Assessment of Sludge Management Options in a Waste Water Treatment Plant

By
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Bachelor of Applied Science, Civil and Environmental Engineering
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Submitted to the Department of Civil and Environmental Engineering in Partial
Fulfillment of the Requirements of the Degree of

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Abstract

This thesis is part of a larger project which began in response to a request by the Spanish water agengy, Cadagua, for advice on life cycle assessment (LCA) and environmental impacts of Cadagua operated wastewater treatment plants. The project uses the LCA software GaBi and focuses on La Gavia Wastewater Treatment Plant in Madrid. This thesis analyzes three sludge management options that La Gavia could have implemented: (1) cogeneration and incineration, (2) cogeneration and land application, and (3) Composting. Life cycle impacts of global warming potential, eutrophication, acidification, ozone layer depletion potential were calibrated using GaBi.

Thesis Supervisor: E. Eric Adams

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Acknowledgement

I would like to thank everyone who helped me and made this thesis possible.

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I would like to thank especially Professor Adams who was my advisor and who always supported me in my ideas.

Emma and Gloria and everyone from Cadagua. Thanks for being such a great host in Spain and supporting the project.

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1. INTRODUCTION

1.1. Background

Global climate change, also known as global warming, is caused by the atmospheric build-up of greenhouse gas. The increased concentration of greenhouse gas in the atmosphere directly leads to global temperature rise, which in turn causes sea level rise, flooding, and extreme weathers. The three major greenhouse gases are generally considered as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O, also known as laughing gas). CO_2 is no doubt the largest amount of all greenhouse gases, followed by CH_4, which has a 21 times greater than global warming potential (GWP) than CO_2. Although N_2O is the least abundant among these three gases, contributing 4.5 percent of total GHG emissions (USEPA, 2011), the high GWP (310 CO_2-eq.) of N_2O has drawn people's increasing attention.

While people have focused on CO_2 emissions from construction, transportation and power generation, wastewater treatment plants (WWTPs) also play a significant role. USEPA (2011) have listed WWTPs as the 7th largest contributors to both CH_4 and nitrous N_2O emissions. Therefore, in order to reduce GHG emissions, more and more regulators worldwide began to require and enforce mandatory reports and measurements on GHG emissions from WWTPs.

A typical WWTP consists of a series of unit processes including primary treatment, biological secondary treatment, occasional tertiary treatment and sludge treatment. There are multiple sources of GHG emissions (direct and indirect) from WWTPs. The major source of CO_2 emission associated with WWTPs is from electricity consumed to operate different treatment processes. CO_2 is also a product of aerobic digestion in biological secondary treatment. CH_4 is a typical product of anaerobic digestion employed in some forms of secondary treatment and in sludge digestion. N_2O is the intermediate product resulting from incomplete reactions in the biological nutrient removal process. The total N_2O is also recognized for its uncertainty among the three GHGs.

To properly account for all these emissions over the entire lifetime of a WWTP, a life cycle assessment (LCA) is often conducted. There are various commercial LCA packages on the market; and the GaBi 5 developed by PE International is used in this project.

1.2. Project Description

This project is sponsored by Cadagua S.A., a water and wastewater utility company in Spain seeking sustainable development and commitment to environmental regulations. In order to better understand the real contributions to global warming from wastewater treatment plants in Spain. It has been requested to evaluate the GHG emissions from WWTPs, investigate potential methods to reduce such gas emissions, and identify particularly the N_2O emission.

In response to Cadagua's request, LDX Environmental has formed a team of three members from MIT's Department of Civil and Environmental Engineering's Master of Engineering Program: Bo Dong, Xin Xu and Jong Hyun Lim. The three students visited Spain during January 2012. Based on the visit, the La Gavia WWTP in Madrid was selected as the plant of interest, due to the data availability and the advanced treatment processes.

1.3. Objectives

Previous studies quantified various emissions from WWTPs, but they are either on the laboratory-scale or site specific. Hence, these studies cannot be applied to any WWTP in Spain. Therefore, the primary goal of this project is to quantify the contribution of WWTPs to global climate change and to estimate the amount of emissions from each individual process within WWTPs.

2. LITERATURE REVIEW

2.1. Green House Gas (GHG)

2.1.1. Emission Sources

The three major greenhouse gases are generally considered as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The estimation of the amount of greenhouse gas emissions can be made by several methods. For example, Figure 2.1 shows the total greenhouse gas emissions by types of greenhouse gases, while Figure 2.2 shows emissions estimated by sectors.

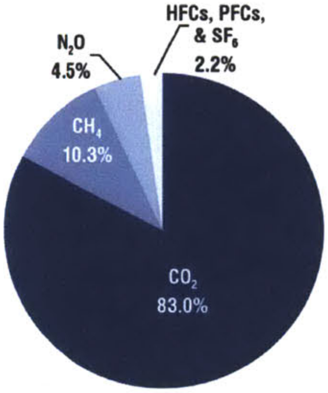


Figure 2.1 Greenhouse Gas Emissions by Types of GHG (USEPA, 2011)

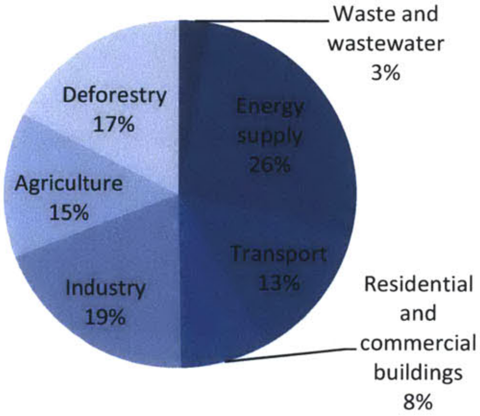


Figure 2.2 Global Anthropogenic Greenhouse Gas Emissions in 2004 (IPCC, 2007)

2.1.2. Global Warming Potential (GWP)

The concept of global warming potential (GWP) is defined as the ratio of the radioactive forcing of an instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). The reference gas used here is CO_2, with the unit of carbon dioxide equivalent (CO_2-Eq). Besides, difference gases have different residence times in the atmosphere. The GWP is normally reported on a 100-year base. For example, CO_2 itself has a GWP of 1 CO_2-Eq on a 100-year base. The GWP of CH_4 is 21 times more powerful than that of CO_2. Hence, the GWP of CH_4 is 21 CO_2-Eq. Similarly, the GWP of N_2O is 310 CO_2-Eq. Table 1 below shows the GWP of the three major greenhouse gases.

Table 1 Global Warming Potential of CO_2, CH_4 and N_2O (USEPA, 2011)

Gas	**GWP (CO_2-Eq) (100 year)**
CO_2	1
CH_4	21
N_2O	310

The term carbon footprint is therefore, defined as the sum of all greenhouse gas emissions and expressed as global warming potential (GWP) in the units of kg CO_2-Eq.

2.1.3. Direct Emissions

Under the concept of LCA, various emissions to the environment can be further grouped into two categories – direct emissions and indirect emissions. Direct emission is easy to visualize. It includes emissions within the treatment plant, such as non-biogenic carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). These gases come from both stationary sources, like biological treatment process, and mobile combustion sources, like cars and trucks. The CO_2 emission from secondary biological treatment process should not be counted as direct emission, due to its biogenic source. The detailed discussion of CO_2 is shown in Section 2.1.5.

2.1.4. Indirect Emissions

Different from direct emissions, indirect emissions refer to emissions outside plants. However, these emissions are directly caused by the product or process studied. Indirect emissions may include emissions from the electricity purchased from power plants, during transportation and from the production of chemicals. Past researches (Knosby et. al, 2010) have demonstrated that indirect emissions would contribute more than 60 percent of the total greenhouse gas emissions in WWTPs.

Biosolids, as the final product of the sludge treatment, need to be carefully studied in terms of indirect GHG emissions. The transportation of waste biosolids is an important source of emissions due to fossil fuel combustion. Moreover, the ultimate disposal of the biosolids can also be a source of fugitive N_2O and CH_4 emissions, especially when waste is placed in landfills or used for composting and agriculture application.

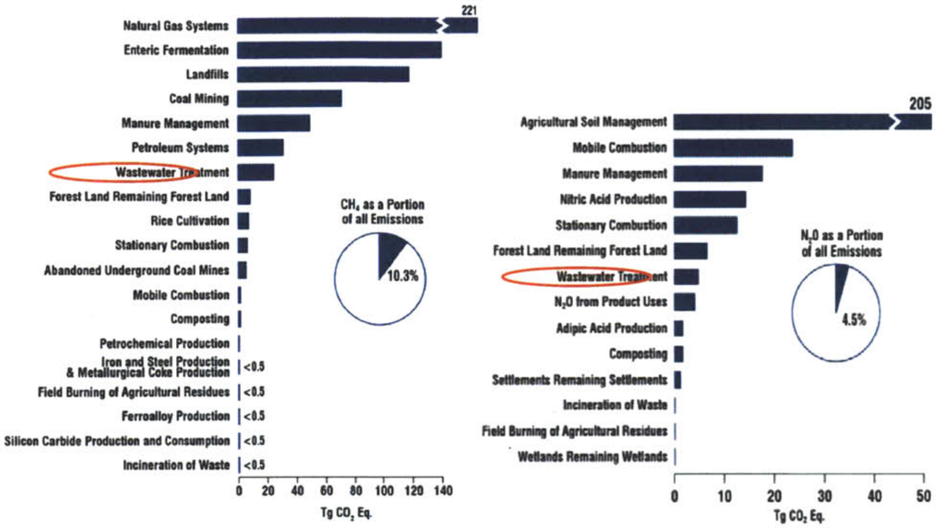
2.1.5. Carbon Dioxide

As shown in Figure 2.1, carbon dioxide (CO_2) contributes to more than 80 percent of total greenhouse gas emissions. It is also the biggest contributor to the carbon footprints of WWTPs. Emissions from both direct sources and indirect sources add up to total CO_2 emission.

Some CO_2 comes from the secondary biological treatment process as a result of respiration of organic matter (BOD). However, this amount of carbon dioxide is often neglected from greenhouse gas accounting due to its biogenic origins (USEPA, 2006). Tillman el al. (1998) adopted a similar approach in the LCA case study of municipal waste water systems, meaning that the biogenic CO_2 is excluded from greenhouse gas emission from WWTPs.

2.1.6. Methane

According to USEPA (2011), CH_4 results in ten percent of the total greenhouse gas emissions. Figure 2.3(a) shows that WWTPs are the 7th largest sectors that contribute to methane emissions.



(a) (b)

Figure 2.3 Methane Emission by Sectors (a) and Nitrous Oxide Emissions by Sectors (b) (USEPA, 2011)

Methane (CH_4) can be released throughout the systems where anaerobic conditions exist. Most of the CH_4 emissions come from open anaerobic reactors, lagoons and the sludge handling processes. Limited amounts of CH_4 can also be emitted from aerobic processes when it is poorly managed. In real practice, CH_4 can be neutralized if burned (flared or employing other forms of combustion). Energy, as a byproduct from this neutralization process, can be in turn used to heat the anaerobic digester. Inefficiencies in the CH_4 gas collection systems combined with the incomplete combustion of the digester gases can still result in CH_4 emissions.

2.1.7. Nitrous Oxide

As Figure 2.3(b) shows, nitrous oxide results in 4.5 percent of the total greenhouse gas emissions, which are often overlooked due to its relatively small amount in the atmosphere. It is still a fact that WWTP is ranked the 7th place in nitrous oxide emissions by sectors.

Nitrous oxide (N_2O) can be generated from a WWTP with a biological nutrient removal process, which is designed to reduce the concentration of total nitrogen in the treated wastewater. N_2O is normally considered as a byproduct of the nitrification process and an intermediate product of the denitrification process. The amount of N_2O released depends on the operational conditions of the biological nutrient removal processes. In addition, N_2O emission can be found in the receiving water, where treated effluent is discharged.

Although there is a lack of reference for a good estimation of nitrous oxide emissions from WWTPs, the fact is that the N_2O emission is bound to increase significantly as stringent effluent nitrogen controls come into force. However, if the biological nutrient removal process is not adopted and excess ammonia continues to pollute the waterways, there would be less N_2O emission to the atmosphere and thus lower global warming potential. But another environment impact to receiving water would inevitably arise, i.e. eutrophication, which would result in excessive plant growth and depletion of oxygen in the water. This impact is of greater concern for wastewater treatment plants whose effluents are discharged directly into small rivers or lakes than those into the oceans. This trade-off between the global warming potential and the eutrophication potential, produces a challenge: how to reduce greenhouse gas emissions and at the same time minimize the ecological effects caused by eutrophication.

2.2 Life Cycle Assessment (LCA)

2.2.1 Concept of LCA

Life Cycle Assessment (LCA) is a tool that is used to evaluate the potential environmental impacts of a product, a process or a service. LCA is also the synonym for 'Life Cycle Analysis' or 'Cradle-to-grave Analysis' (Crawford, 2011). As the name 'cradle-to-grave' suggests, LCA involves the assessment of the entire life cycle of the product, from the preparation of raw materials, the manufacture of the product, and to the disposal of waste. LCA provides both a holistic picture of a product's environment impacts, and comparisons between stages of product life.

LCA application on WWTP

As a technical approach, LCA has been applied to WWTP since the late 90s. The links between the environmental impacts and treatment process are the relevant inputs and outputs of the product system (Crawford, 2011). The inputs normally include raw materials and energy. However, outputs may vary in a broad range, including products, emissions to air, emissions to water, solid wastes and other byproducts. As for the case of wastewater treatment plants, the major inputs would be wastewater from sewage collection systems, electricity used for pumping and mixing, and other chemicals added. In contrast, outputs include treated effluent to receiving water, sludge and various gas emissions.

There are several different ways to assess the environmental impact of wastewater treatment plants (WWTPs) under the concept of LCA. According to Emmerson et al. (1995), the life cycle of WWTPs generally involves the construction of phase of WWTPs, production of wastewater phase (or use phase) and the final demolition phase. They also pointed out that both construction phase and demolition phase have only trivial impact on the environment within the life cycle of the plant. Later researches have placed more focuses on the operational phase. Tillman et al. (1998) have studied alternatives for WWTPs in Sweden using LCA approach. And Lassaux et al. (2007) conducted case study on the anthropogenic water cycle ('from the pumping station to the wastewater treatment plant'). Other analysis on this increasingly popular topic also includes the comparison of environmental impacts between different WWTPs (Hispido et al., 2008), the comparison between different LCA methods for WWTPs, and the assessment of WWTPs with seasonal variations (Hospido, 2004).

As mentioned in Section 2.1, both direct emissions and indirect emissions are counted as anthropogenic greenhouse gas emissions. Therefore, in the LCA application to WWTPs, these two emission sources should be both considered.

2.2.2 The LCA Framework

A life cycle assessment is a complex process that involves several different stages. The International Organization for Standardization (ISO) has standardized a framework for LCA. According to the most updated ISO 14040:2006, LCA contains the following phases:

- goal and Scope definition
- inventory analysis
- impact assessment
- interpretation

The relationship between the different phases is shown in Figure 2.4. Goal and scope definition, inventory analysis and impact assessment are performed in sequence, while interpretation occurs through processes.

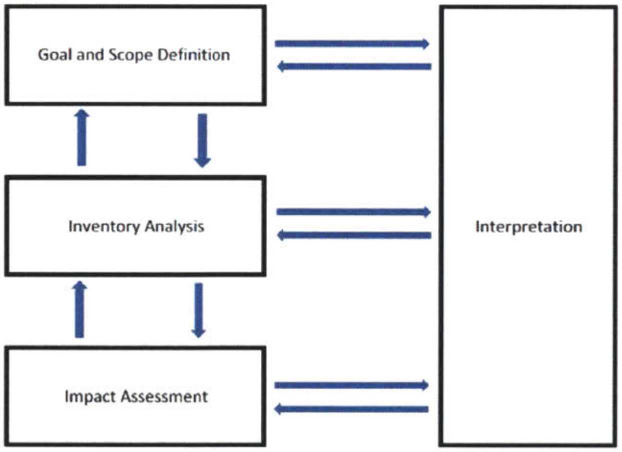


Figure 2.4 Four Phases of LCA (ISO14040:2006)

2.2.3 Goal and Scope Definition

Goal and Scope are stated in the first stage of LCA. The goal statement of an LCA application defines the purpose of the study. It includes parts or all of the following elements: reasons for the study, type of approach, targeted audience and use of final results. The scope definition normally explains which stage of the product life cycle and what boundaries are considered. ISO 14040:2006 have listed twelve items for scope definition. Some of them include:

- the product system to be studied
- the functions of the product/system
- functional unit
- impact category selected and methodology of impact assessment and interpretation to be used
- initial data requirement and quality
- assumptions
- limitations
- types of critical review, if any

Scope definition is an important step that defines the breadth, depth and details of the study.

Functional Unit

The definition of functional unit is the first key step in goal definition. A product system normally has several functions which represent different fates of raw materials. Functional unit defines both the type and quantification of the selected product function. It is used as a reference unit and enables the quantitative analyses between inputs and outputs. The concept of functional unit becomes particularly critical when the performances of different product systems are studied. The same functional units allow meaningful comparisons on a common basis. For example, a functional unit could be a ton of concrete or a vehicle seating five passengers.

In wastewater treatment literature, functional units are chosen based on different purposes of study. According to Suh and Roisseacux (2001), it is better to adopt flow rate (volume of wastewater treated within a certain period of time) as the functional unit, because it is clear and easy to establish inventory. Hospido et al. (2008) chose person equivalent as functional unit for the comparison between different plants. Lassaux el al. (2007) used one cubic meter of water at consumer tap. However, under certain circumstances, some functional units are interchangeable through a scaling factor. For example, a WWTP has a capacity of treating 10,000m^3/d. We can set functional units either as 10,000m^3/d or 1 m^3. And the final results will have a ten-thousand-time difference.

Although a functional unit could be a very small volume or a flow rate in a short time period, it should represent the long-term averaged performance of a WWTP. Details of data collection and quality are discussed in Section 4.1.1.

System boundaries

In general, a product system consists of several unit processes; and each unit process could have one or more inputs and outputs. Therefore, the system boundary defines which unit processes to include and hence, which inputs and outputs to include. The system boundary may also be affected by the access to data, relative assumptions, project budget and other constraints. According to ISO14040:2006, some processes, inputs and outputs only have minor effects on the final results, and hence they can be excluded from the system boundary.

By the definition from Sonnemann et al. (2004), LCA can be focused on either the life-cycle time boundaries of WWTPs (i.e. construction phase, operational phase and demolition phase) or the geographical boundaries of the anthropogenic water cycle.

Based on the discussion of time boundaries, Lundie el al. (2004) and Lassaux et al. (2006) have demonstrated that the environmental impacts of the construction phase is much smaller than that of the operational phase. The reasonable assumption for the demolition phase is that its environmental impact is smaller than those of operational phases and construction phases.

From the geographical point of view, conventional municipal WWTPs often include primary treatment, secondary treatment and sludge treatment. These basic processes should be included in LCA, due to their important impacts on the environment. The availability of other treatment processes, such as tertiary treatment, nutrient removal and disinfection differ from plant to plant. However, these plant-based processes should be carefully considered, due to their different impacts on the final results.

2.2.4 Inventory Analysis

Life Cycle Inventory (LCI) Analysis, the second phase of an LCA, involves data collection and processing and allocation of resources. Sonnenmann et al. (2004) summarized a four-step methodology in inventory analysis. These steps are:

- data collection
- normalization
- allocation
- data evaluation

However, different literatures may have slightly different methodologies. For example, ISO14040 standard prefers doing normalization in the life cycle impact assessment phase. And the data evaluation step is not unique in LCIA. Instead, data should be evaluated throughout the entire LCA.

Data collection

Once the system boundary is well defined, data can be collected according to the inputs and outputs of each unit process. Figure 2.5 describes a generic overview of data collection regarding system boundary. Similar approaches also apply to the individual unit process data collection. In some analyses, data collection could involve intensive labor, time and money.

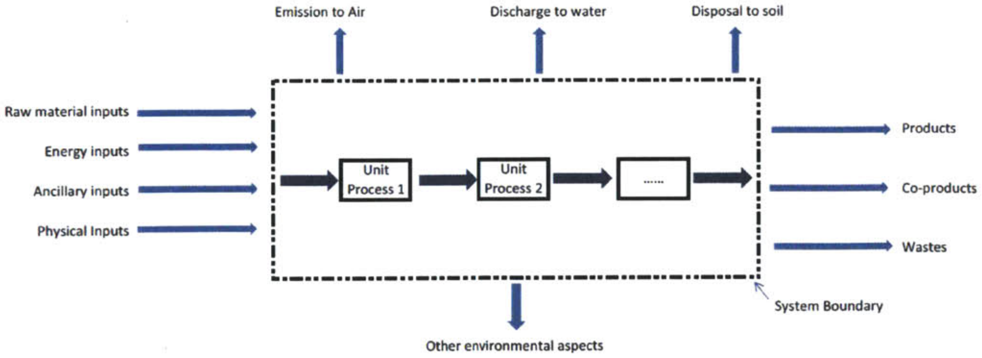


Figure 2.5 Generic Data Collection

Raw data needs to be further processed before the final life cycle inventory. Besides, the initial data quality must be checked with the following requirements (Sonnemann, 2004):

- time-related coverage
- geographical coverage
- technology coverage

These requirements guarantees the final LCA results are valid through a relative long time scale, a wide range of geological locations and a variety of technology mixes.

For the LCA of WWTP, data is mainly gathered from the daily plant operation. The flow rate varies between seasons and even years. An adequate time frame (e.g. 5years) is necessary to eliminate seasonal and meteorological variances. Geographical coverage depends on the goal and scope of study. For a single plant analysis, only local information should be used. Technology coverage reflects the types of technology used, whether a single operation or a technology mix. The wastewater treatment processes could have various treatment technologies for a single stage. For example, sludge digested gas can be ignited, recycled or the mix of both.

Normalization

As discussed in the previous data collection section, raw data needs to be further processed before allocation. This step is called normalization in some literatures. Based on the functional unit defined in the goal and scope phase, raw data needs to be normalized according to the functional unit. For example, in WWTP, if flow rate is used as the functional unit, all other raw data collected should be recalculated based on this flow rate.

Allocation

Allocation means the distribution of resources, wastes and emission for each single unit process to relative environmental impacts. The functional unit is the key that connects inputs and outputs and connects unit processes.

2.2.5 Impact Assessment

The main purpose of Impact Assessment (LCIA) is to translate the results from inventory analysis to a more understandable and precise interpretation of the environmental impacts of a product system. Despite the requirements for LCI, the three mandatory elements for impact analysis are:

- selection and definition of impact categories
- classification
- characterization

Selection and Definition of Impact Categories

The selection and definition is closely related to the goal of the LCA study. Different impact categories may include global warming, eutrophication, human toxicity, and ozone depletion. The results from inventory analysis can then be assigned to the respective impact categories.

Classification

Continued from the impact categories selection step, this step is to assign the LCI results into different environmental impacts. However, it becomes confusing when two or more flows have the same impacts. A characterization factor is defined for each impact category. For example, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) all have impacts on global warming, but their relative contributions to global warming are different. Therefore, global warming potential (GWP) is used as the characterization factor, with the unit of CO_2 equivalent (CO_2-Eq). From IPCC report, the GWP for CH_4 is 21 CO_2-Eq. And similarly, the GWP for N_2O is 310 CO_2-Eq.

Characterization

Characterization refers to the calculation of category indicator results. The results from LCI are calculated using the common factors defined in classification. This step can be achieved in various ways, like using matrices. Computer software can also be used to assist calculation.

2.3 Cadagua and the La Gavia WWTP

2.3.1. Company Profile

Cadagua, S.A., the sponsor of this project and one of Ferrovial's subsidiaries, is a Spanish company well recognized as a leading force in the field of engineering and construction of water purification and treatment plants.

Founded in 1971 and with 40 years' experience, Cadagua has been very active in the development of water treatment and desalination. It has successfully designed and built more than 200 water treatment plants all over the world (drinking, wastewater plants, desalination installations as well as industrial facilities), achieving a total treatment capacity of over 14,500,000 m^3/d. Over 17,000,000 inhabitants benefit from the company's operation and maintenance services. Figure 2.6 is a chart showing Cadagua's main service areas and installed treatment capacity (Cadagua, 2011)

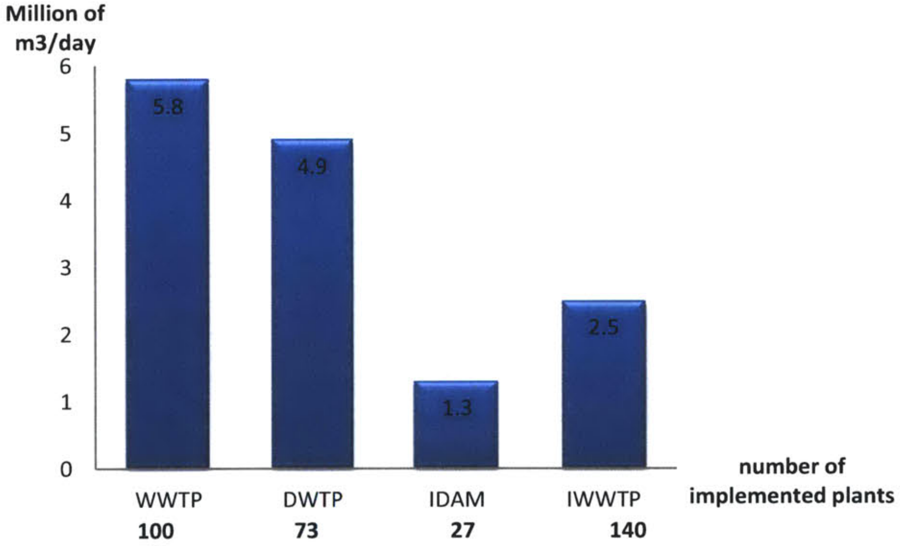


Figure 2.6 Treatment Capacity of Cadagua

Research, Development and Innovation (R&D&i) Department in Cadagua aims at providing better measure-made solutions for each of the installations, in order to improve global efficiency and lower operation and maintenance costs. Recent projects include process study to minimize sludge production, nutrients recovery and optimization of power consumption in treatment plants. The project *Assessment of the Carbon Footprint in Wastewater Treatment Plants and Sustainability Analysis for Process Selection* is also one of the ongoing projects, with collaboration with our consulting group LDX Environmental at MIT.

Four WWTPs were visited by our team in January 2012: La Gavia and Boadilla near Madrid, and Ribadesella and Villapérez near Oviedo, Spain. While all four WWTPs were visited data was only collected, and potential measurements are only considered for the La Gavia and Boadilla WWTPs.

Since all four WWTPs employed similar treatment processes, a comprehensive life cycle assessment is carried out on La Gavia WWTP based on the data acquired from Cadagua. The GaBi 5 software is used to assist the LCA. Later, the LCA on Boadilla WWTP will be conducted in a similar manner..

2.3.2. La Gavia Wastewater Treatment Plant

Inaugurated in June of 2005, La Gavia WWTP is located in the district of Villa de Vallecas, in southeastern Madrid. The plant resides on the left bank of the Manzanares River and it treats sewage from the La Gavia I and II sewer mains as well as the surplus that the La China plant cannot handle. Figure 2.7 is a plane view of La Gavia Wastewater Treatment Plant, and Figure 2.8 depicts the treatment plant's service areas (encompassed by red line).

Figure 2.7 La Gavia Wastewater Treatment Plant Plan View

(http://www.acciona.com.au/press/photoGallery/index.php/Water/Waste%20Water%20Treatment%20Plants/)

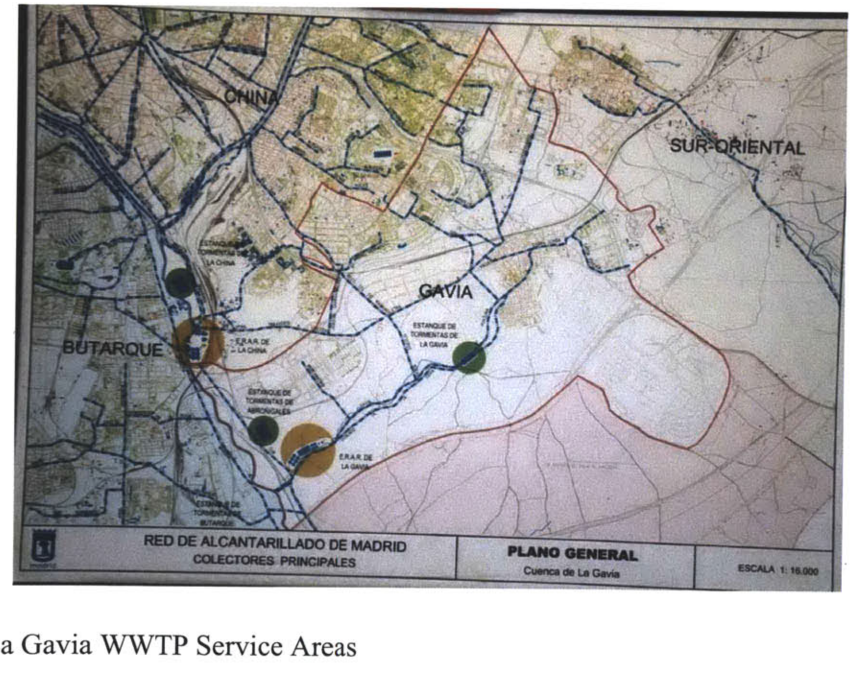


Figure 2.8 La Gavia WWTP Service Areas

La Gavia WWTP treats waste water from about a million people (residential and industrial) and has a designed capacity of 2m3/sec average flow. Using advanced biological treatment processes incorporated with nutrient removal, La Gavia WWTP is able to eliminate 97% of organic matter and suspended solids and about 85% of nitrogen and phosphorous from the water (Table 2.1), thus meeting the strictest sewage treatment standards. The plant is also in line with the National Sewerage and Wastewater Treatment Plan (1995-2005), which was enforced by the Ministry of the Environment in Spain to improve the quality of water in the Manzanares River.

Table 2.1 Removal Efficiency at the La Gavia WWTP

	Influent	**Effluent**	**Removal Rate**
	mg/l	mg/l	%
BOD	350	12	97
SS	340	12	96
TN	62	10	84
TP	8	1	87

In addition, the plant is designed to allocate approximately 10% of the treated water to watering green areas using a tertiary treatment process. This is part of the Madrid Water Re-Use Plan, a large-scale strategy to use recycled water for park irrigation and street cleaning services, to the benefit of around three million inhabitants.

Treatment Processes

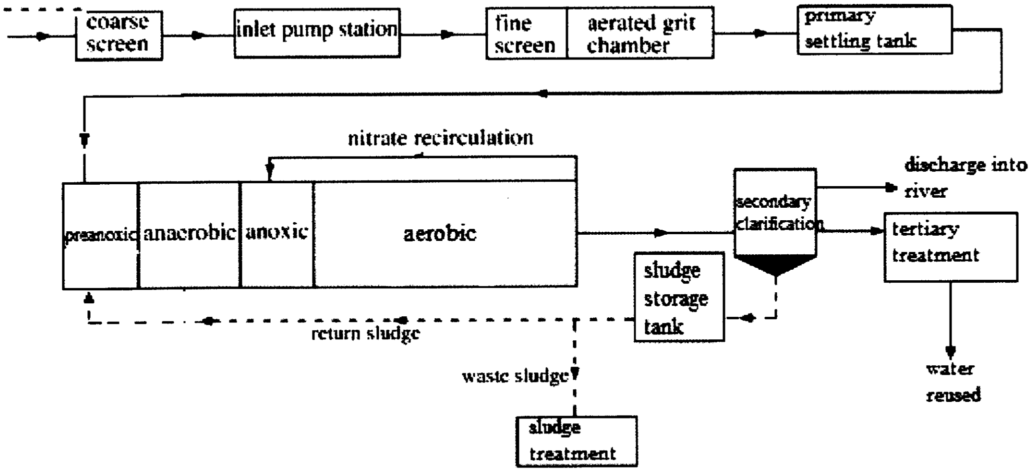


Figure 2.9 Schematic Diagram of Treatment Processes at the La Gavia WWTP

Figure 2.9 shows the simplified schematic of each treatment process employed in the La Gavia WWTP. Basically, the plant consists of two lines, treating wastewater and residual sludge separately (the Figure above shows mostly the water line). There are typically four stages associated with wastewater treatment processes: pretreatment, primary, secondary and tertiary treatment respectively. In case of high flow rate, certain amount of wastewater is bypassed after the primary treatment. Some of the functions and design parameters of each stage will be discussed in details as follows.

1) Pretreatment

At the entrance of the plant, wastewater is loaded with a large volume of solids that must be removed so that they won't obstruct the pumps and machinery used in further treatment. This stage is called pretreatment, which can be divided into several parts:

Coarse/wide screens (see Figure 2.10 left) separate large solids) and consist of a deep tank, located at the inlet to the treatment plant, where the walls are angled to facilitate the descent of the solids and the sands decanted to a specific area. This treatment typically removes material larger than about 10 or 15 cm.

Fine screens (see Figure 2.10 right) are placed after wide screens. Water passes through a gate that prevents materials (normally of a size greater than 6 cm) from passing by. The bars must be purged continuously, or they will become blocked. This is achieved by means of automatic movable elements that are driven by chains or curved grids with rotating combs.

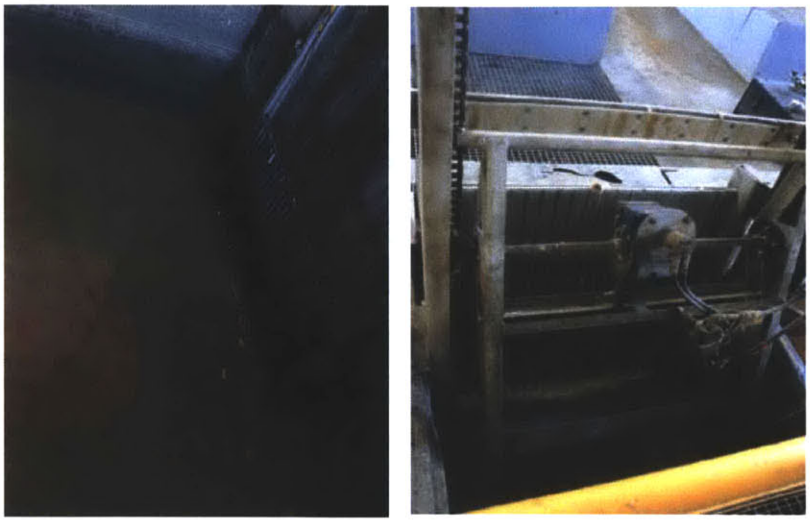


Figure 2.10 Coarse screen (left) and Fine screen (right)

Aerated grit chamber (Figure 2.11) is where grit is removed by aerating and stirring the water with a blower which causes the grit to settle down to the bottom of the chamber while keeping lighter organic matters in suspension to be processed further downstream. The lightest grease on the water surface is then skimmed out with combs.

Figure 2.11 Aerated Grit Chamber

Most waste generated in the pretreatment (sand, grease, large solids) are compacted and collected in containers. Finally, they are sent to sludge treatment or directly go to landfills where they can be reutilized as fertilizer.

2) Primary Treatment

Primary treatment usually referred to as primary settling tanks or primary clarifiers, is designed to remove organic and inorganic solids (which could not be removed in the previous treatment due to their small size) by the physical process of sedimentation. There are 6 circular primary tanks in La Gavia WWTP, which allow water to stand for 1.43 hours. Approximately 40 to 60 percent of the suspended solids are removed from the wastewater. The solids that remain in suspension as well as dissolved solids will usually be biologically treated in subsequent processes. And the debris will settle to the bottom of the tank to form primary sludge.

3) Secondary Treatment

Secondary treatment in the La Gavia WWTP is an advanced biological nutrient removal reactor (BNR), which contains four zones connected in series (preanoxic-anaerobic-anoxic-aerobic). Each zone plays a different role in the removal of nutrient. There are totally 6 parallel reactors, with a total volume of 100,800 m^3, and the total retention time is 14 hours.

The preanoxic zone is designed for denitrification and enhanced growth of phosphorus-accumulating microorganisms. The activated sludge from the secondary clarifier is pumped back to this zone (external recycle). In the absence of dissolved oxygen, bacteria utilize BOD in the influent, reducing the nitrates to gaseous nitrogen, thus alleviating the nitrate loading from the return sludge in the subsequent anaerobic zone.

Wastewater treated by the preanoxic zone is then introduced into the anaerobic tank (shown in Figure 2.12 left) in which a phosphorous release reaction by microorganisms occurs under anaerobic conditions.

In the anoxic zone, wastewater is mixed with the nitrified mixed liquor recycled from the aerobic zone at an internal recycling rate of 300% of the influent flow. This is the zone where the bulk of denitrification occurs, and where N_2O is most likely to be produced. (Sedlak, 1991)

In the aerobic zone (Figure 2.12 right), nitrification takes place where ammonia is reduced to nitrate and nitrite, and luxury uptake of phosphorous also occur. The aerobic zone is also responsible for aiding the growth of bacteria that feeds on organic matter. In order to assimilate organic matters, these microorganisms require a significant amount of oxygen, which is added through 12,420 submerged membrane diffusers at the bottom of the aerobic tanks. The air added to the water has been condensed to improve the efficiency.

Figure 2.12 Secondary Biological Treatment process: Anaerobic Zone (left) and Aerobic Zone (right)

4) Tertiary Treatment

The design of the La Gavia WWTP initially contemplated the incorporation of a water reuse system in response to the objectives set by the Madrid Water Re-Use Plan. So new tertiary treatment was built which employed a system of filtration and ultraviolet (UV) disinfection (shown in Figure 2.13). Designed for a flow of 21,600m3/day, to be doubled in a future enlargement, this will ultimately make it possible to reutilize 25% of the purified water from the WWTP currently in operation. At this time, about 10% of the purified water is treated for reuse. (Hernanz, 2007)

Figure 2.13 Tertiary Treatment: Filtration Tanks and UV Disinfection

5) Sludge treatment

Both primary and secondary processes generate sludge, which consists of mostly water (approximately 97%) and solids. Therefore, before being treated biologically, sludge is thickened to reduce mass and volume by the partial removal of water. In the La Gavia WWTP, two types of thickening are employed: gravitational thickener for primary sludge and centrifugal thickeners for secondary sludge.

After passing through the thickener, the sludge is taken to separate anaerobic digesters. Anaerobic digestion is a biological process that allows a significant degradation of organic matter through fermentation carried out by microorganism in the absence of air. Greenhouse gases, particularly methane and carbon dioxide, are produced during this process.

The sludge must be contained within the digesters at a suitable temperature (about 35 °C). External sources of heat are required in cold seasons. In La Gavia, part of the digester gas is used as feed for cogeneration, providing heat for digestion. The excess biogas is then stored in a storage tank called a gasholder (Figure 2.14) and superfluous gas is burned and released into the atmosphere.

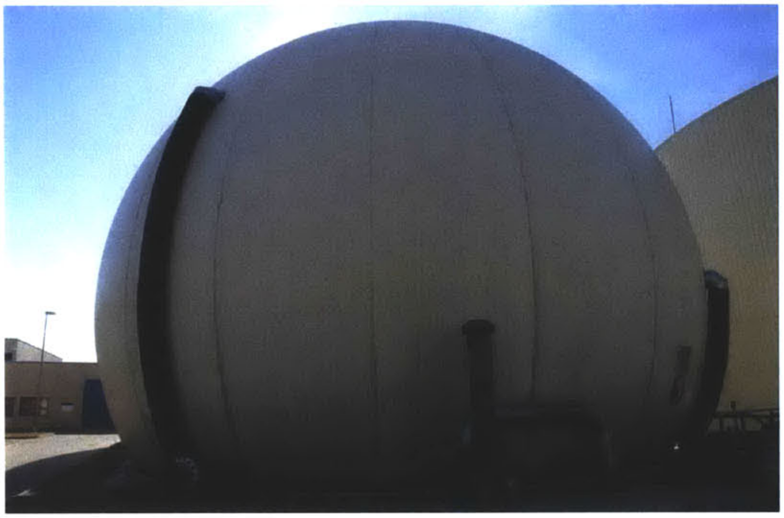


Figure 2.14 Gasholder for Biogas Produced from Sludge Digesters

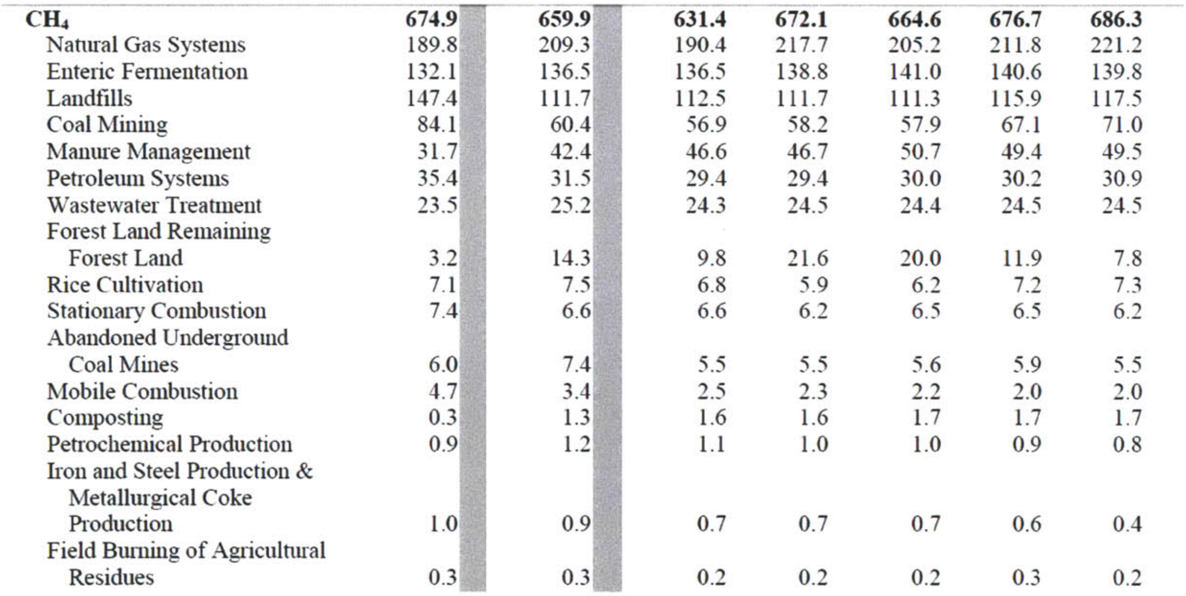
Up to this point in the treatment of sludge, the reduction of water is minimal, which means the sludge still has a large volume. Dehydration is responsible for eliminating, in large part, the water in the sludge. There are four centrifuges serving for this purpose in the La Gavia plant. After this process, the outgoing sludge contains about 75% water, and is transported to another thermal drying plant for further treatment.

One thing that should be mentioned about the sludge treatment at La Gavia plant is cogeneration, which is the simultaneous production and utilization of electricity and heat. The plant is able to produce electricity at a lower cost to supply other facilities in the plant, and at the same time generate enough heat for sludge digestion at zero cost. There are 3 motor generators (Figure 2.15 shows two of them) in the plant, producing more than 7,000,000 kWh of electricity every year.

Figure 2.15 Motor Generators

3. EVALUATION OF SLUDGE MANAGEMENT OPTIONS

According to the Inventory of U.S. Greenhouse Gas Emissions and Sinks between year 1990 and 2009, the methane gas produced from wastewater contributes 3 -4% GHG emissions of the total methane production (Inventory of U.S. Greenhouse Gas Emissions and Sinks, 2010). Also, as methane is more than 20 times as strong as CO_2 at capturing heat in the atmosphere, it is crucial to properly analyze the production of methane and its potential impacts, and find optimal solutions on reducing methane emissions from conventional sludge treatment system of wastewater treatment process.



CH_4	**674.9**	**659.9**	**631.4**	**672.1**	**664.6**	**676.7**	**686.3**
Natural Gas Systems	189.8	209.3	190.4	217.7	205.2	211.8	221.2
Enteric Fermentation	132.1	136.5	136.5	138.8	141.0	140.6	139.8
Landfills	147.4	111.7	112.5	111.7	111.3	115.9	117.5
Coal Mining	84.1	60.4	56.9	58.2	57.9	67.1	71.0
Manure Management	31.7	42.4	46.6	46.7	50.7	49.4	49.5
Petroleum Systems	35.4	31.5	29.4	29.4	30.0	30.2	30.9
Wastewater Treatment	23.5	25.2	24.3	24.5	24.4	24.5	24.5
Forest Land Remaining Forest Land	3.2	14.3	9.8	21.6	20.0	11.9	7.8
Rice Cultivation	7.1	7.5	6.8	5.9	6.2	7.2	7.3
Stationary Combustion	7.4	6.6	6.6	6.2	6.5	6.5	6.2
Abandoned Underground Coal Mines	6.0	7.4	5.5	5.5	5.6	5.9	5.5
Mobile Combustion	4.7	3.4	2.5	2.3	2.2	2.0	2.0
Composting	0.3	1.3	1.6	1.6	1.7	1.7	1.7
Petrochemical Production	0.9	1.2	1.1	1.0	1.0	0.9	0.8
Iron and Steel Production & Metallurgical Coke Production	1.0	0.9	0.7	0.7	0.7	0.6	0.4
Field Burning of Agricultural Residues	0.3	0.3	0.2	0.2	0.2	0.3	0.2

Figure 3.1 Recent Trends in U.S. Methane Gas Emissions (Tg CO2 Eq.)

The aim of the study is to assess the sludge management process that has been used in La Gavia WWTP and analyze potential alternatives that could have been implemented. As discussed in above, La Gavia implemented a cogeneration process that uses biogas with high methane content from sludge for heat and electricity production. The alternatives assessed throughout the study were chosen based on its their capability of handling methane gas.

Gas	GWP
CO_2	1
CH_4*	21
N_2O	310
HFC-23	11.700
HFC-32	650
HFC-125	2.800
HFC-134a	1.300
HFC-143a	3.800
HFC-152a	140
HFC-227ea	2.900
HFC-236fa	6.300
HFC-4310mee	1.300
CF_4	6.500
C_2F_6	9.200
C_4F_{10}	7.000
C_6F_{14}	7.400
SF_6	23.900

Source: IPCC (1996)

*** The CH_4 GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.**

Figure 3.2 Global Warming Potential of Methane

Sludge Management System in La Gavia Wastewater Treatment Plant

As discussed in previously, La Gavia WWTP adopted cogeneration process that recycles the biogas produced from the anaerobic digestion process of sludge collected from both primary and secondary treatment. The biogas combustion process uses biogas as a fuel source to produce both electricity and heat that are used throughout the plant. According to data retrieved from Cadagua, there is a daily average of 9,100 Nm^3 of biogas combustion which produces 19,800 kWh per day and 200 kWh of heat energy per day in La Gavia WWTP. Total electricity usage throughout the plant is about 40,000 kWh per day; hence, the cogeneration covers approximately half of the plant's electricity consumption. However, the amount of heat energy getting recycled is relatively low due to the warm climate in Madrid, Spain. The heat energy is typically used for heating sludge in anaerobic digestion process, but the heat source for such use is only required during winter months in Madrid. Throughout the study, these numbers have been used as baseline data for cogeneration process.

Sludge Management Options

LCA is used to analyze sludge management options. The scenarios that are assessed include:

1. Cogeneration and incineration of digested sludge
2. Cogeneration and agricultural land application of digest sludge
3. Composting of sludge and agricultural land application of sludge waste

These scenarios have been chosen based on technologies that can reduce substantial amounts of methane gas emissions.

3.1 Life Cycle Assessment of Sludge Management

Objective

The goal of this study is to analyze the environmental impacts of various techniques of sludge management that can be adopted in wastewater treatment plant. The work has been completed through use of LCA software, GaBi. The case study of La Gavia WWTP uses cogeneration process and land application. The results of the study are anticipated to be useful in determining current environmental performance of sludge treatment in La Gavia plant.

System Boundaries

The system boundary of the study begins with the generation of raw sludge from the primary and secondary treatment processes of the WWTP. The LCA through GaBi sets the boundary from collection of sludge to the ultimate disposition of sludge in waste form, either from incineration or through agricultural application. The approach adopted for this specific LCA is called Cradle to Cradle as the recycle of energy and environmental credits for producing fertilizers are reflected. The processes analyzed include the following data:

- Raw material input and output
- green house gas emissions

- transportation
- production and use of heat, electricity, and fuel sources
- credits with respect to energy and fertilizers

The flow chart of Figure 3.3 illustrates the overall system boundary of study for different scenarios.

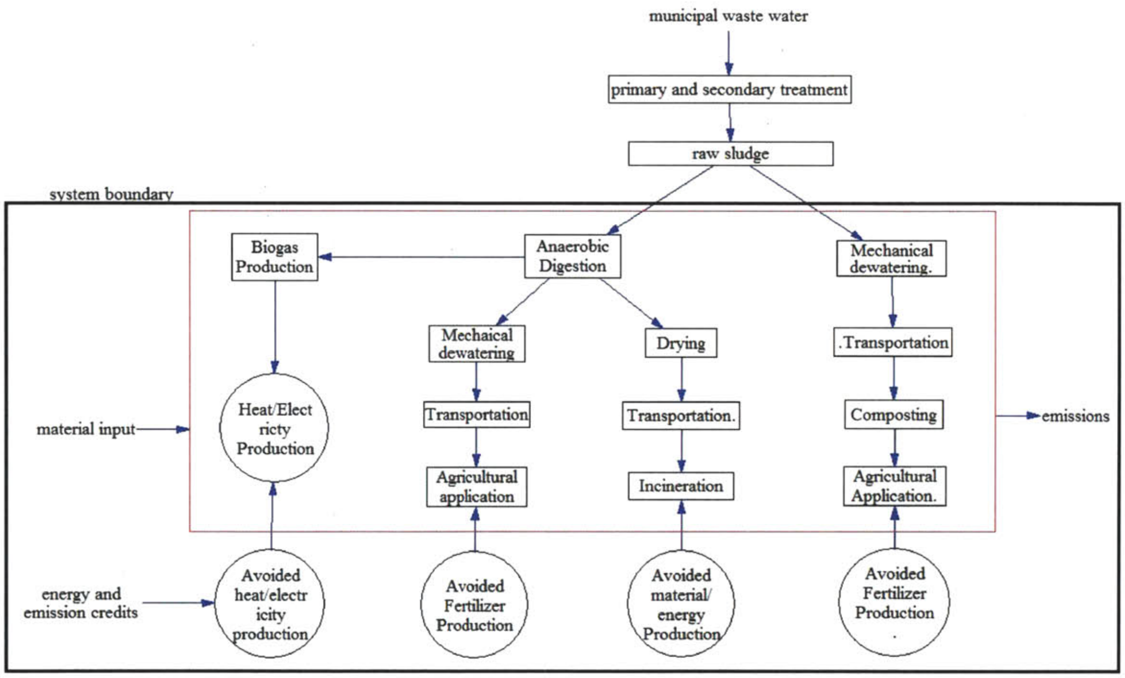


Figure 3.3 System boundary of study

Functional Unit

As this chapter focuses on the assessment of sludge treatment process, the functional unit is chosen as one tonne of incoming mixed sludge collected from primary and secondary treatment of WWTP. Gabi enables all the processes throughout its LCA to be scaled based on this functional unit.

Life Cycle Impact Assessments

Overall, there are four types of environmental impact categories assessed by GaBi's LCA analysis:

1. Global Warming Potential
2. Eutrophication
3. Acidification
4. Ozone Depletion Potential

Each of the above categories potentially contributes significant environmental impact, and hence these four categories of environmental impacts are analyzed in details later in this chapter.

General Assumptions of Study

- Operation of the wastewater treatment plant is not considered as part of LCA since it is shared among all the scenarios.

- Geographic boundary is set to Madrid, Spain and most of the life cycle inventory data are gathered for Spain, if available, or Europe in general.

- A few processes and products (i.e. construction of biogas combustion chamber) that have small impact potential to overall LCA are omitted.

3.2 Life Cycle Inventory of Three Scenarios

3.2.1 Scenario One: Anaerobic Digestion and Incineration

La Gavia adopted a sludge digestion and cogeneration process which uses the biogas produced for heat and electricity production. Overall, the raw sludge goes through a three step process in which ethane and other gases are produced. The first step is hydrolysis of lipids where macromolecules are converted into smaller and more digestible forms by inhabiting bacteria. The second step decomposes these molecules into fatty acids by facultative and anaerobic bacteria. Finally, methogenic bacteria digest these acids and emit methane gas. Throughout anaerobic digestion, constant heat is typically required.

The incineration process involves the thermal treatment of municipal waste with typical technology used in Europe. Two different incineration models are reflected in the LCA model; one with a wet and one with a dry flue gas treatment gas treatment are mixed and built in this analysis. The incineration has capacity to produce energy in form of both heat an energy as well.

Figure 3.4 depicts the general process of Scenario 1 and its system boundary used in GaBi.

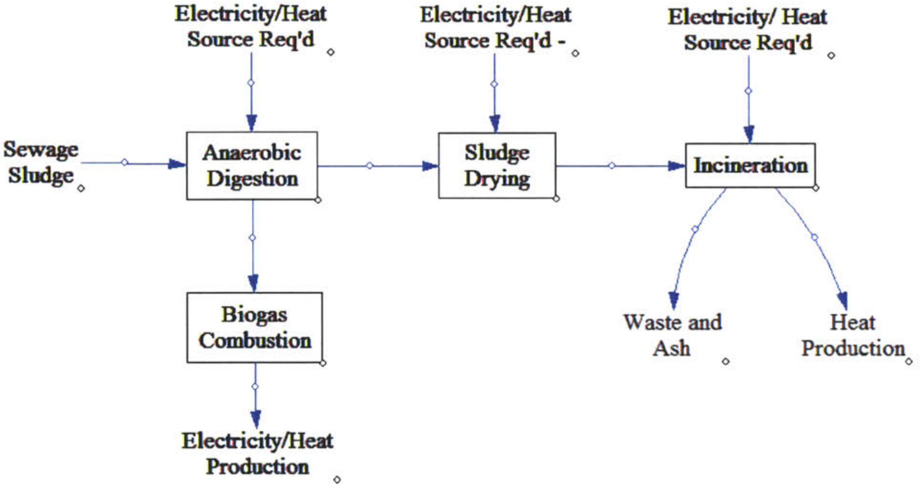


Figure 3.4 Flow chart of Scenario 1

Anerobic Digestion

Throughout the system, one tonne of raw sludge resulting from primary and secondary treatment is subject to anaerobic digestion. Data for the digestion process is gathered from literature review and La Gavia WWTP.

According to data retrieved by Cadagua, La Gavia WWTP produces about 12.4 tonne of sludge per day and 9,111 Nm^3 of biogas per day on average. Hence, the daily production of biogas per tonne of sludge in La Gavia WWTP is approximately 735 Nm^3.

The energy consumption numbers from Table 3.1, expressed on a per tonne of sludge basis, are applied throughout the LCA (Hospido et al 2005). The heat consumption for La Gavia is relatively low due to the warm temperature in Madrid that doesn't require constant heating of sludge.

Table 3.1 Energy usage of anaerobic digestion process for 1 tonne of sludge (Hospido, 2005)

Consumption	Value
Heat Consumption	14.7 kWh
Electricity Consultion	88.3 kWh

Emissions associated with the digestion process include emissions of biogenic CO2, methane gas escapes to the air, and breakdown of organics emitting nitrogen which produces nitrogen oxides. The data is collected from Hospido et al (2005) and emissions are summarized later in this chapter.

Biogas Combustion

Biogas produced from the anaerobic digestion process is burned to produce energy in both electricity and heat format. Data from Cadagua indicates an average of 2 kWh of energy production per 1 Nm^3 of biogas and that 99% of the energy is recycled as electricity and 1% as heat. Hence, one tonne of sludge producing 735 Nm^3 of biogas would generate the following energy.

Table 3.2 Energy recycle from biogas combustion in La Gavia

Energy	Value
Electricity Production	1455 kWh
Heat Recycled	14.69 kWh

The electricity production from the cogeneration production is considered as a credit in LCA and the energy production saved from the process would give positive environmental impacts. Through using GaBi's built in data for electricity production in Spain, the environmental credit was reflected in LCA. GaBi's data assumes the following mix of electricity production as shown in Figure 3.5.

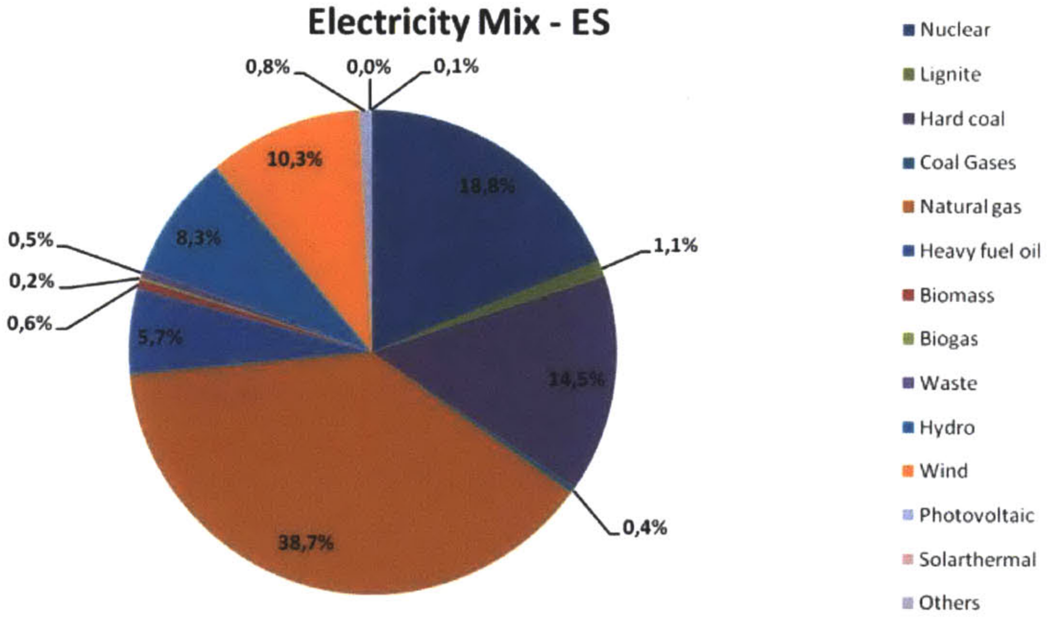


Figure 3.5 Electricity production in Spain built into GaBi

The electricity mix includes imported electricity from neighboring countries, distribution losses and own use by energy producer. The data set considers the whole supply chain of the fuels from exploration, to the extraction and refinement, and to the transport to the power plants.

Drying

Sludge drying is typically part of wastewater treatment plants. Drying involves a thermal process that requires intensive energy consumption. According to Poulsen & Hansen (2002), about 1638 kWh of electricity is required to dry one tonne of sludge. Also, the process emits VOC particles to the air at 0.04kg per tonne of sludge.

Sludge drying has also has an ability to produce heat energy at 1230 kWh per tonne of sludge (Poulsen & Hansen 2003); however, there would not be a proper use of heat recycle in the warm weather in Madrid, Spain. Hence, the heat energy recycle from thermal drying process has not been considered throughout the study.

Subsequent to the drying process, the mass of sludge is reduced to 0.78 tonne.

Incineration in Europe

Data for an incineration plant in Europe is built into GaBi and represents an average European municipal solid waste (MSW) to energy incineration plant. Environmental impacts for collection of the sludge and pretreatment are not included within GaBi inventory; however, the drying process described in previous section includes these missing data. The overall process is summarized in Figure 3.6.

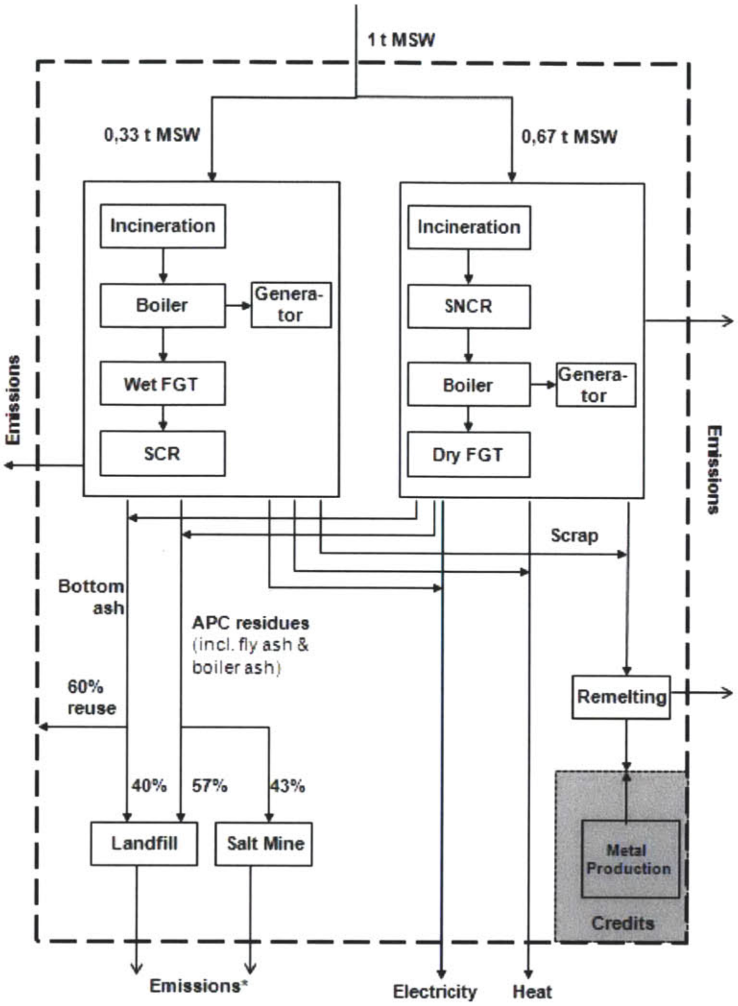


Figure 3.6 Typical incineration process used in Europe

All the inputs and output data for incineration process are scaled for 0.78 tonne of sludge waste which are carried from the drying process. For 0.78 tonne of waste, there is a production of 105 kWh of electricity. However, the heat that can be recovered from the incineration process is omitted for the same reason as heat production for drying. The energy credit given to LCA used the same data built into GaBi as the electricity recycled from biogas combustion process. These data are based on the electricity grid mix in Spain.

Summary of Input and Output Data

Throughout Option 1, one tonne of sludge collected from WWTP is used as a base. Table 3.3 summarizes all of the data used in GaBi.

Table 3.3 Life Cycle Inventory for Scenario 1

Anaerobic Digestion		
INPUT		
Heat Consumption	14.7	kWh
Electricity Consumption	88.3	kWh
Sludge	1	Ton
OUTPUT		
Biogas	734.65	Nm3
CH_4 gas engine	9.73	Kg
CO_2 (biogenic)	991	Kg
CO	0.84	Kg
NO_2	0.85	Kg
N_2O	0.02	Kg
Air emission of particles	0.08	Kg

Biogas Combustion		
INPUT		
Biogas	734.65	Nm3
OUTPUT		
Energy Production	1454.6	kWh
Heat Production	14.69	kWh
NOx	9.11	kg
CH_4	5.45	kg
CO	4.60	kg
N_2O	0.0084	kg
SO_2	0.32	kg
CO_2	83.60	kg

Drying		
INPUT		
Electricity Consumption	1638.00	kWh
Sludge	1.00	ton
OUTPUT		
Dried Sludge	0.78	ton
VOC Air Emissions	0.04	kg

Incineration		
INPUT		
Electricity Consumption	34.68	kWh
Natural Gas	3594.14	kWh
Polymer	7.10	kg
Fuel	40.50	kg
Acid	5.40	kg
Dried Sludge	0.78	ton
OUTPUT		
Electricity recovered	107.22	kWh
Waste	2.10	kg
Heavy Metal		
As	2.98E-03	kg
Be	1.95E-03	kg
Cd	2.65E-03	kg
Cr	0.15	kg
Pb	0.21	kg
GHG Emissions		
CO_2	2.59E+02	kg
N_2O	0.12	kg
CO	0.88	kg
VOC	4.89E-02	kg
NH_3	2.63E-02	kg
NOx	2.48	kg
CH_4	4.89E-02	kg

3.2.2 Scenario Two: Anaerobic Digestion and Agricultural Land Application

Instead of transporting the sludge for incineration, this scenario includes direct land application for agricultural use. The sludge can substitute for the use of fertilizer from available nutrients including nitrogen, phosphorous and potassium (NPK). However, the spreading of sludge on agricultural land can cause pollutions from heavy metal contamination to soil and greenhouse gas emissions to air. Figure 3.7 illustrates the overall scope of Scenario 2.

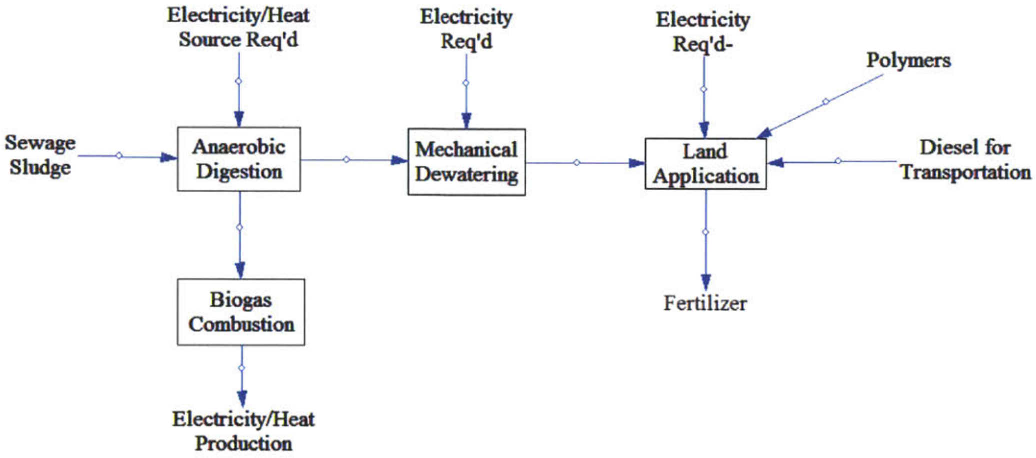


Figure 3.7 Scenario 2: Anaerobic Digestion and Agricultural Land Application

Anaerobic Digestion

The anaerobic digestion process for Scenario 2 implements the same set of data set as for Scenario 1 which is based on the La Gavia WWTP.

Biogas Combustion

The cogeneration process of the La Gavia WWTP through biogas combustion is used as the base process and the same data set is used as in Scenario 1.

Mechanical Dewatering

The electricity consumption for mechanical the dewatering process includes the electricity used for the operation of the facility and for dehydration subsequent to the dewatering process. The average electricity consumption for 1 tonne of sludge is about 50 kWh. Also, 5.5 kg of acrylonitrile polymer are consumed by the process per 1 tonne of sludge (Houillon, 2005).

At the end of the mechanical dewatering process, 1 tonne of sludge is reduced to approximately 0.78 tonne.

Agricultural Land Application

Spreading sludge waste over agricultural land typically transfers heavy metals to the soil. The degree of contamination depends on the quality of the influent wastewater. However, the general data in Table 3.4 were obtained from Hospido et al (2005).

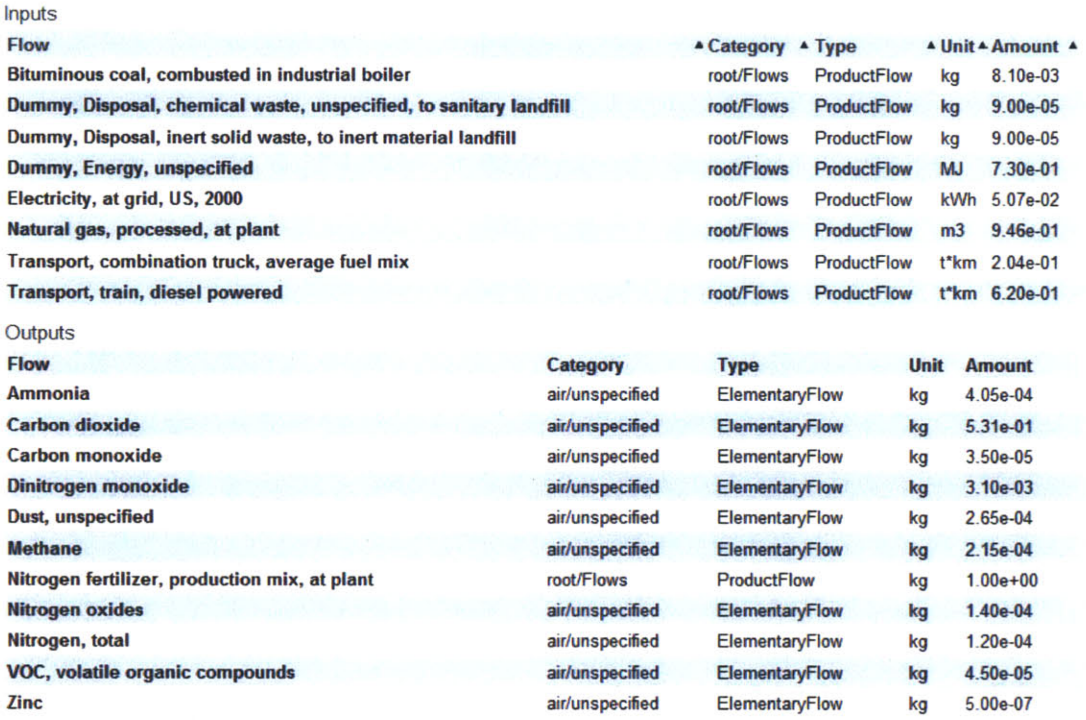
Table 3.4 Heavy metal pollutants from land application

Type of Pollutant	Mass	
Soil emission Cr	0.08	kg
Soil emission Cu	0.19	kg
Soil emission Pb	0.33	kg
Soil emission Zn	1.51	kg

The spreading over farm land requires electricity and fuel sources such as diesel as well as use of chemicals such as lime and sulfuric acid. These data are summarized later in this section.

Also, there are substantial savings of fertilizer (NPK) throughoutfrom the land application of sludge due to the high concentration of nitrogen, phosphorous and potassium (NPK) in digested sludge. For 1 tonne of sludge, about 274 kg of fertilizer are produced (Poulson and Hansen, 2003). The LCA reflects these savings in fertilizer as an environmental credit and the data for the fertilizer production from a plant is gathered from U.S Life Cycle Inventory Database of National Renewable Energy Laboratory at https://www.lcacommons.gov/nrel. The summary of data for a production of 1 kg of fertilizer is shown in Table 3.5. LCA from GaBi also indicates that there are 274 kg of natural gas and 71 MJ of electricity savings from the fertilizer production.

Table 3.5 Life cycle inventory of fertilizer production from NREL



Inputs

Flow	Category	Type	Unit	Amount
Bituminous coal, combusted in industrial boiler	root/Flows	ProductFlow	kg	8.10e-03
Dummy, Disposal, chemical waste, unspecified, to sanitary landfill	root/Flows	ProductFlow	kg	9.00e-05
Dummy, Disposal, inert solid waste, to inert material landfill	root/Flows	ProductFlow	kg	9.00e-05
Dummy, Energy, unspecified	root/Flows	ProductFlow	MJ	7.30e-01
Electricity, at grid, US, 2000	root/Flows	ProductFlow	kWh	5.07e-02
Natural gas, processed, at plant	root/Flows	ProductFlow	m3	9.46e-01
Transport, combination truck, average fuel mix	root/Flows	ProductFlow	t*km	2.04e-01
Transport, train, diesel powered	root/Flows	ProductFlow	t*km	6.20e-01

Outputs

Flow	Category	Type	Unit	Amount
Ammonia	air/unspecified	ElementaryFlow	kg	4.05e-04
Carbon dioxide	air/unspecified	ElementaryFlow	kg	5.31e-01
Carbon monoxide	air/unspecified	ElementaryFlow	kg	3.50e-05
Dinitrogen monoxide	air/unspecified	ElementaryFlow	kg	3.10e-03
Dust, unspecified	air/unspecified	ElementaryFlow	kg	2.65e-04
Methane	air/unspecified	ElementaryFlow	kg	2.15e-04
Nitrogen fertilizer, production mix, at plant	root/Flows	ProductFlow	kg	1.00e+00
Nitrogen oxides	air/unspecified	ElementaryFlow	kg	1.40e-04
Nitrogen, total	air/unspecified	ElementaryFlow	kg	1.20e-04
VOC, volatile organic compounds	air/unspecified	ElementaryFlow	kg	4.50e-05
Zinc	air/unspecified	ElementaryFlow	kg	5.00e-07

Summary of Input and Output Data

LCA of Scenario 2 is based on one tone of sludge collected from the primary and secondary stages of WWTP. Table 3.6 summarizes all of the input and output data that were used in GaBi.

Table 3.6 LCI for Scenario 2

Anaerobic Digestion		
INPUT		
Heat Consumption	14.7	kwh
Electricity Consumption	88.3	kwh
Sludge	1	ton
OUTPUT		
Biogas	734.65	Nm3
CH_4 gas engine	9.73	kg
CO_2 (biogenic)	991	kg
CO	0.84	kg
NO_2	0.85	kg

N_2O	0.02	kg
Air emission of particles	0.08	kg

Biogas Combustion		
INPUT		
Biogas	734.65	Nm3
OUTPUT		
Energy Production	1454.60	kWh
Heat Production	14.69	kWh
NOx	9.12	kg
CH_4	5.45	kg
CO	4.61	kg
N_2O	0.01	kg
SO_2	0.32	kg
CO_2	83.61	kg

Mechanical Dewatering		
INPUT		
Electricity Consumption	49.09	kWh
Electricity dehydration	0	kWh
Electricity Storage	0	kWh
Acrylonitrile consumption	5.5	kg
OUTPUT		
Dry Sludge	0.78	ton

Land Application		
INPUT		
Electricity Consumption	58.5	kWh
Diesel for sludge application	0.73	kg
Lime	400	kg
Polymer	7.1	kg
Dry Sludge	0.78	ton
OUTPUT		
NPK Fertilizer	274	kg
CH_4	3.18	kg
NH_3	1.9	kg
Nox	0.82	kg
CH_4	3.18	kg
NH_3	1.9	kg
Soil emission Cr	0.08	kg
Soil emission Cu	0.19	kg
Soil emission Pb	0.33	kg
Soil emission Zn	1.51	kg

Scenario 3: Composting and Agricultural Land Application

Figure 3.8 Windrow Composting

Through the waste composting process, pathogens and organic pollutants in the sludge are reduced. The type of waste composting analyzed in this study is windrow composting. The process is known to destroy pathogens and produce waste that can be used fertilizer. The waste is shredded and piled into windrows which are of an ideal shape for composting. Slow aeration and decomposition are continued until the waste is stabilized. The composted waste is transported to agricultural land to be spread out. The overall scheme of process is depicted in Figure 3.9.

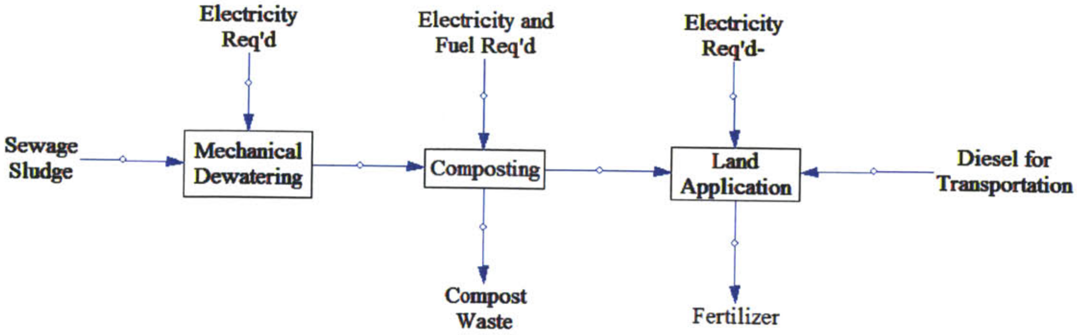


Figure 3.9 Scenario 3: Composting and Agricultural Land Application

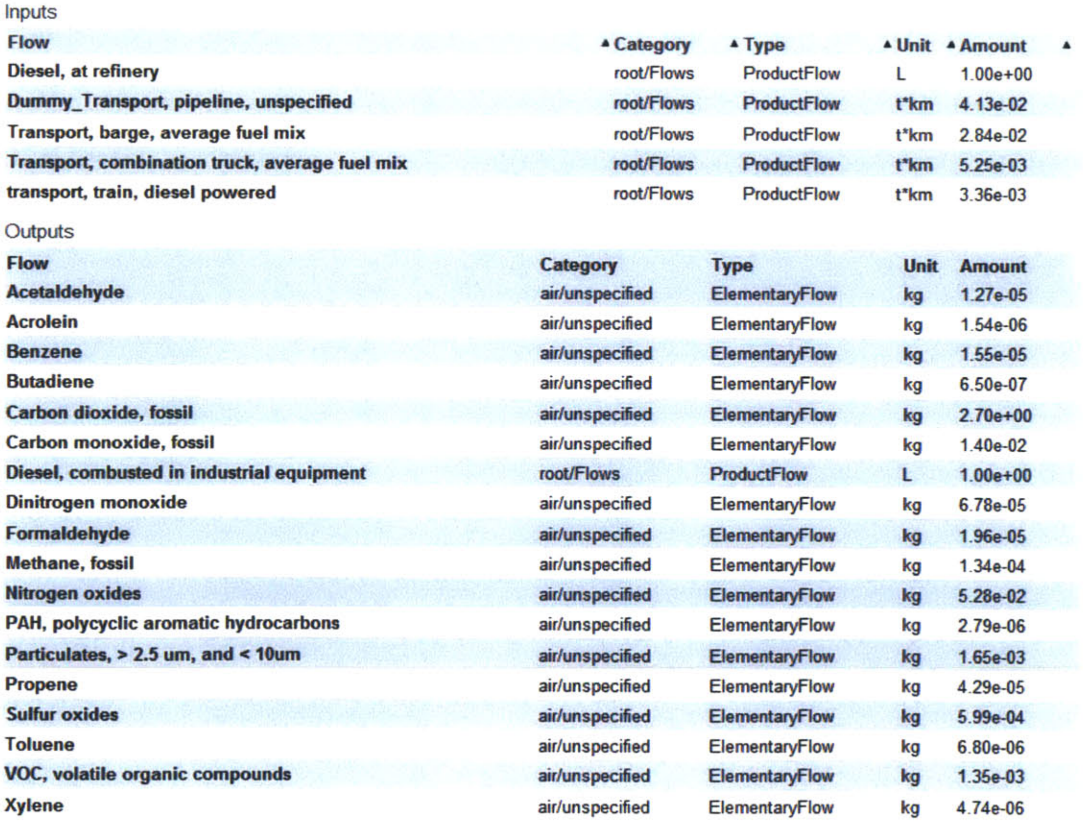
Mechanical Dewatering

The same set of data is used as for the dewatering process in Scenario 2 resulting in sludge reduction to 0.78 tonne in weight.

Composting

Electricity is consumed for further dewatering within a composting plant. According to Poulsen and Hansen (2003), about 1.1kWh of electricity is consumed for 0.78 tonne of sludge. Also, tractors are extensively used for forming waste into strips of windrows and about 1.7kg of diesel is used to operate the machinery. The use of diesel and its combustion would require another subset of LCI process for GaBi to run LCA. Hence, the greenhouse gas emissions and other life cycle inventories are collected from U.S Life Cycle Inventory Database of National Renewable Energy Laboratory at https://www.lcacommons.gov/nrel. The details of LCI are shown in Table 3.7 for the combustion of 1L of diesel.

Table 3.7 LCI of Diesel Combustion



Inputs

Flow	▲ Category	▲ Type	▲ Unit	▲ Amount
Diesel, at refinery	root/Flows	ProductFlow	L	1.00e+00
Dummy_Transport, pipeline, unspecified	root/Flows	ProductFlow	t*km	4.13e-02
Transport, barge, average fuel mix	root/Flows	ProductFlow	t*km	2.84e-02
Transport, combination truck, average fuel mix	root/Flows	ProductFlow	t*km	5.25e-03
transport, train, diesel powered	root/Flows	ProductFlow	t*km	3.36e-03

Outputs

Flow	Category	Type	Unit	Amount
Acetaldehyde	air/unspecified	ElementaryFlow	kg	1.27e-05
Acrolein	air/unspecified	ElementaryFlow	kg	1.54e-06
Benzene	air/unspecified	ElementaryFlow	kg	1.55e-05
Butadiene	air/unspecified	ElementaryFlow	kg	6.50e-07
Carbon dioxide, fossil	air/unspecified	ElementaryFlow	kg	2.70e+00
Carbon monoxide, fossil	air/unspecified	ElementaryFlow	kg	1.40e-02
Diesel, combusted in industrial equipment	root/Flows	ProductFlow	L	1.00e+00
Dinitrogen monoxide	air/unspecified	ElementaryFlow	kg	6.78e-05
Formaldehyde	air/unspecified	ElementaryFlow	kg	1.96e-05
Methane, fossil	air/unspecified	ElementaryFlow	kg	1.34e-04
Nitrogen oxides	air/unspecified	ElementaryFlow	kg	5.28e-02
PAH, polycyclic aromatic hydrocarbons	air/unspecified	ElementaryFlow	kg	2.79e-06
Particulates, > 2.5 um, and < 10um	air/unspecified	ElementaryFlow	kg	1.65e-03
Propene	air/unspecified	ElementaryFlow	kg	4.29e-05
Sulfur oxides	air/unspecified	ElementaryFlow	kg	5.99e-04
Toluene	air/unspecified	ElementaryFlow	kg	6.80e-06
VOC, volatile organic compounds	air/unspecified	ElementaryFlow	kg	1.35e-03
Xylene	air/unspecified	ElementaryFlow	kg	4.74e-06

Furthermore windrow composting requires significant amounts of bulking agent such as wood chips and straw as mixing agents. Approximately, 380 kg of these materials are required for 0.78 tonne of sludge (Poulsen & Hansen, 2003). LCI. GaBi calculations indicate that the production of 380kg of woodchips consumes 1,500 kWh of energy. In addition, Hospido et al. (2005) indicate that the composting of 1 tonne of sludge produces greenhouse gas emission of about 55kg of methane and 55kg of carbon dioxide as direct emission to air.

Subsequent to the windrow composting process, 0.43 tonne of sludge waste is transported for land application for agricultural use.

Agricultural Land Application

The composting process reduces the NPK content of sludge, so the amount of fertilizer that can be produced from 1 tonne of sludge is less than that of Scenario 2 as windrow composting loses more NPK content as waste. Overall, about 151kg of fertilizer is produced from windrow composting process (Poulsen & Hansen, 2003) whereas 257kg of fertilizer is produced in Scenario 2.

Similar to the LCA of Scenario 2, 151 kg of fertilizer is credited in GaBi and the same set of LCI for the fertilizer production is used which is scaled to 151kg of fertlizer. Also, the electricity consumption of storage facility operation and heating is about 55 kWh and the diesel fuel consumption of tractors is approximately 0.73kg. The same set of LCI is used for diesel combustion as for the windrow composting.

Summary of Input and Output Data

Summaries of each sub process of Scenario 3 are shown in Table 3.8. Similar to the LCA of other Scenarios, the analysis is based on one tonne of sludge from the WWTP.

Table 3.8 LCI for Scenario 3

Mechanical Dewatering		
INPUT		
Sludge	1	ton
Electricity Consumption	49.09	kWh
Electricity dehydration	0	kWh
Acrylonitrile consumption	5.5	kg
OUTPUT		
Dried Sludge	0.73	ton

Windrow Composting		
INPUT		
Diesel Consumption	1.7	kg
Electricity Consumtion	1.1	kWh
Woodchips and straws	380	kg
sludge		
OUTPUT		
Dried Sludge	0.43	ton
CO_2	54.5	kg
CH_4	54.5	kg

Land Application		
INPUT		
Electricity Consumption	58.5	kWh
Diesel for sludge application	0.73	kg
Lime	400	kg
Polymer	7.1	kg
Dried Sludge	0.43	ton
OUTPUT		
NPK Fertiliser	151	kg
CH_4	3.18	kg
Heavy metal content		
Hg	0.0011	kg
Cd	0.0013	kg
Pb	0.05	kg
Cr	0.021	kg
Ni	0.02	kg
Zn	0.7	kg
Cu	0.243	Kg

3.3 Life Cycle Impact Assessment

The life cycle impact assessment is performed in accordance with CML 2001 which is established environmental standard by institute of the Faculty of Science of Leiden University. The procedure constrains quantitative modeling "to early stages in the cause-effect chain to limit uncertainties." (http://cml.leiden.edu/about/research-cml.html) Results are grouped in common categories (e.g. climate change) in CML 2001.

Global Warming Potential (GWP 100)

As discussed previously, global warming is the phenomenon whereby the Earth's atmosphere gets heated by absorbing infra radiation energy that Earth emits towards space. This process is exacerbated by the presence of CO_2, CH_4 and N_2O. The global warming potential of the ensemble of GHGs is expressed in terms of kg CO2-eq as defined over a period of 100 years. The GWP of each scenario, as computed by GaBi, is shown in Figure 3.10.

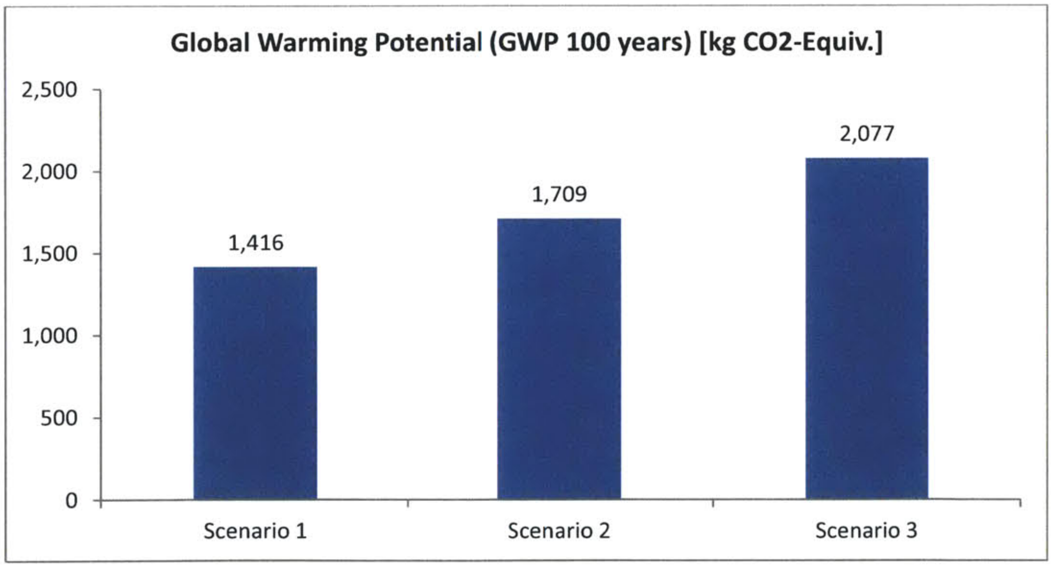


Figure 3.10 Global Warming Potential in kg CO_2 Eq

Both Scenario 1 and 2 include cogeneration of electricity and heat through biogas combustion which produces 5,240 MJ of electricity. The electricity is then recycled to operate the WWTP and this recycle is credited within GaBi. Due to substantial savings in electricity production, green house gas emissions are considered to be reduced throughout the system. Hence, GaBi indicates that the cogeneration process is treated as a credit to the environment with magnitude of -640 kg of CO_2 eq with respect to the GWP. As a result, Scenario 1 and 2 show about 30% and 15 % less GWP than Scenario 3 which does not use cogeneration process.

However, high amounts of CO_2 emission from the anaerobic digestion process within Scenario 1 and Scenario 2 make significant contribution to GWP with 1,240 kg of CO_2 equivalence. If the anaerobic digestion could be replaced by a different type of digestion process, cogeneration may become even more attractive as a sludge management option. Also, if the WWTP were situated in a colder climate that required a constant heat source, the recycle of heat energy from cogeneration could save more energy, reducing the overall GWP.

The details of GWP of each subprocesses are shown in Table 3.9 where environmental credits are highlighted.

Table 3.9 GWP of subprocesses of each scenario

	Scenario 1	**Scenario 2**	**Scenario 3**
Digestion	1240	1240	-
Biogas Combustion	222	222	-
Electricity Saving	-649	-649	-
Electricity Incineration	53	-	-
Incineration Waste	529	-	-
Fertilizer Production	-	-147	-81
Lime Consumption	-	879	484
Windrow Composting		-	336
Electricity Composting	-	-	701
Woodchip Production	-	-	532

Eutrophication

Eutrophication results from the growth of phytoplankton in water bodies due to excess nutrients such as phosphate and nitrate contributed by fertilizer runoff or the discharge of sewage. For instance untreated sewage discharged to water bodies can cause algae blooms which degrade the water body's ecosystem. The eutrophication potential is measured in kg of phosphate equivalence and Figure 3.11 summarizes this potential for each option.

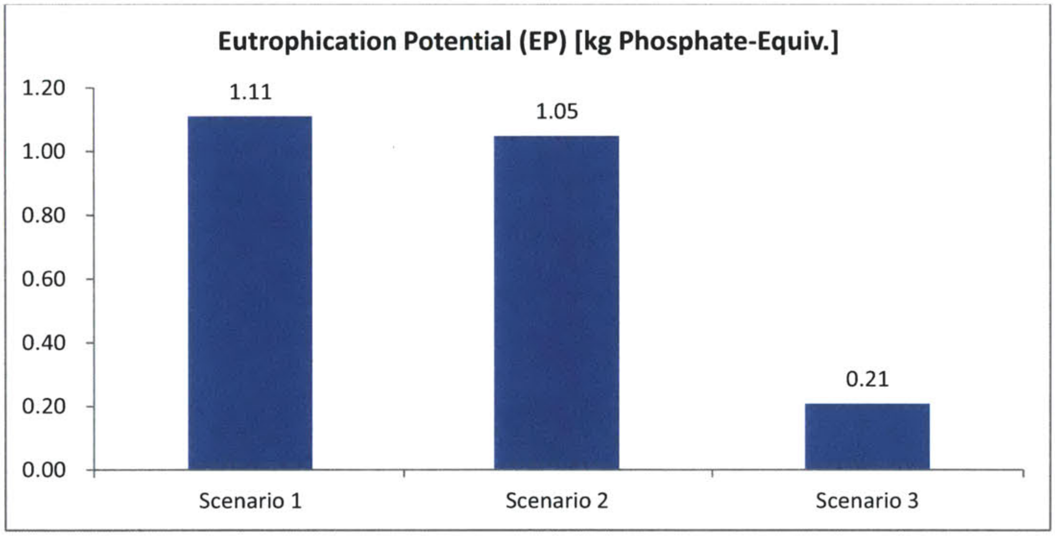


Figure 3.11 Eutrophication Potential in kg of Phosphate

Both Scenario 1 and 2 demonstrate substantially higher eutrophication potential due to high amounts of gas emissions such as NOx and SO2 whereas Scenario 3 does not include any process that emits such gases that contribute to Eutrophication. Overall, the biogas combustion process could provide significant amounts of environmental benefits by producing electricity; however, the gases emitted from the cogeneration process have higher eutrophication potentials than composting. Eutrophication potentials of the subprocesses of each scenario are summarized in Table 3.10, where environmental credits are highlighted.

Table 3.10 Eutrophication Potential of sub-processes of each scenario

	Scenario 1	Scenario 2	Scenario 3
Biogas Combustion	1.187	1.187	-
Electricity Saving	-0.17	-0.17	-
Electricity Incineration	0.14	-	-
Incineration Waste	0.69	-	-
Fertilizer Production	-	-0.04	-0.024
Lime Consumption	-	0.04	0.02
Windrow Composting	-	-	0.014
Electricity Composting	-	-	0.181
Woodchip Production	-	-	0.012

Acidification

Acidification is the ongoing process whereby the pH of the decreases by acid-forming compounds deposited from the atmosphere. When the anthropogenic gases are emitted to the atmosphere, acidification is known to be accelerated, causing a threat to the food chains. Acidification is measured in units of kg SO_2-eq.

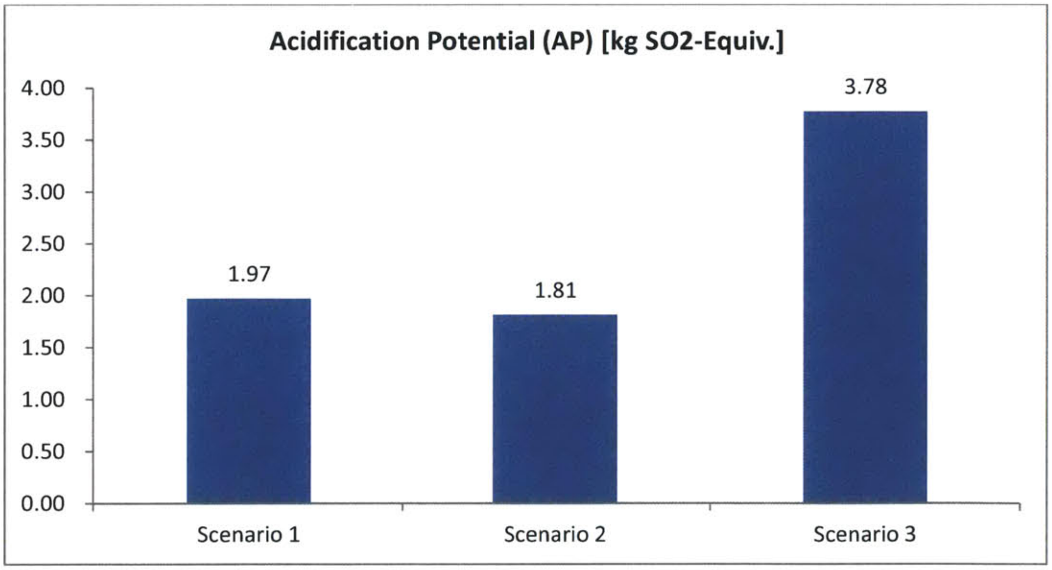


Figure 3.12 Acidification Potential in kg of SO_2 Equivalence

As shown in Figure 3.12, Scenario 1 and 2 contribute about 2 kg SO_2-eq of acidification whereas Scenario 3 contributes about twice as much. The two major direct gas emissions impacting acidification potentials are SO_2 and CO_2.

Table 3.11 Acidification Potential of sub-processes of each scenario

	Scenario 1	**Scenario 2**	**Scenario 3**
Biogas Combustion	4.56	4.56	-
Electricity Saving	-3.19	-3.19	-
Electricity Incineration	0.26	-	-
Incineration Waste	0.36	-	-
Fertilizer Production	-	-0.35	-0.19
Lime Consumption	-	0.26	0.13
Windrow Composting	-	-	0.26
Electricity Composting	-	-	3.45
Electricity Land Application	-	0.23	0.13

Table 3.11 shows that most of the acidification potential comes from the biogas combustion process in Scenario 1 and 2. Due to the significant amounts of direct CO_2 and SO_2 emissions in this process, about 4.6 kg of SO_2 equivalence is generated whereas electricity saved from the cogeneration credits 3.2 kg of SO_2 equivalence to the environment. Because of the lack of energy recycling in Scenario 3, the composting process is assessed to be the option that causes most acidification from its intensity electricity consumption in composting.

Ozone Depletion Potential

Ozone depletion is a phenomenon whereby the total volume of ozone in the Earth's stratosphere is decreased, especially in polar regions. It is typically caused by trichlorofluoromethane (R-11 or CFC-11) and chlorodifluoromethane (R-22). Also chlorocarbons are known to have potential to form these molecules (Solomon, 1999). Ozone depletion is characterized by kg R11-eq.

Figure 3.13 summarizes the ozone depletion potential for each scenario.

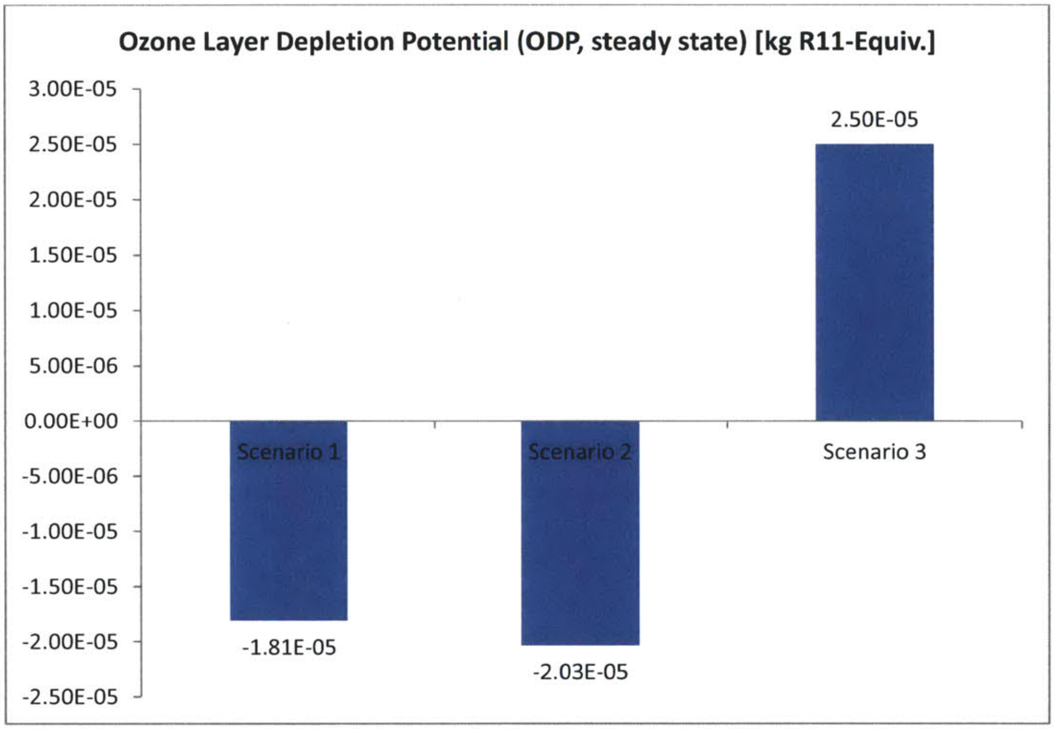


Figure 3.13 Ozone Layer Depletion Potential in kg of R-11 Equivalence

The ozone depletion potential ranges from a credit of order 2.0 E-05 kg of R11-eq for Scenarios 1 and 2 to a debit of 2.5 E-05 kg of R-11-eq for Scenario 3. All three options have miniscule amounts of direct emissions of chlorocarbons. Also, the indirect emissions from production of electricity is minimal as well due to the phasing out in Spain of all ozone depleting chemicals in related to energy production (GaBi LCI, 2011).

Hence, the three advanced sludge management options discussed in the study would not contribute much to the ozone layer depletion.

3.4 Conclusion

Sewage sludge is a waste product that can be recycled by production of biogas from anaerobic digestion and land application for agricultural use which then can be converted into energy or fertilizers. Despite the environmental benefits from such recycling, the advanced sludge treatment options assessed in this study still possess certain environmental impacts. Table 3.12 assesses each scenario in terms of the four environmental impact categories. For each category the best scenario is highlighted.

Table 3.12 Environmental impact assessments of three sludge treatment options

	Scenario 1	Scenario 2	Scenario 3
Global Warming Potential [kg CO2-Equiv.]	1,416	1,709	2,077
Acidification Potential [kg SO2-Equiv.]	1.97	1.81	3.78
Eutrophication Potential [kg Phosphate-Equiv.]	1.11	1.05	0.21
Ozone Layer Depletion Potential [kg R11-Equiv.]	-1.81E-05	-2.03E-05	2.50E-05

Scenario 1 and 2 showed lower global warming potential than Scenario 3 because of their biogas combustion process with significant energy production. Even more heat could be recycled if the cogeneration were used in locations with lower temperatures that those required to operate the WWTP. Overall, Scenario 1 contributes the least GWP as the incineration produces electricity.

Scenario 3 exhibits the highest acidification potential due to the lack of energy recycling with composting. This is despite the fact that Scenarios 1 and 2 directly emit acidification related gases through their biogas combustion process. Hence, the cogeneration process in sludge management is a preferred option for sludge management if acidification is a major concern.

On the other hand, the energy recycling from biogas combustion does not provide much environmental credit regarding eutrophication potential. The high amounts of eutrophication related gas emissions from the digestion and biogas combustion processes of Scenarios 1 and 2 impact eutrophication potential more than Scenario 3.

Due to minimal chlorocarbon related gas emissions from any of the sludge management options, and the fact that CFCs are not created in electricity production in Spain, environmental impacts from ozone layer depletion are insignificant.

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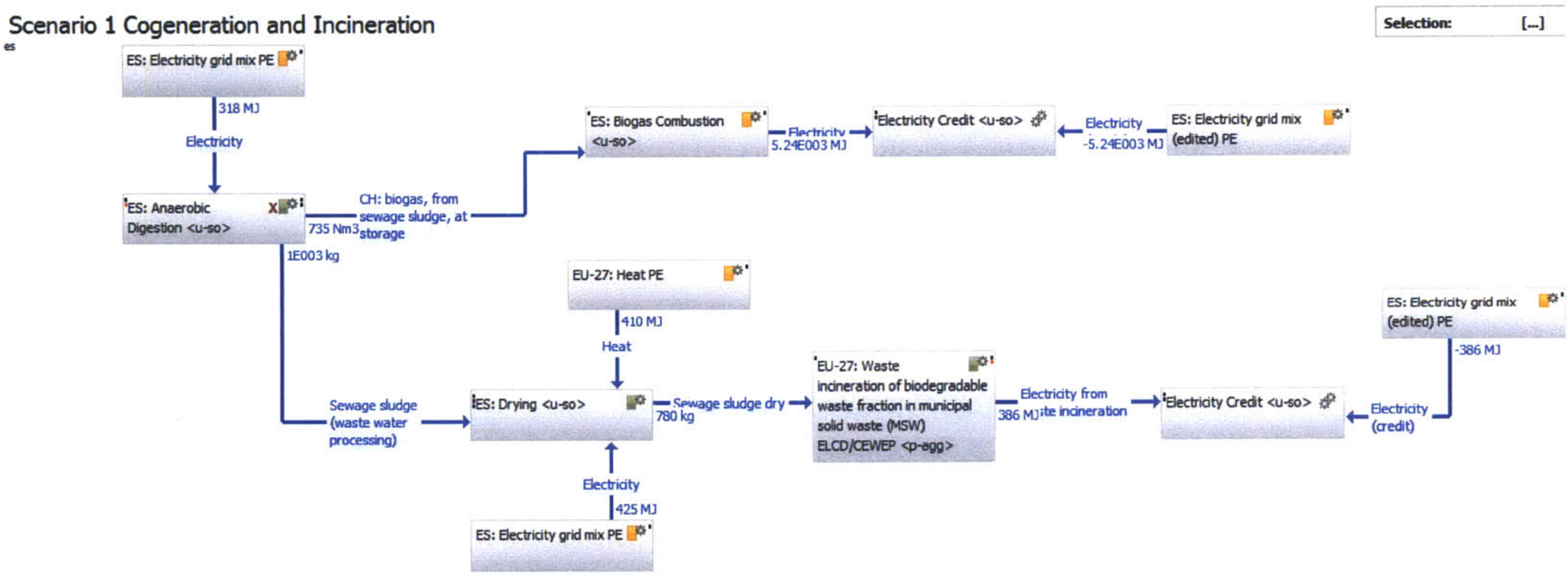
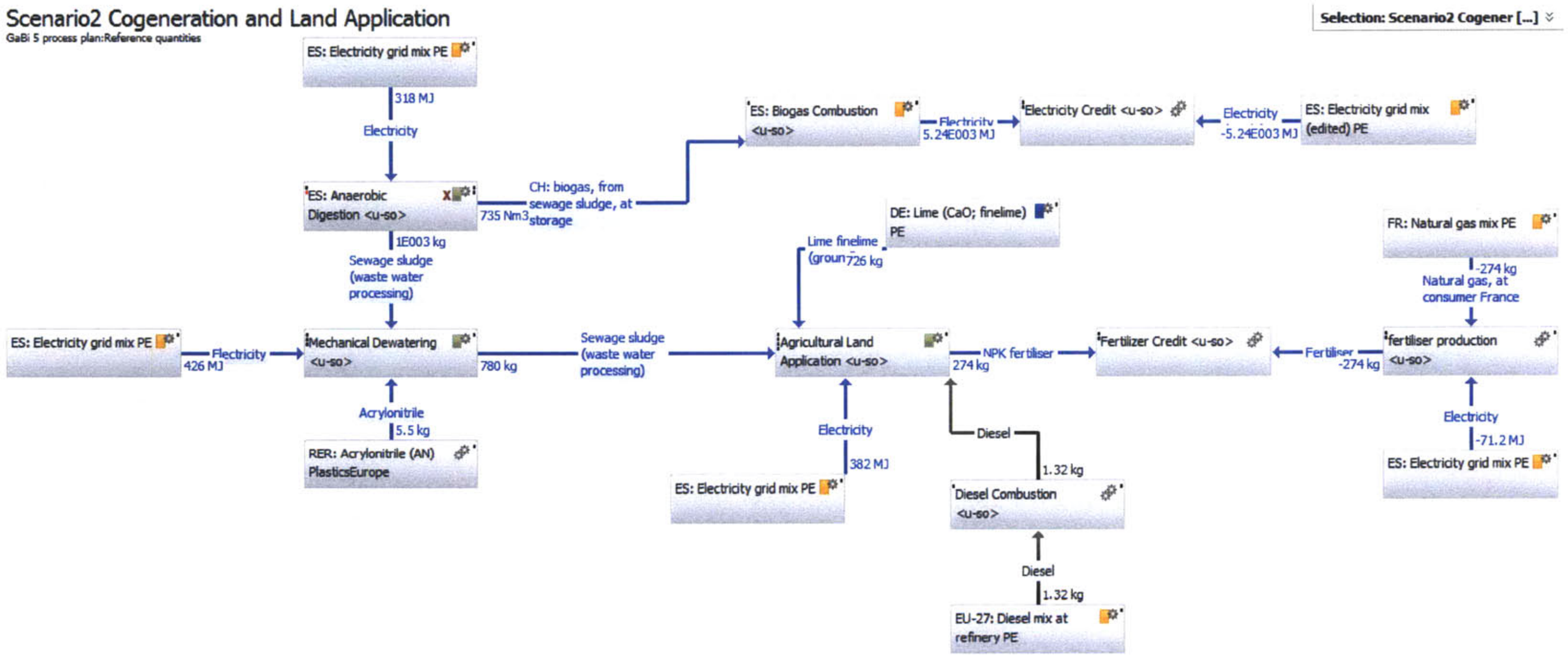
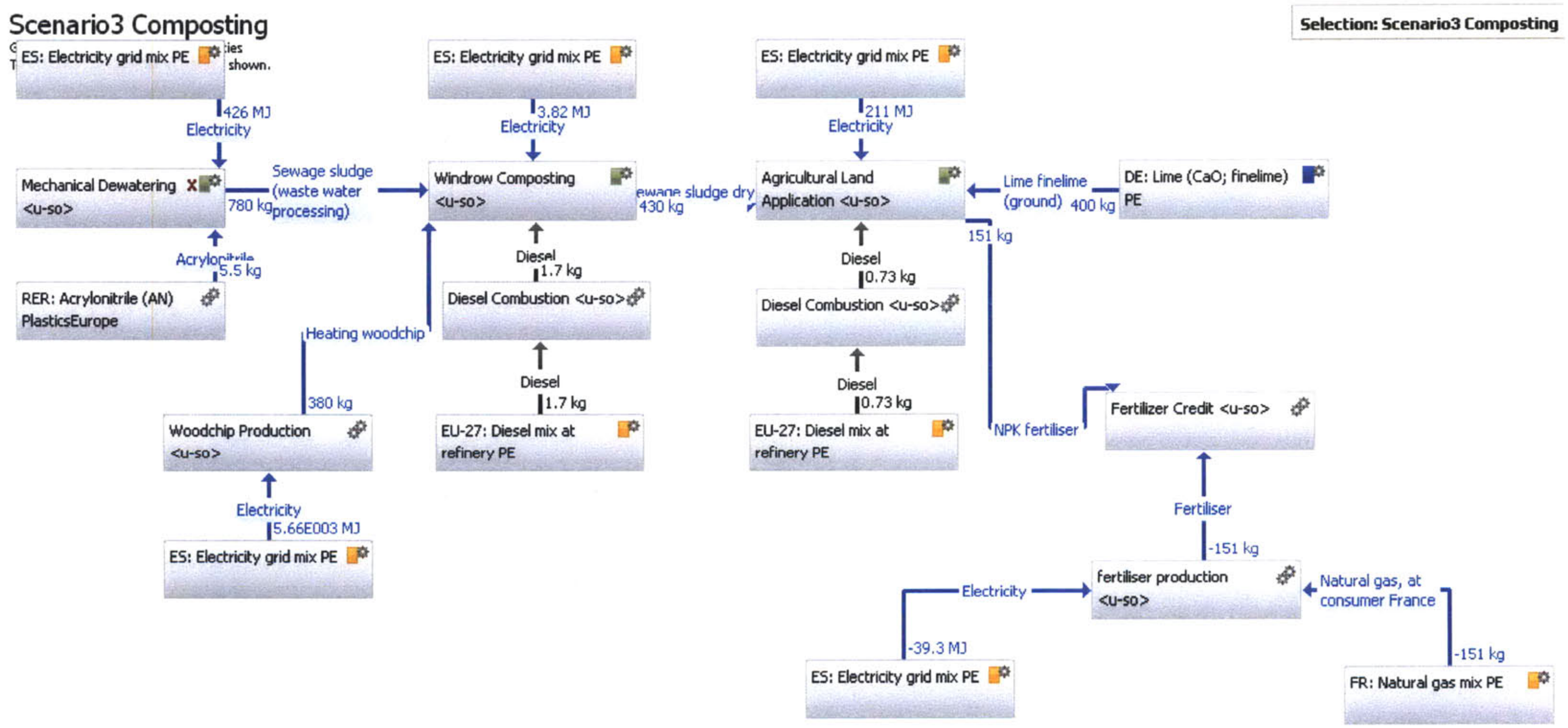
Appendix A GaBi Flow Charts of Sludge Management Scenarios

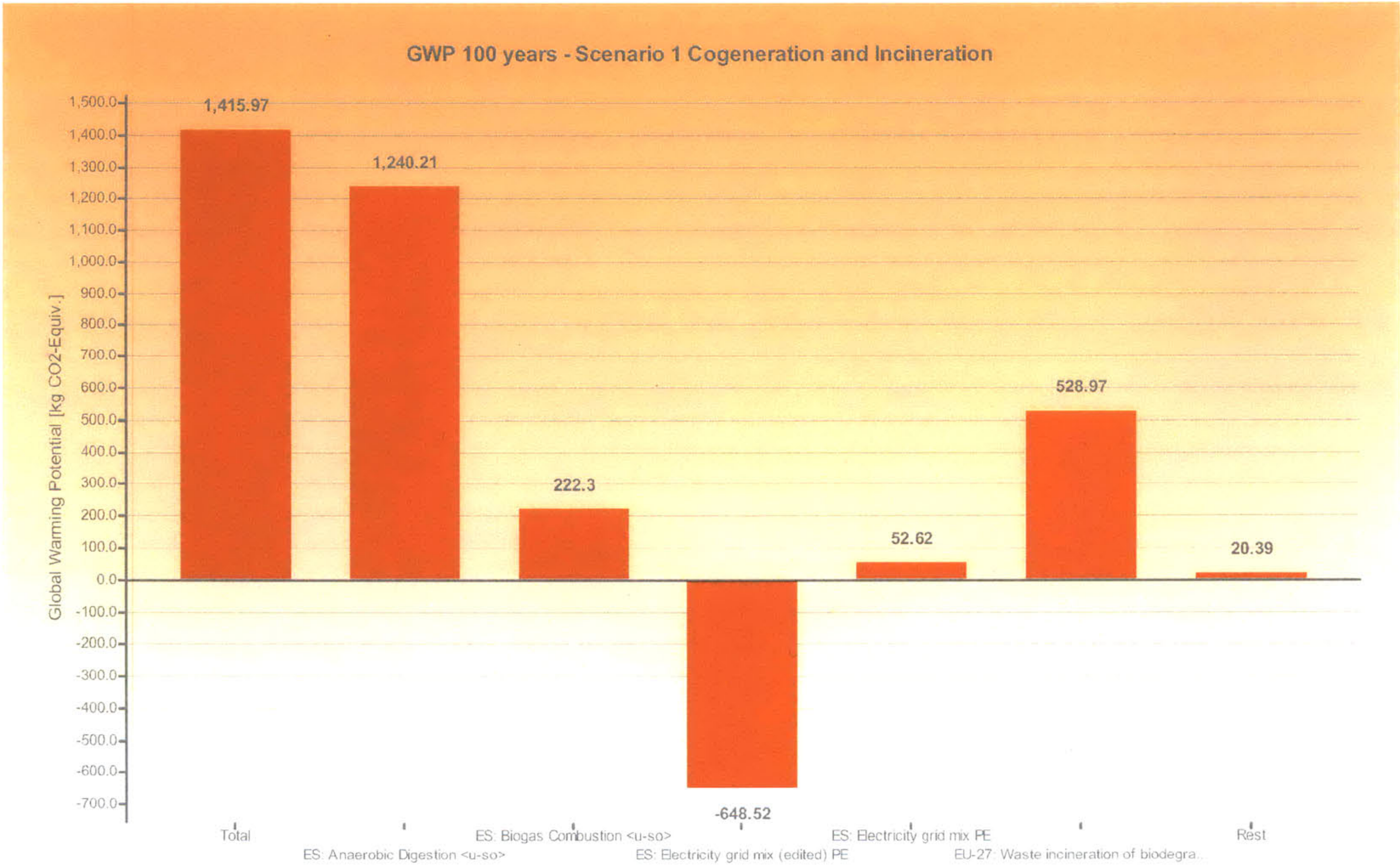


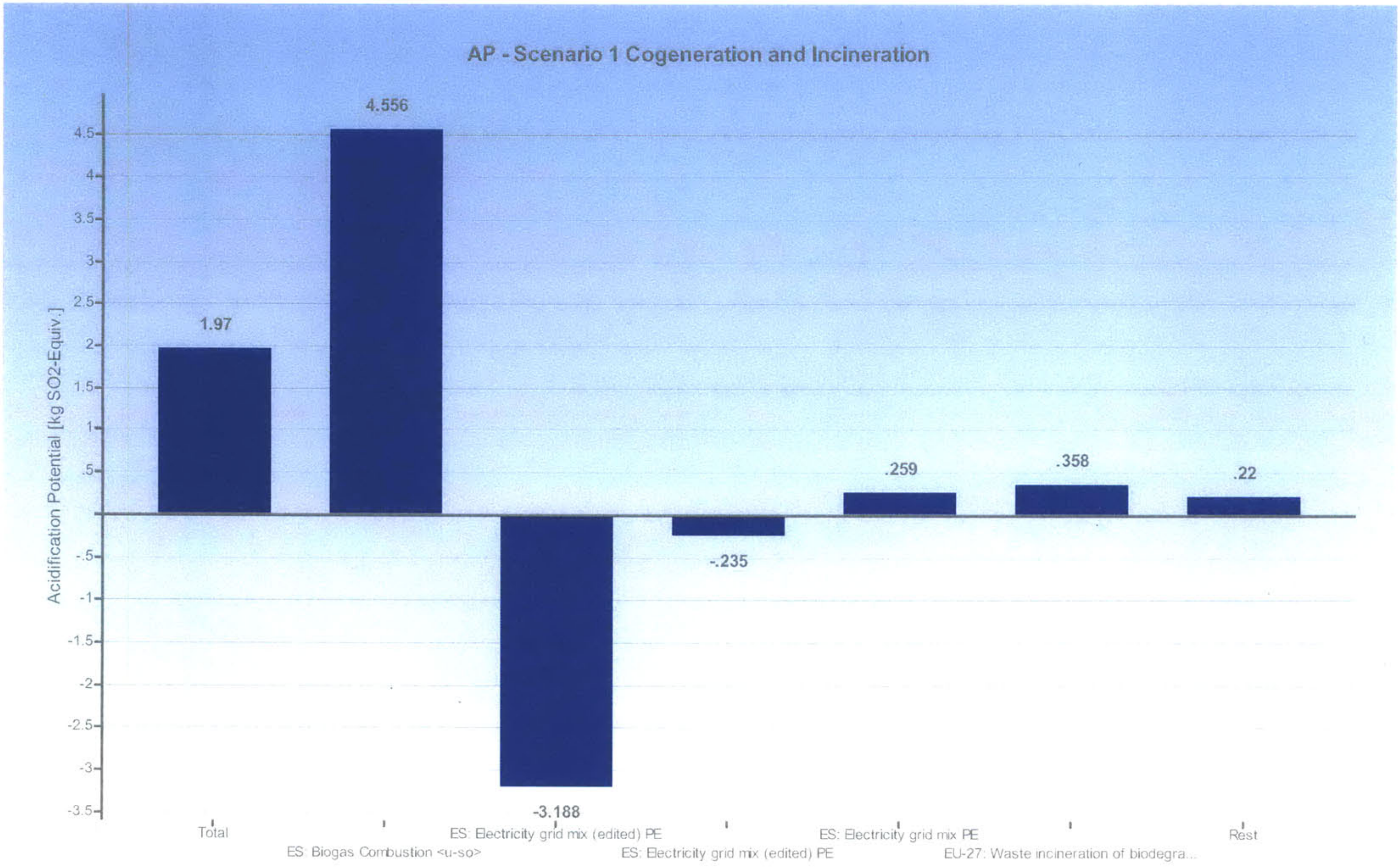
Scenario 1 Cogeneration and Incineration

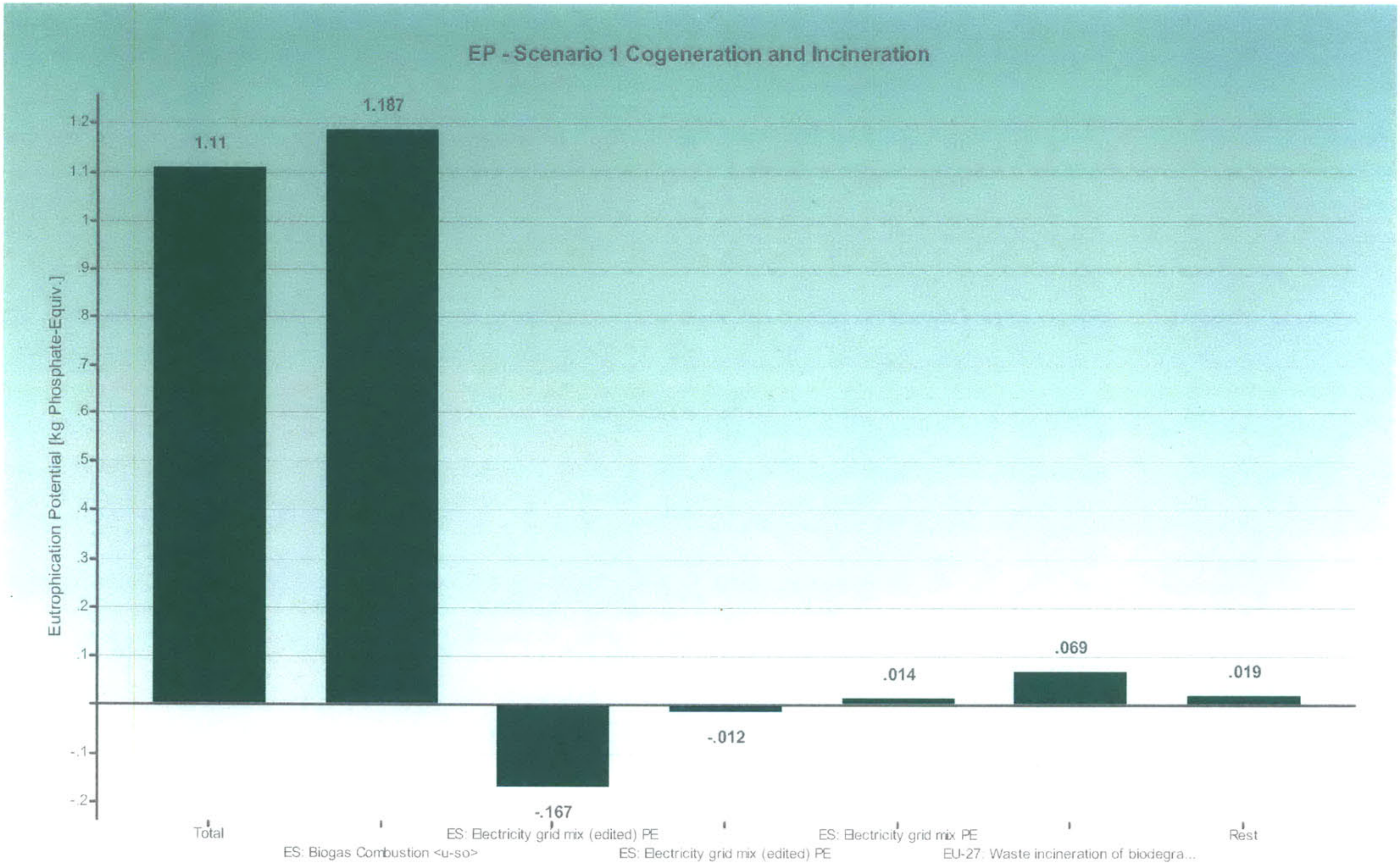

Scenario2 Cogeneration and Land Application
GaBi 5 process plan:Reference quantities
Selection: Scenario2 Cogener [...]
ES: Electricity grid mix PE
318 MJ
Electricity
ES: Anaerobic Digestion <u-so>
735 Nm3
CH: biogas, from sewage sludge, at storage
1E003 kg
Sewage sludge (waste water processing)
ES: Electricity grid mix PE
Electricity
426 MJ
Mechanical Dewatering <u-so>
780 kg
Sewage sludge (waste water processing)
Acrylonitrile
5.5 kg
RER: Acrylonitrile (AN) PlasticsEurope
ES: Biogas Combustion <u-so>
Electricity
5.24E003 MJ
Electricity Credit <u-so>
Electricity
-5.24E003 MJ
ES: Electricity grid mix (edited) PE
DE: Lime (CaO; finelime) PE
Lime finelime (groun
726 kg
Agricultural Land Application <u-so>
NPK fertiliser
274 kg
Fertilizer Credit <u-so>
Fertiliser
-274 kg
fertiliser production <u-so>
FR: Natural gas mix PE
-274 kg
Natural gas, at consumer France
Electricity
-71.2 MJ
ES: Electricity grid mix PE
Electricity
382 MJ
ES: Electricity grid mix PE
Diesel
1.32 kg
Diesel Combustion <u-so>
Diesel
1.32 kg
EU-27: Diesel mix at refinery PE

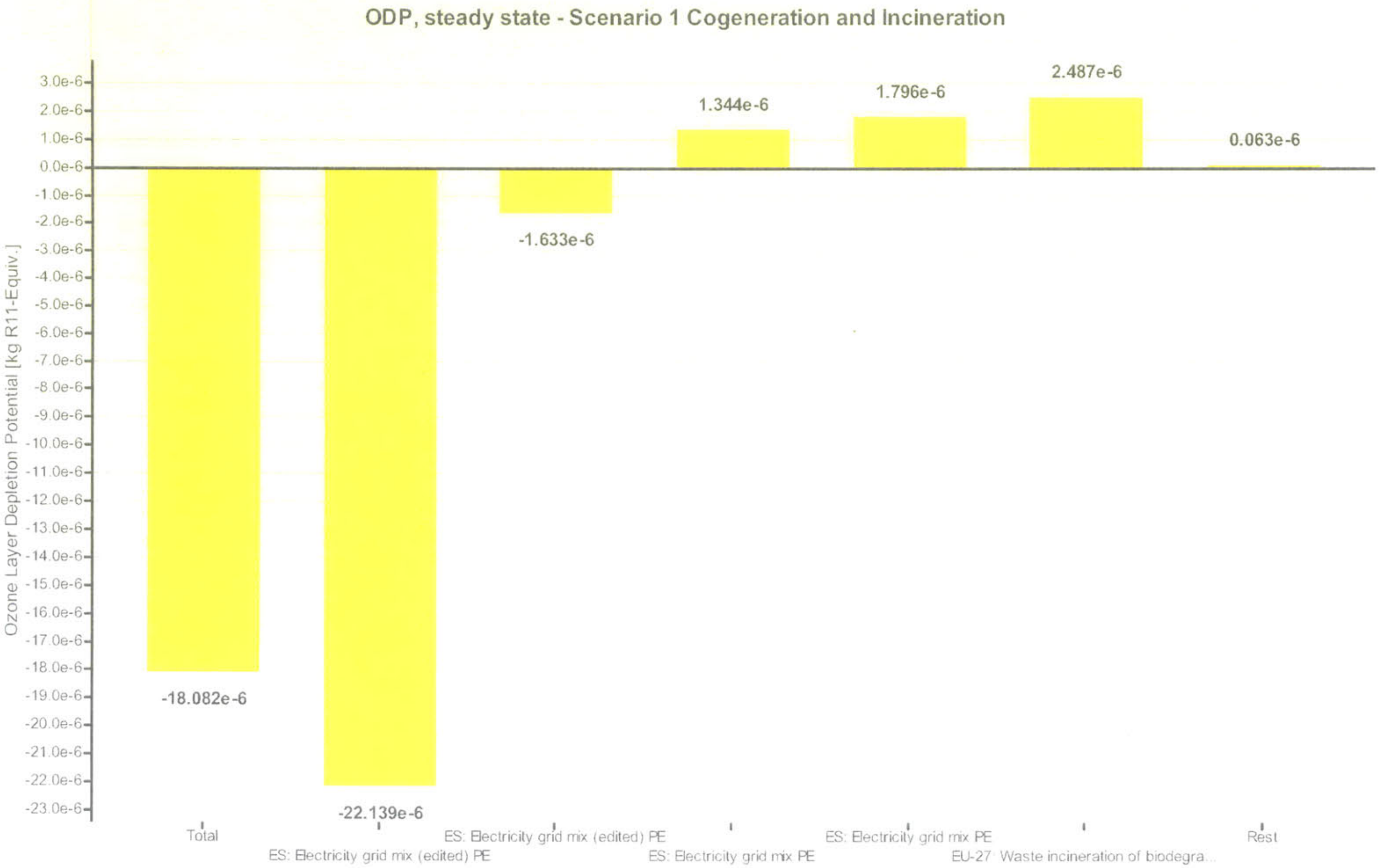

Scenario3 Composting
Selection: Scenario3 Composting
ES: Electricity grid mix PE
426 MJ
Electricity
Mechanical Dewatering <u-so>
Sewage sludge (waste water processing)
780 kg
Acrylonitrile
5.5 kg
RER: Acrylonitrile (AN) PlasticsEurope
ES: Electricity grid mix PE
3.82 MJ
Electricity
Windrow Composting <u-so>
Heating woodchip
380 kg
Woodchip Production <u-so>
Electricity
5.66E003 MJ
ES: Electricity grid mix PE
Diesel
1.7 kg
Diesel Combustion <u-so>
Diesel
1.7 kg
EU-27: Diesel mix at refinery PE
Sewage sludge dry
430 kg
ES: Electricity grid mix PE
211 MJ
Electricity
Agricultural Land Application <u-so>
Diesel
0.73 kg
Diesel Combustion <u-so>
Diesel
0.73 kg
EU-27: Diesel mix at refinery PE
Lime finelime (ground)
400 kg
DE: Lime (CaO; finelime) PE
151 kg
NPK fertiliser
Fertilizer Credit <u-so>
Fertiliser
-151 kg
fertiliser production <u-so>
Electricity
-39.3 MJ
ES: Electricity grid mix PE
Natural gas, at consumer France
-151 kg
FR: Natural gas mix PE

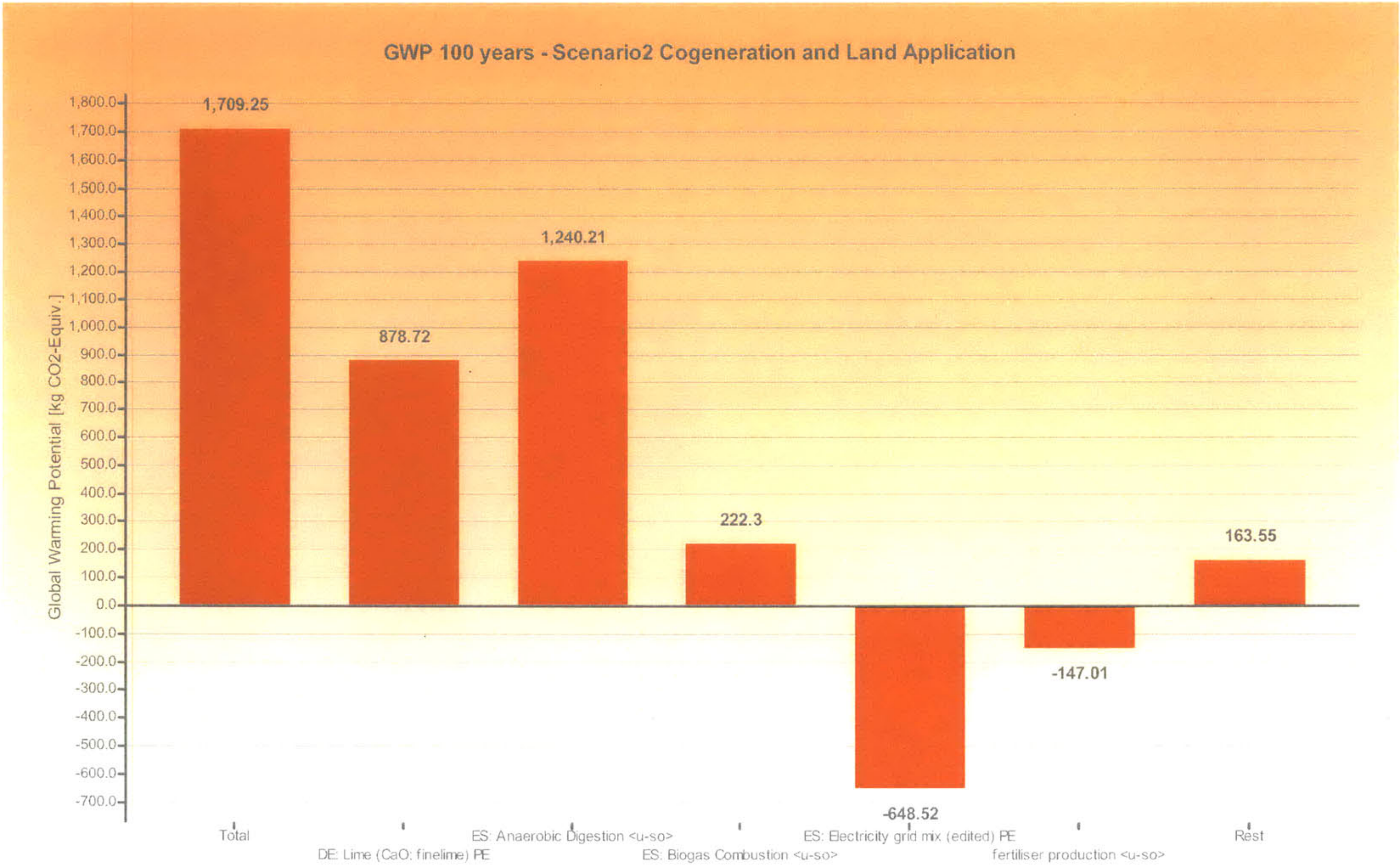
Appendix B GaBi Life Cycle Impacts Assessments of Slunge Management Scenarios

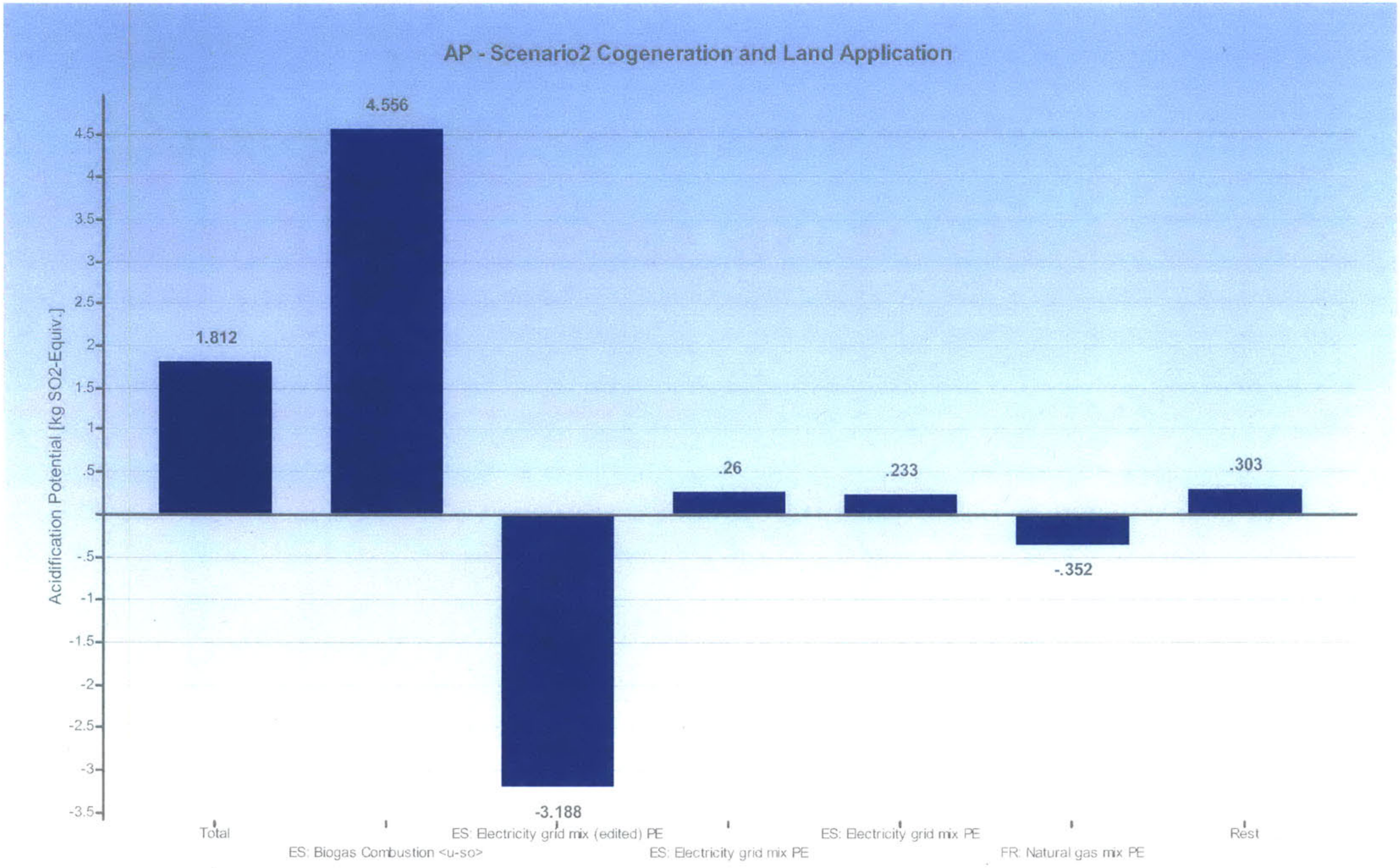


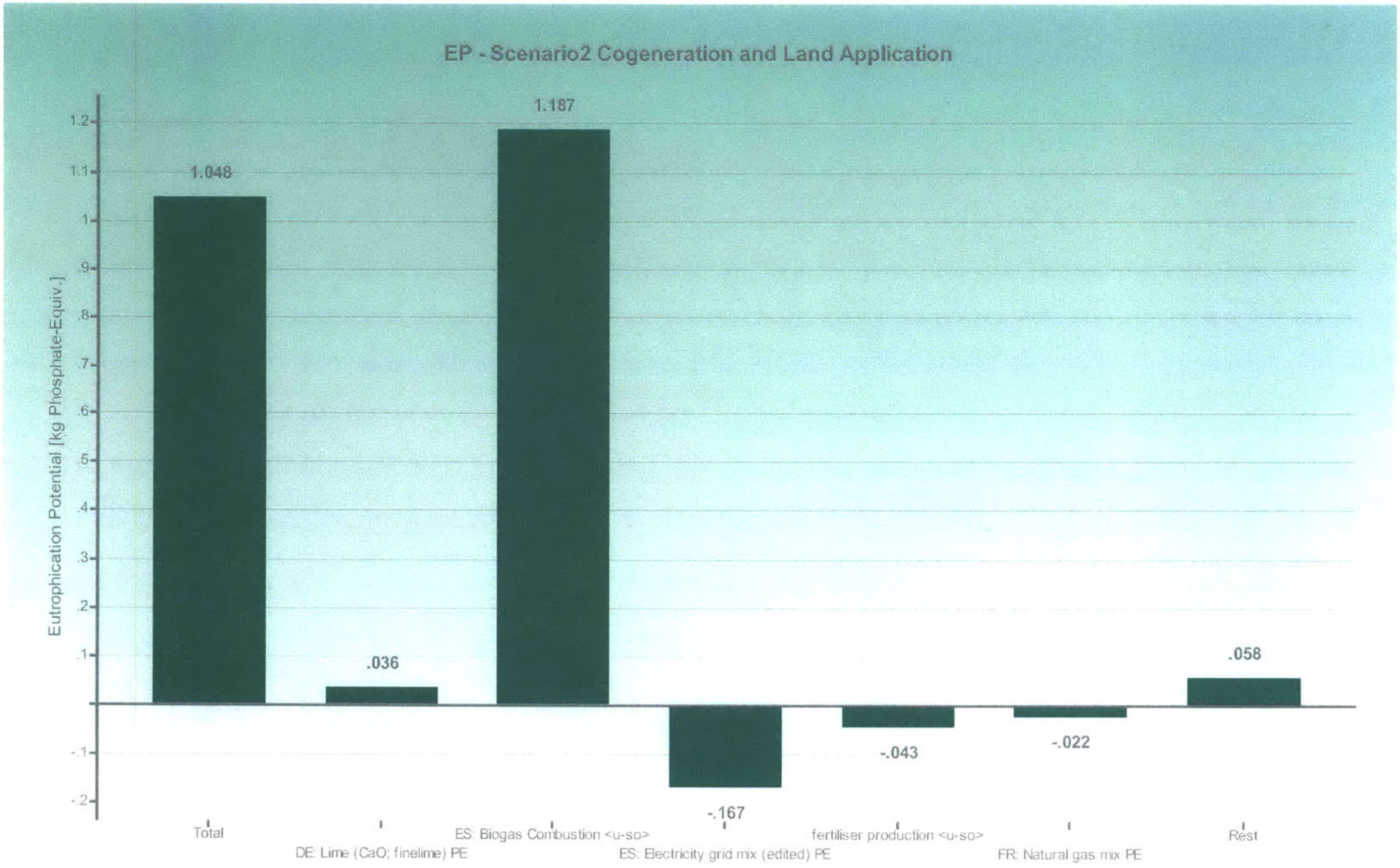

AP - Scenario 1 Cogeneration and Incineration
Acidification Potential [kg SO2-Equiv.]
4.5
4
3.5
3
2.5
2
1.5
1
.5
-.5
-1
-1.5
-2
-2.5
-3
-3.5
1.97
4.556
-3.188
-.235
.259
.358
.22
Total
ES: Biogas Combustion <u-so>
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix PE
EU-27: Waste incineration of biodegra...
Rest

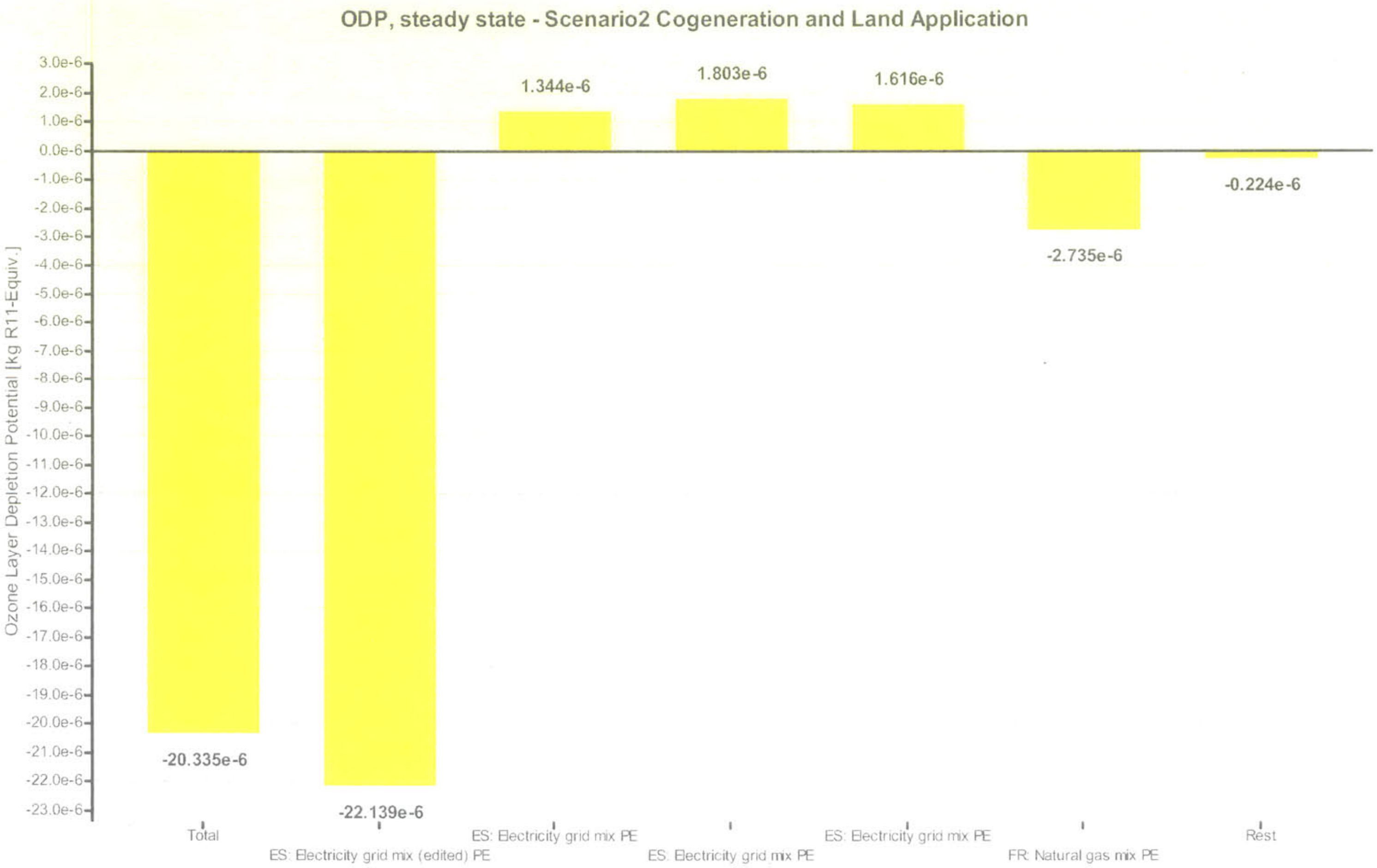

EP - Scenario 1 Cogeneration and Incineration
Eutrophication Potential [kg Phosphate-Equiv.]
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
1.11
1.187
-.167
-.012
.014
.069
.019
Total
ES: Biogas Combustion <u-so>
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix PE
EU-27: Waste incineration of biodegra...
Rest

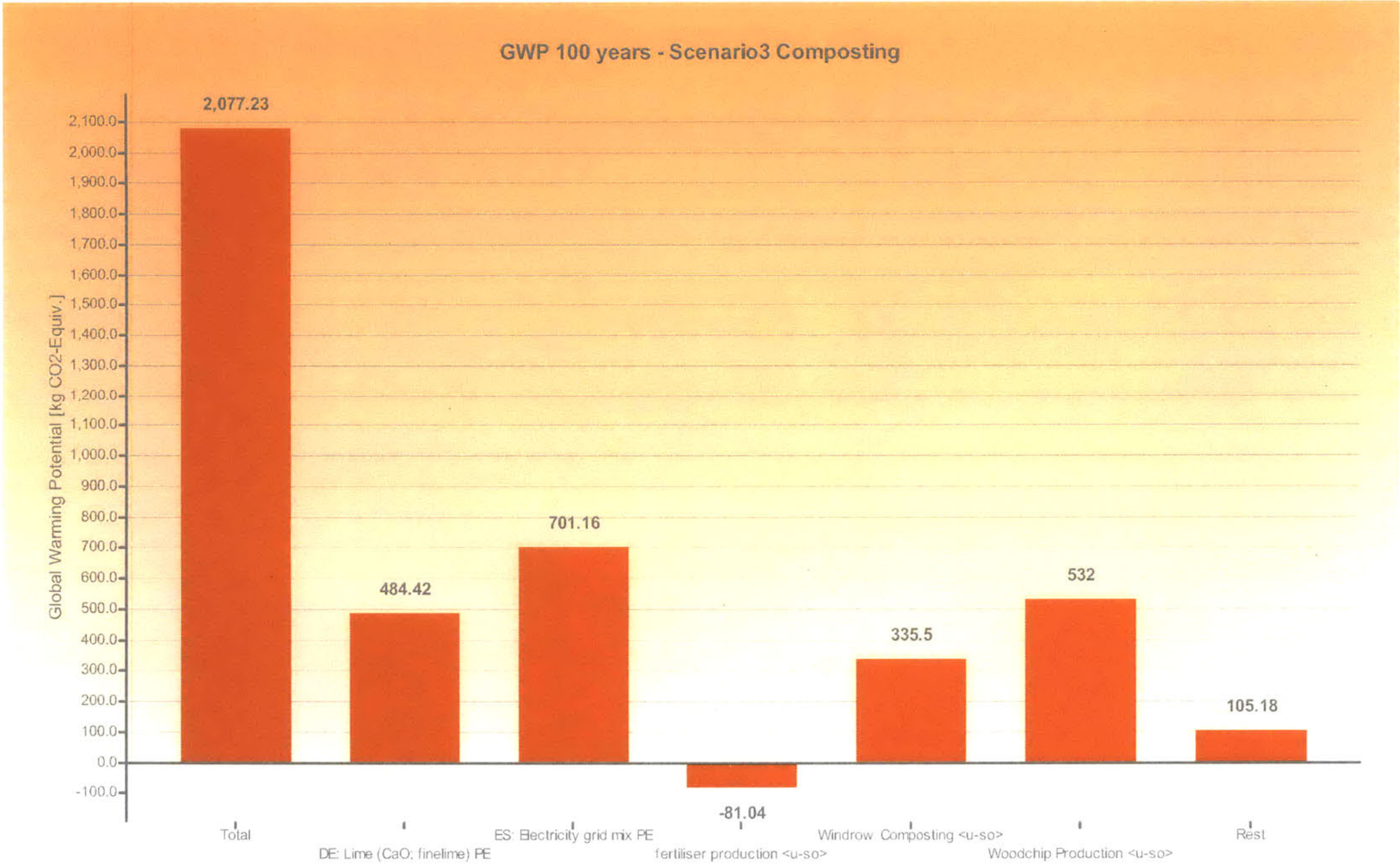

ODP, steady state - Scenario 1 Cogeneration and Incineration
Ozone Layer Depletion Potential [kg R11-Equiv.]
3.0e-6
2.0e-6
1.0e-6
0.0e-6
-1.0e-6
-2.0e-6
-3.0e-6
-4.0e-6
-5.0e-6
-6.0e-6
-7.0e-6
-8.0e-6
-9.0e-6
-10.0e-6
-11.0e-6
-12.0e-6
-13.0e-6
-14.0e-6
-15.0e-6
-16.0e-6
-17.0e-6
-18.0e-6
-19.0e-6
-20.0e-6
-21.0e-6
-22.0e-6
-23.0e-6
-18.082e-6
-22.139e-6
-1.633e-6
1.344e-6
1.796e-6
2.487e-6
0.063e-6
Total
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix PE
ES: Electricity grid mix PE
EU-27: Waste incineration of biodegra...
Rest

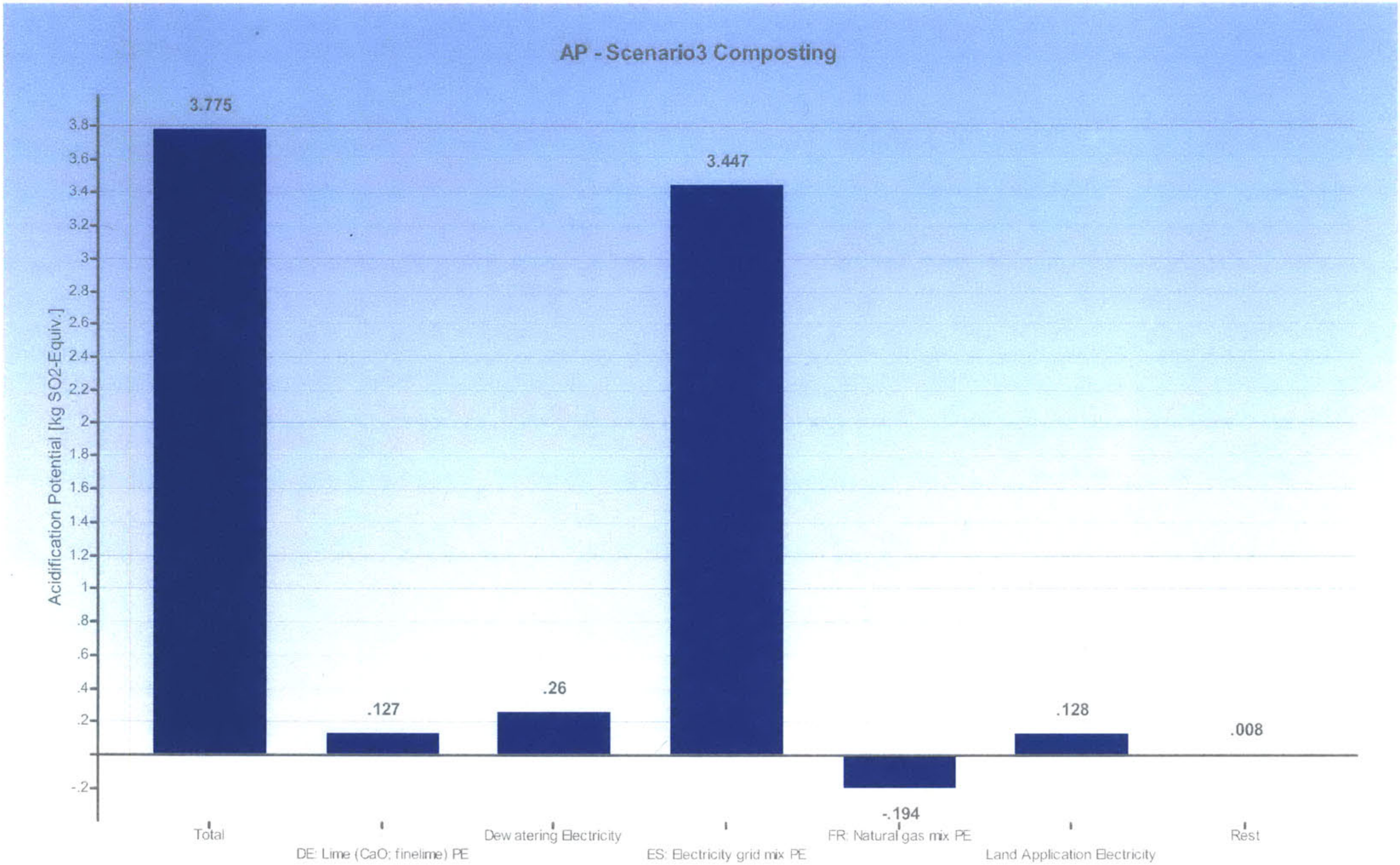

GWP 100 years - Scenario2 Cogeneration and Land Application
Global Warming Potential [kg CO2-Equiv.]
1,800.0
1,700.0
1,600.0
1,500.0
1,400.0
1,300.0
1,200.0
1,100.0
1,000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
-700.0
1,709.25
878.72
1,240.21
222.3
-648.52
-147.01
163.55
Total
DE: Lime (CaO; finelime) PE
ES: Anaerobic Digestion <u-so>
ES: Biogas Combustion <u-so>
ES: Electricity grid mix (edited) PE
fertiliser production <u-so>
Rest

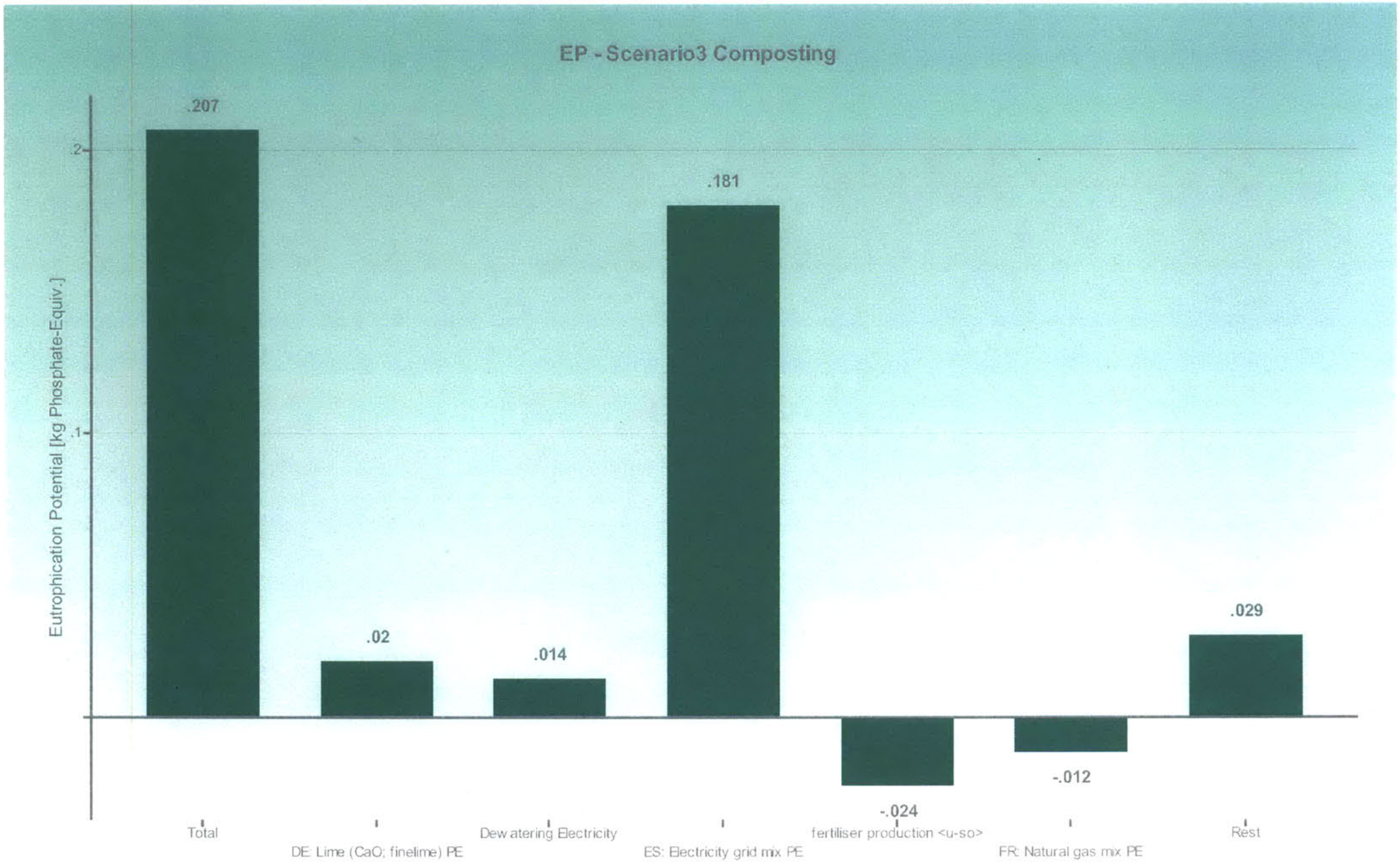

AP - Scenario2 Cogeneration and Land Application
Acidification Potential [kg SO2-Equiv.]
4.5
4
3.5
3
2.5
2
1.5
1
.5
-.5
-1
-1.5
-2
-2.5
-3
-3.5
1.812
4.556
-3.188
.26
.233
-.352
.303
Total
ES: Biogas Combustion <u-so>
ES: Electricity grid mix (edited) PE
ES: Electricity grid mix PE
ES: Electricity grid mix PE
FR: Natural gas mix PE
Rest

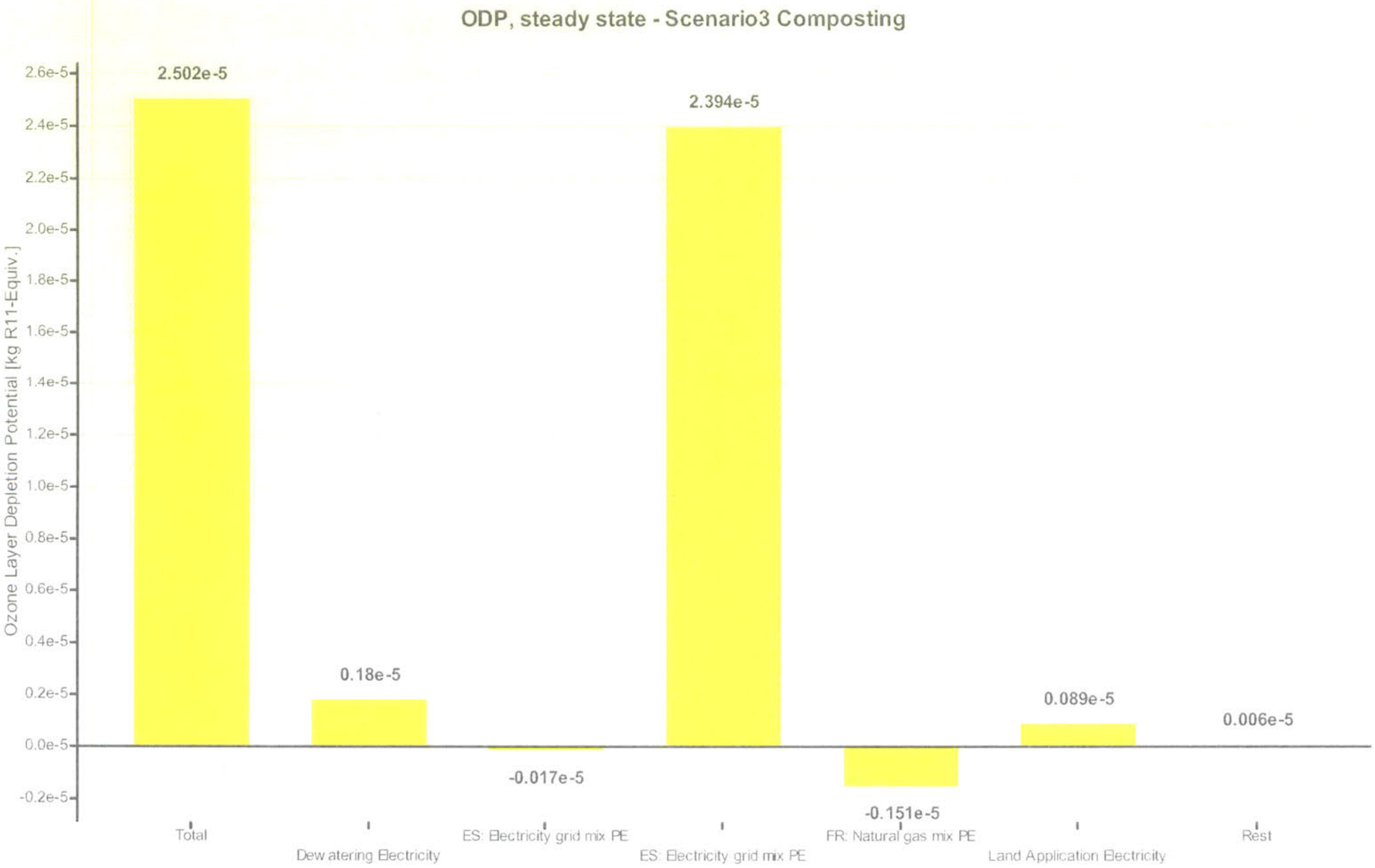

EP - Scenario2 Cogeneration and Land Application
Eutrophication Potential [kg Phosphate-Equiv.]
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
1.048
.036
1.187
-.167
-.043
-.022
.058
Total
DE: Lime (CaO; finelime) PE
ES: Biogas Combustion <u-so>
ES: Electricity grid mix (edited) PE
fertiliser production <u-so>
FR: Natural gas mix PE
Rest


ODP, steady state - Scenario2 Cogeneration and Land Application


GWP 100 years - Scenario3 Composting
Global Warming Potential [kg CO2-Equiv.]
2,100.0
2,000.0
1,900.0
1,800.0
1,700.0
1,600.0
1,500.0
1,400.0
1,300.0
1,200.0
1,100.0
1,000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
-100.0
2,077.23
484.42
701.16
-81.04
335.5
532
105.18
Total
DE: Lime (CaO; finelime) PE
ES: Electricity grid mix PE
fertiliser production <u-so>
Windrow Composting <u-so>
Woodchip Production <u-so>
Rest


AP - Scenario3 Composting
Acidification Potential [kg SO2-Equiv.]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
-.2
3.775
.127
.26
3.447
-.194
.128
.008
Total
DE: Lime (CaO; finelime) PE
Dew atering Electricity
ES: Electricity grid mix PE
FR: Natural gas mix PE
Land Application Electricity
Rest


EP - Scenario3 Composting
Eutrophication Potential [kg Phosphate-Equiv.]
.2
.1
.207
.02
.014
.181
-.024
-.012
.029
Total
DE: Lime (CaO; finelime) PE
Dewatering Electricity
ES: Electricity grid mix PE
fertiliser production <u-so>
FR: Natural gas mix PE
Rest


ODP, steady state - Scenario3 Composting
Ozone Layer Depletion Potential [kg R11-Equiv.]
2.6e-5
2.4e-5
2.2e-5
2.0e-5
1.8e-5
1.6e-5
1.4e-5
1.2e-5
1.0e-5
0.8e-5
0.6e-5
0.4e-5
0.2e-5
0.0e-5
-0.2e-5
2.502e-5
0.18e-5
-0.017e-5
2.394e-5
-0.151e-5
0.089e-5
0.006e-5
Total
Dew atering Electricity
ES: Electricity grid mix PE
ES: Electricity grid mix PE
FR: Natural gas mix PE
Land Application Electricity
Rest

Appendix C LaGavia WWTP Data Related to Sludge Management

Energy Production

DATA	ENERGY		
	PRODUCED (Motogeneration)	PURCHASED	Cos f
	kWh	kWh	
Total January	684,767.00	723,914.00	30.67
Total February	603,980.00	710,224.00	27.36
Total March	672,867.00	775,504.00	29.92
Total April	650,652.00	692,865.00	29.27
Q Total May	680,715.00	699,656.00	29.80
Total June	617,544.00	654,547.00	29.15
Total July	569,733.00	687,885.00	29.25
Total August	480,532.00	719,712.00	30.04
Total September	562,908.00	754,805.00	25.72
Total October	589,678.00	729,809.00	29.91
Total November	594,043.00	871,237.00	28.21
Total Diciember	531,836.00	996,047.00	29.20

Sludge Collected

DATA	Q SLUDGE TO DIGESTION (Digestor A)	Q SLUDGE TO DIGESTION (Digestor B)	Q SLUDGE TO DIGESTION (Digestor C)	Q SLUDGE TO DIGESTION (Digestor D)	**Q SLUDGE TO DIGESTION**	**Q DIGESTED SLUDGE**
	m^3	m^3	m^3	m^3	m^3	m^3
Total January	6,274.56	0.00	6,258.24	6,461.16	**18,993.96**	**18,993.96**
Total February	5,804.28	0.00	5,852.00	5,884.00	**17,540.28**	**17,540.28**
Total March	6,700.00	0.00	6,767.00	6,821.00	**20,288.00**	**20,288.00**
Total April	6,365.08	0.00	6,347.64	6,336.00	**19,048.72**	**19,048.72**
Total May	5,721.08	0.00	5,726.80	5,748.44	**17,196.32**	**17,196.32**
Total June	5,109.00	0.00	5,145.00	5,170.00	**15,424.00**	**15,424.00**
Total July	4,810.85	0.00	4,787.52	4,862.66	**14,461.03**	**14,461.03**
Total August	3,622.00	0.00	3,595.00	3,680.00	**10,897.00**	**10,897.00**
Total September	5,036.00	0.00	5,138.00	5,119.00	**15,293.00**	**15,293.00**
Total October	5,404.00	0.00	5,436.00	5,416.00	**16,256.00**	**16,256.00**
Total November	5,076.00	0.00	5,069.00	5,073.00	**15,218.00**	**15,218.00**
Total December	6,815.60	0.00	6,714.54	6,778.07	**20,308.21**	**20,308.21**

Biogas

DATA	GAS				
	Biogas recovered	Biogas recovered/Volatile matter removed	Boilers consumption	Torch consumption	Cogeneration consumption
	Nm3	Nm3/Kg	Nm3	Nm3	Nm3
Total January	327,361.76	17.12	4,891.00	0.00	322,470.76
Total February	287,558.00	16.52	15,186.00	0.00	272,372.00
Total March	313,277.00	17.42	4,193.00	0.00	309,084.00
Total April	301,822.92	15.49	0.00	0.00	301,822.92
Total May	322,882.64	20.29	0.00	0.00	322,882.64
Total June	275,417.00	19.07	0.00	0.00	275,417.00
Total July	259,947.12	19.29	0.00	0.00	259,947.12
Total August	225,477.00	23.78	510.00	410.00	224,557.00
Total September	259,521.00	16.69	40.00	2,200.00	257,281.00
Total October	259,109.00	17.24	109.00	0.00	259,000.00
Total November	280,600.00	19.09	26.00	400.00	280,174.00
Total December	249,705.87	12.46	1,132.00	0.00	248,573.87