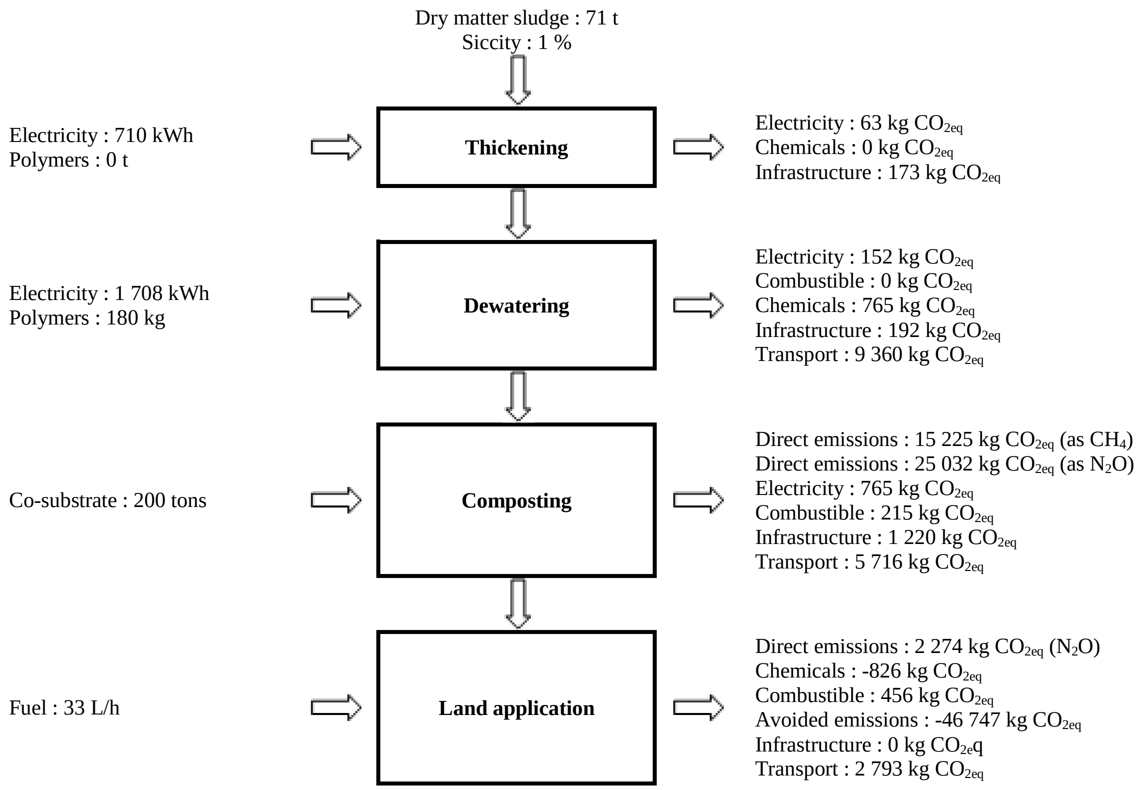

FIGURE 4 **Example of mass and energy balance obtained with $^{G}E_{S}$TABoues tool**

4 CONCLUSION

This paper proposes a method to assess GHG emissions and Global Warming impact assessment of sludge treatment and disposal routes. Its originality lies in the consideration of each process involved in the stream. However, this method needs to evolve as biogenic emissions are not taken into account while it appears from a great importance to assess the environmental impact of processes based on biological treatment. Accounting biogenic CO_2 emissions will provide a better understanding of process efficiency in sludge treatment and their inclusion in Global Warming assessment is currently a big concern in research development and for worldwide environmental agencies (EPA, 2011).

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