NTNU – Trondheim
Norwegian University of
Science and Technology

Analysis of Sewage Sludge Recovery System in EU - in Perspectives of Nutrients and Energy Recovery Efficiency, and Environmental Impacts

Guochang Xu

Master in Industrial Ecology
Submission date: March 2014
Supervisor: Helge Brattebø, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Acknowledgements

This thesis concludes my Masters programme in Industrial Ecology (IndEcol) at Norwegian University of Science and Technology (NTNU). I would like to give a warm thanks to my professor Helge Brattebø, who has been very supportive throughout my last 1.5 years as a Masters student.

Furthermore I would like to thank the PE INTERNATIONAL for their contribution to this thesis by providing me with full version of Gabi 6.0, and also Samantha Peverill for her help on editing.

A special thanks goes to my supportive family.

Trondheim, 22nd February 2014

Guochang Xu

Abstract

The purpose of this research is to contribute to sewage sludge management by providing a scientific benchmark of the performance of sewage sludge recovery systems (SSRS). This can serve as input to improved policy development, management practices and technology development. This report also contributes to the BioTEnMaRe project by examining resource recovery efficiency (nutrients and energy) and life cycle environmental impacts quantitatively in a systems-wide perspective.

Firstly, a literature study on the status quo provides an understanding of the technologies and state-of-the-art strategies for sludge management. As well, a review of previous researches on the performances of sludge treatment system was carried out to identify the potential academic improvements in this field.

The research method is comprised of material flow analysis (MFA) and life cycle assessment (LCA). Based on the principles of MFA and LCA, a non-quantitative generic model was built to describe the profile and framework of the sludge recovery system.

In addition, an analysis at more specific level was carried out by using the European Union (EU) as the study case, according to the generic model. Three technological configurations were used as the three following scenarios; composting combined with land application, anaerobic digestion combined with land application and CHP, and anaerobic digestion combined with land application and biogas upgrading.

The scenarios each have their own advantages and disadvantages. In summary, Scenario 1 has the highest relative nutrients recovery efficiency, but it cannot recover energy in sludge. Although Scenario 3 represents the highest energy recovery efficiency, it does not perform as well as Scenario 2 in terms of environmental impacts. Scenario 2 performs the best with regards to environmental impacts, and it also has acceptable performance in nutrient and energy recovery efficiency. Therefore, Scenario 2 can be considered as the optimal option.

Table of Contents

Table of Figures

Tables

1. Introduction

Sewage sludge is formed as the by-product of the different treatment stages of wastewater from domestic households, and sometimes it also includes industrial and commercial effluents (Williams 2005). Due to the multiple inflow sources, the composition of sludge can vary considerably, but in general raw sludge is comprised of water and its solid components. The solid part of sludge contains substances like organic pollutants, heavy metals and pathogens that are potentially harmful to both the environment and human health. On the other hand, it also contains nutritional substances and energy, which are valuable and can be recovered. The sludge can be a double-edged sword, with inappropriate treatment it is just waste, but with appropriate treatment it becomes an important resource.

1.1 Background

For years, treating sewage sludge has been considered a secondary issue compared to the main wastewater treatment (Suh and Rousseaux 2002). However, it is gradually becoming one of the most significant focuses and challenges in wastewater management, because of the introduction of a “Sustainable Sludge Handing” strategy which is to meet as high as recovery rate of sludge as a resource without supply of harmful substances to human or environment (Fytili and Zabaniotou 2008).

Additionally, many countries have recently recognized that sewage sludge components can be recycled in a “Productification” strategy which is aimed at making products from sludge which are intended for sale in the market place. Sludge based products can be used for energy and also reused with matter recovery for land application. According to the “Productification” strategy, these products could be used not only on-site, such as at the treatment plants, as has been practiced for many years, but can be sold in the open market as well.

There is a wide range of uses for sewage sludge that exploit its nutrient, material and energy contents, for instance, drying, incineration, composting, anaerobic digestion, and so on.

Among these processes, sludge composting and anaerobic digestion have been receiving more and more attention in terms of their marketable products.

1.2 Motivation

This thesis is a fraction of BioTEnMaRe project which is under the Polish-Norwegian Research-Funding Programme. The idea of the BioTEnMaRe project is to devise innovative technologies allowing for a maximum reduction of the negative impact of sewage sludge on the natural environment. It focuses on improving sludge composting, anaerobic digestion, spreading of high quality compost for phytoremediation of contaminated areas as well as cultivation of energy plants (BioTEnMaRe 2014).

It is of valuable to explore how resource recovery efficiency and life cycle environmental impacts can be examined quantitatively, in a systems-wide perspective. This could be done by developing a generic system definition of the sewage sludge recovery system (SSRS), and then applying this generic definition at a more specific level for several selected technological configurations.

1.3 Objective and research question

The goal of this work was to contribute BioTEnMaRe project by carrying out a literature study, developing system definitions and modelling the system performance, with the use of appropriate indicators. This report also contributes to sludge management by providing a scientific benchmark of the performances of scenarios which as serve as input to improved policy development, management practices and technology development.

According to the goal, the research questions were formed and illustrated as follows:

1) Carry out a literature study to understand what are technologies and state-of-the-art strategies for sludge recovery.
2) Use the collected information and data to develop a generic system definition that

reflects how SSRS is structured, and what the important processes and flows are.

3) Following the BioTEnMaRe project select several system configurations as scenarios, with given technologies and system conditions, and develop for each scenario a Material Flow Analysis (MFA) based on system definition with quantitative flows for evaluation of nutrients and energy recovery efficiency. Then, develop a Life Cycle Assessment (LCA) model for quantitative analysis of environmental impacts. Discuss likely improvement potentials when shifting from one scenario to the other, and what are the critical variables and hypotheses in the model.
4) Discuss what are the advantages and disadvantages of each system configuration (scenario), which system configuration is the optimal option, and how the model could be improved (by others, or later) towards a more detailed model evaluating the resource recovery efficiency and life cycle environmental impacts of SSRS.

2. Literature study

2.1 Sewage Sludge Characteristics

Sewage sludge originates from wastewater treatment processes. It is the by-product generated during the primary (physical and/or chemical), the secondary (biological), and sometimes the tertiary (additional to secondary, often is disinfection) treatment (Fytili and Zabaniotou 2008). The type of plant, the operational method, and the physical and chemical characteristics of sludge can vary based on the source of sewage.

The sewage is mainly water, but after wastewater treatment, the particulate and colloidal matter is concentrated to form sludge (Williams 2005). Because sludge is directly separated from sewage, it is unsurprising that the sludge contains high level of water. Generally, the water content of sludge is over 90% of total wet weight (Yao 2010).

Water in sludge is present in the following four forms (Figure 1); interstitial water, capillary water, adhesive water and internal water (Yao 2010).

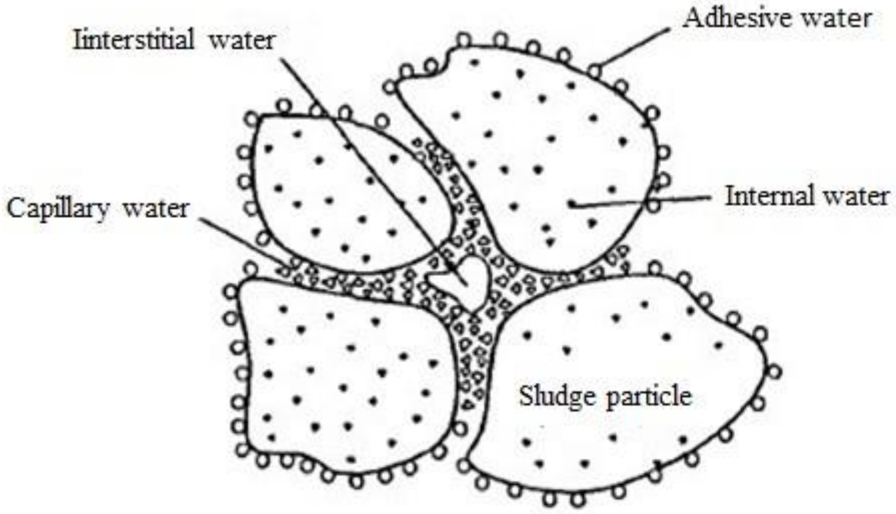

Figure 1: Forms of water in sewage sludge

According to Yao (2010), interstitial water is located between sludge particles, represents about 70% of total water content in sludge, and can be separated by a thickening process.

Capillary water exists in capillaries which are located between sludge particles, represents approximately 20% of total water content, and can be separated by process like belt and/or centrifuge dewatering. Adhesive water is the water that adheres to the surface of a sludge particle, and it is harder to separate out due to the strong surface adhesive force provided by tiny sludge particles. Internal water is the chemical combined water inside sludge particle. It can only be separated by changing the chemical structure of sludge particles. Therefore it is very difficult to remove adhesive water and internal water other than by using thermal treatment (Yao 2010).

A high level of water content will certainly hinder the sludge recovery processes. In practice, before the main treatment (e.g. composting, anaerobic digestion and incineration), the sludge is usually dehydrated through pre-treatments (e.g. thickening and dewatering). Table 1 shows the water content in sludge before and after pre-treatment (Hong, Hong et al. 2009).

Table 1: Water content in sludge before and after pre-treatments

Item	Raw sludge	Thickened sludge	Dewatered sludge
Water content (%)	99%	96%	80%

Sewage sludge can have negative impacts on environmental and human health, mostly due to containing three categories of destructive substances, which are organic pollutants, pathogens and heavy metals.

Organic pollutants include dioxins and polychlorinated biphenyls (PCBs), and they are mainly found in the wastewater from incineration, paper production, aluminum products manufacture, fertilizer and pesticide production, and preservatives production (Yao 2010). Both dioxins and PCBs have low water solubility but high lipid solubility, and due to these features they can easily bioaccumulate which makes them long-term pollutants and hard to remove (Baily 2009).

Pathogens are mainly viruses, bacteria, fungi and parasites. They can cause diseases in their host (e.g. animal, human, plant, even other microorganisms). The typical diseases caused by pathogens are smallpox, influenza, mumps, measles, and so on (Yao 2010). Thus, the stabilization process is essential and significant in sludge treatment, in order to eliminate pathogens.

Heavy metals generally come from industrial effluents. The category of heavy metal is determined by the category of effluent. For years, heavy metal has been a focus issue in sewage sludge treatment, because sludge tends to accumulate heavy metals existing in the sewage at wastewater treatment plant (WWTP) (Fytili and Zabaniotou 2008). Typical metal components in sludge are presented in Table 2 (Fytili and Zabaniotou 2008). It illustrates that a large range of material concentrations exist, due to large variations in industrial activity in catchment areas of WWTPs. Therefore the typical value may not reflect the real situation in different cases. It is better to measure the concentration of heavy metals in a specific case. Otherwise it may cause large uncertainty on the result of environmental impact analysis such as the human toxicity potential.

Table 2: Typical metal components in sludge

Item	Dry sludge (mg/kg)	
	Range	Typical
Arsenic	1.1-230	10
Cadmium	1-3410	10
Chromium	10-990000	500
Cobalt	11.3-2490	30
Copper	84-17000	800
Iron	1000-154000	17000
Lead	13-26000	500
Manganese	32-9870	260
Mercury	0.6-56	6
Molybdenum	0.1-214	4
Nickel	2-5300	80
Selenium	1.7-17.2	5
Tin	2.6-329	14
Zinc	101-49000	1700

In recent decades, a great variety of extraction schemes have been developed, but none of them have been unreservedly accepted by the scientific community (Fytili and Zabaniotou 2008). The recycling of trace metals in sludge is still a technical challenge.

In addition, sewage sludge contains inorganic matters, organic matters, nutritional components, and energy. The typical chemical components and properties are reported in Table 3 (Fytili and Zabaniotou 2008). With appropriate treatment and processing, the sludge can be utilized as potential resources for benefiting plant growth, soil improvement, energy saving, and extend to construction materials.

Table 3: Typical chemical components and properties of sewage sludge (TS=total solid)

Item	Primary sludge		Secondary sludge	
	Range	Typical	Range	Typical
Volatile solids (% of TS)	60-80	65	30-60	40
Grease and fats (% of TS)				
Ether soluble	3-60	-	5-20	18
Ether extract	7-35	-	-	-
Protein (% of TS)	20-30	25	15-20	18
Nitrogen (N, % of TS)	1.5-4	2.5	1.6-6.0	3
Phosphorous (P_2O_5, % of TS)	0.8-2.8	1.6	1.5-4.0	2.5
Potash (K_2O, % of TS)	0-1	0.4	0.0-3.0	1
Cellulose (% of TS)	8.0-15.0	10	8.0-15.0	10
Silica (SiO_2, % of TS)	15.0-20.0	-	10.0-20.0	-
Alkalinity (mg/l as $CaCO_3$)	500-1500	600	2500-3500	-
Organic acids (mg/l as Hac)	200-2000	500	100-600	3000
Energy content (MJ DS)	10000-12500	11000	4000-6000	-
pH	5.0-8.0	6	6.5-7.5	7

2.2 Sewage Sludge Treatment Technologies

Previously sludge was considered a category of waste, but now it is recognized as a potential resource. After years of development and practice, there are many technologies (Table 4) that can be chosen to treat the sludge.

Table 4: Major sludge treatment technologies

Option	Examples of application
No recycling	Landfill, Storage, Dumping
Substance Reuse	Drying, Land use
Substance conversion	Composting, Anaerobic digestion, Incineration, Wet oxidation
Energy Recovery	Incineration, Anaerobic digestion, Gasification

These technologies range in complexity and novelty. Their use depends on different levels of economic and technical support, and the chosen technology should match the relevant legal requirement in applied scope.

2.2.1 Wastewater Treatment

The characteristics of the particular sludge in question strongly affect the choice of sludge management strategy.

Sewage can be treated close to where it is produced, in a decentralized system, or be collected and transported by a network of pipes and pump stations to a WWTP, as in a centralized system (Tokich 2004). A complete wastewater treatment (Figure 2) generally involves at least two stages, primary and secondary treatment. Tertiary treatment is often considered as an additional option to further improve the quality of produced water in final phase (DEFRA 2012).

In primary treatment, sewage is temporarily held in a quiescent basin where heavy solids can settle to the bottom while oil, grease and lighter solids float to the surface. The settled and floating materials are removed and the remaining liquid may be discharged or subjected to secondary treatment (SOUL 2012).

Secondary treatment removes dissolved and suspended biological matter. Secondary treatment is typically performed by indigenous, water-borne micro-organisms in a managed habitat. Additionally, a separation process to remove the micro-organisms from the treated water prior to discharge or tertiary treatment may be required during the secondary treatment (SEAGATEFILTERA 2014).

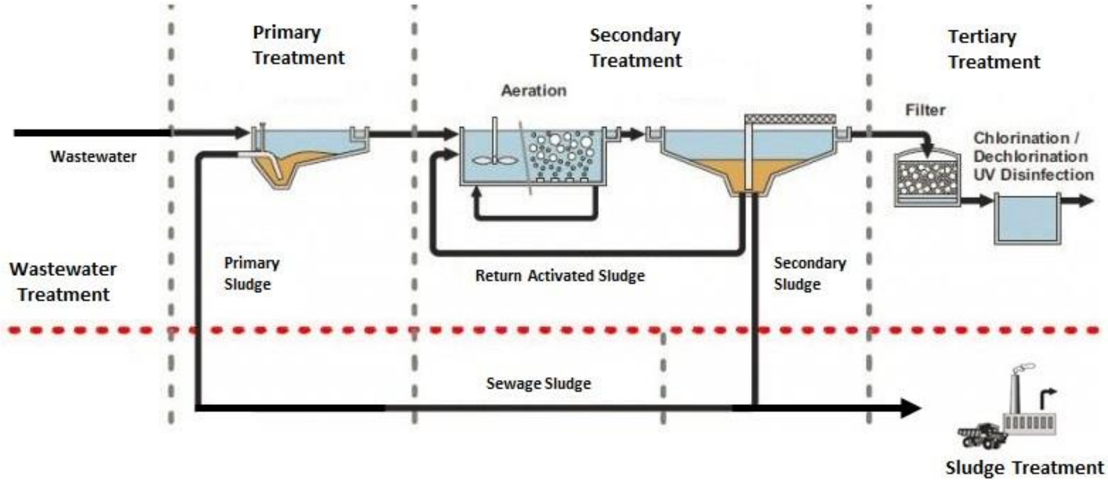

Figure 2: Process of wastewater treatment

Tertiary treatment is often defined as anything more than primary and secondary treatment (e.g., by lagoons and microfiltration) and is often required in order to allow treated water into a highly sensitive or fragile ecosystems such as estuaries, low-flow rivers and coral reefs (SEAGATEFILTERA 2014).

Treated water re-enters the anthropological circle and environment. The by-product sewage sludge is then entered into a sludge treatment system.

2.2.2 Drying

For application of sewage sludge on land and landfill, drying can decrease its volume, and consequently the costs of transportation and disposal. However, due to the concern over the resource and environment, the application of dried sludge onto agricultural land and landfill is being continuously decreased.

Drying of sludge is currently preferred as a pre-treatment when the sludge is going to be incinerated, because it can increase the lower heating value and decrease the water content of sludge (Baily 2009).

Sludge drying can be carried out in different types of drying technology, based on the type of heat transfer between heat medium and sludge, these technologies can be differentiated as follows (Baily 2009):

1) Contact drying technology – indirect drying with heat medium separated from heat exchanging wall.
2) Convection drying technology – direct drying with drying medium (air usually) is in direct contact with sludge.
3) Radiating drying technology – drying by solar energy.

Presently, the most common type of contact drying technology is the disk dryer (Figure 3).

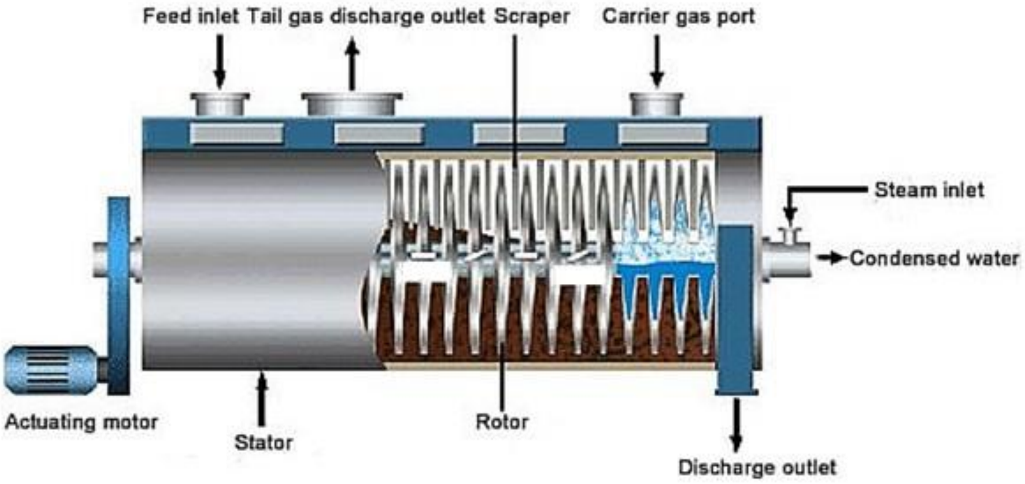

Figure 3: Structure of disc dryer (Source: TDG TI Clean Co., Ltd)

Convection drying technology is sometimes used, including the drum and fluid dryer. In addition, the utilization of solar sludge drying is considered the least demanded technology, due to its investment and operation (Baily 2009).

2.2.3 Landfill

Landfill can be classified into two categories, simple landfill and well-designed landfill. Simple landfill is considered to be one of the oldest methods of waste treatment. In this method, sludge is directly buried underground with fettle or no protection.

On the contrary, a well-designed landfill is built in an appropriate location and equipped with full protection systems (e.g. liner system and off-gas treatment system) which reduce the environmental impacts (Williams 2005). However, the drawback of well-designed landfill is its relative high cost and it extracts no value from the sludge, unless it has a gas collection system. In many developed countries the trend today is towards methods with more recycling.

Landfilling has low priority in the waste hierarchy, and should only be chosen when no other way of disposing sludge is available (Bresters 1997).

2.2.4 Incineration

The landfilling of sludge is subject to increasing regulatory controls. For this reason, incineration of sludge has increased in recent years, even though it can be a capital intensive investment and is also subject to strict regulation with respect to combustion criteria, treatment of tail gases, fly and bottom ashes (Baily 2009).

Incineration of sludge greatly reduces its weight and volume. Ash is produced as by-product in incineration, which is an inert material without pathogenic and biodegradable components, so it can be easily disposed of in landfill. Moreover, ash can be used as a material for construction, if it complies with legislation. The off-gas produced contains several types of harmful substance, for instance, sulphur dioxide, nitrogen oxides, and dioxins. Therefore, a sludge incineration plant must be equipped with efficient system of off-gas cleaning (Bresters 1997).

Incineration of sludge can be performed in a designated incinerator or in a municipal solid waste (MSW) incinerator under the particular constraints (Williams 2005). Designated sludge incineration facilities have been operating for many years, such as fluidized bed systems (Figure 4) for example.

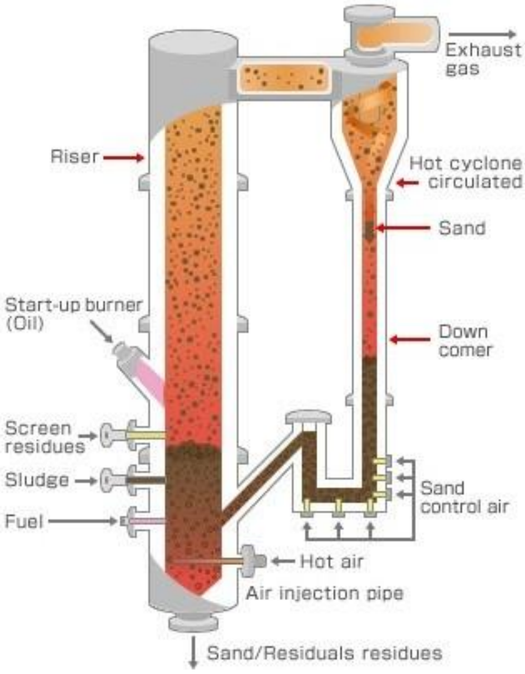

Figure 4: Fluidized bed system for incinerating sludge (Source: METAWATER)

Incinerating sludge alone is restricted by its high operational energy consumption for operation, because sludge is wet and dense, and the pre-treatment drying can also use considerable energy.

The use of MSW incinerators to treat mixed MSW and sludge maybe more feasible, particularly if the incinerator is close to the WWTP that generates the sludge. However, mixing MSW with sludge must be carefully designed, because a decrease of the heating value affects the incineration process (Bresters 1997).

2.2.5 Composting

Sludge composting occurs via an aerobic bacterial decomposition process that stabilizes the organic substances in sludge and produces compost (humus). The overall chemical reaction of composting is (Finstein, Cirell et al. 1980):

$$C_{10}H_{19}O_8N + 12.5O_2 \rightarrow 10CO_2 + 8H_2O + NH_3 \qquad (1)$$

The sludge composting aims to biologically stabilize sludge and control pollution risks, in order to develop agriculture or other end use outlets based on the nutritional or organic value (Bresters 1997).

A wide range of composting systems exists, and they tend to be classified into two categories, closed systems and open systems. Composting can occur in a closed system, for instance, an inclined rotating cylinder, fed on one side with the raw materials, and the product is collected at the other side. As the materials are slowly tumbled over, they are fully mixed and aerated. Bacterial decomposition produces heat, so temperatures in the insulated composter can easily reach 55 ℃ (the optimal temperature). Afterwards, the immature compost is continuously aerated outside for about 3 months to allow the composting process to complete (Halls 2000).

Also, composting can be more simply processed in an open system such as direct windrows. Regular turning of the windrows is required to help mixing of the materials and more importantly to supply oxygen to the bacteria. Because compost has a property of good heat insulating, the temperature can rise to the optimal temperature for composting. Furthermore, the turning also ensures that all parts of the windrow reach the required temperature which is essential for pathogen destruction. Turning is required every two to three days in the first half month. After this period frequent turning is not needed as less heat is generated and less oxygen is required while the compost goes to maturation (Halls 2000).

2.2.6 Anaerobic digestion

Anaerobic digestion is a bacterial decomposition process in the absence of oxygen that stabilizes organic wastes and produces biogas, a mixture of methane and carbon dioxide. The heat value of methane is about similar to natural gas, therefore biogas is considered as a valuable energy resource (Halls 2000).

There are four key biochemical stages in anaerobic digestion, which are hydrolysis, acidogenesis, acetogenesis and methanogenesis (Williams 2005). The sequence of these four stages is shown in Figure 5.

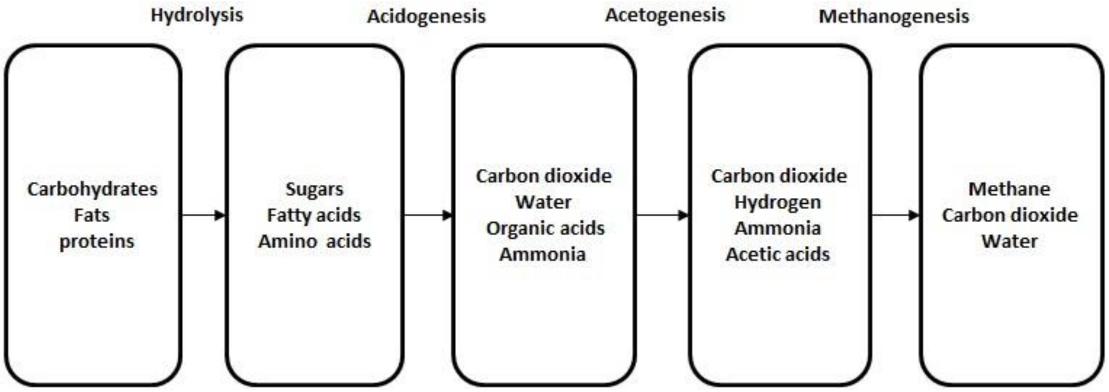

Figure 5: Key stages of anaerobic digestion

Hydrolysis is the first stage in the decomposition of macromolecular substances such as carbohydrates, fats and proteins. Afterwards some low-molecular substances arise from hydrolytic bacteria activities, such as sugars, fatty acids and amino acids (Baily 2009).

Acidogenesis is the second stage in which products of hydrolysis are decomposed by fermentation bacteria into organic acids, carbon dioxide, water, and sometimes ammonia. The main reaction equation is (Baily 2009):

$$C_6H_{12}O_6 \rightarrow CH_3(CH_2)_2COOH + 2CO_2 + 2H_2O \quad (2)$$

Acetogenesis and methanogenesis usually run simultaneously. The former uses bacteria to decompose organic acids into acetic acid and hydrogen. The latter uses methanogenic bacteria to further decompose acetic acid into methane and carbon dioxide, at the same time more methane is created from hydrogen and carbon dioxide by another type of methanogenic bacteria. The reaction equations are (Baily 2009):

$$CH_3(CH_2)_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2 \qquad (3)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (4)$$

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad (5)$$

The processes of anaerobic digestion of sludge are shown in Figure 6 (Henley and Barker 2011). Anaerobic digestion is usually carried out in a specially built digester, where the content is mixed and the digester maintained at 35 ℃ (the optimal temperature) (Bresters 1997). After digestion, biogas as one of its products is collected from the digester. Another product, raw digestate is passed to a further dewatering process where the raw digestate is dewatered to form mature digestate.

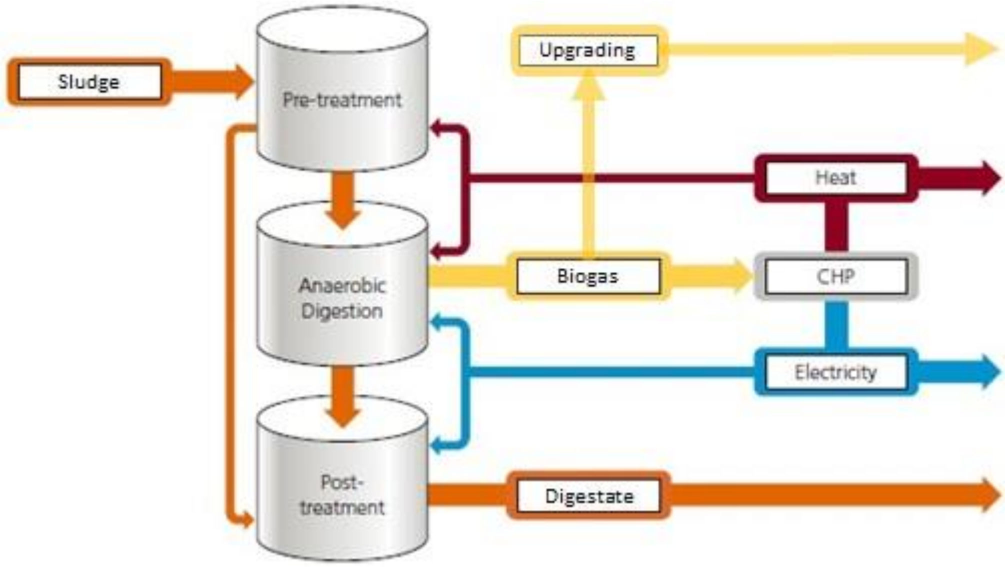

Figure 6: Process of anaerobic digestion

The collected biogas can be directly used as fuel in combined heat and power (CHP) plant or upgraded to natural gas-quality biomethane (Henley and Barker 2011). Moreover, the produced nutrient-rich digestate can be used as fertilizer or soil conditioner. Anaerobic digestion has received increased attention in recent years among EU countries, for instance, in Germany, United Kingdom, Denmark and Sweden due to the reuse of sludge as a resource and that it is a technological approach which has a lowered capital cost (Henley and Barker

2011).

2.2.7 Gasification

Gasification is a thermal process that can convert organic based sludge materials with air (sometimes oxygen or steam) into an inflammable gas (Baily 2009). The main process of gasification is shown in Figure 7.

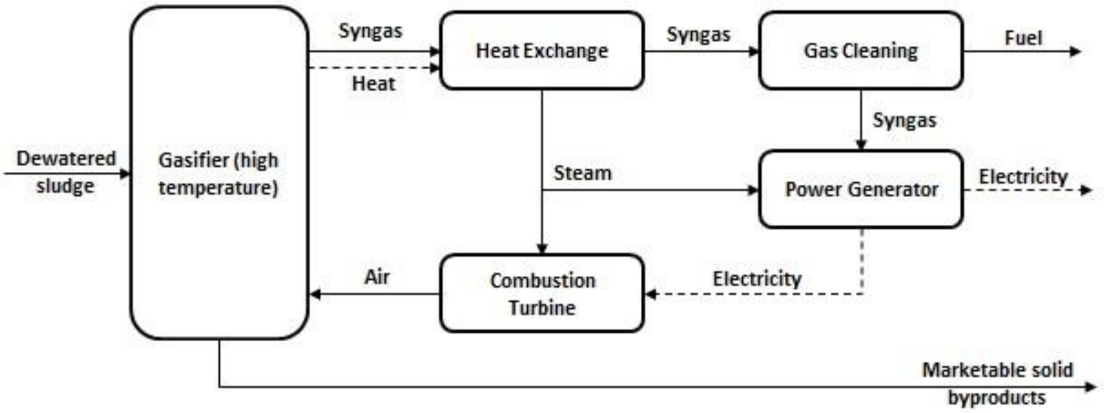

Figure 7: Process of gasification

In sludge gasification, the first step is to feed mechanically dewatered sludge into the gasifier. Then numerous reactions take place in the reduction zone of the gasifier under the condition of high temperature. However, the overall process can be described by the following three reactions (Bresters 1997):

$$C + CO_2 \rightarrow 2CO \tag{6}$$

$$C + H_2O \rightarrow CO + H_2 \tag{7}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{8}$$

The produced heat in combustion can be reused to heat steam for supporting the combustion turbine. Moreover, the resulting syngas is itself a fuel which can be considered as a source of renewable energy (Williams 2005).

Nevertheless, since the composition of the sludge varies greatly, the quality and quantity of syngas from gasification will also vary to a great extent. This is the biggest disadvantage of reusing syngas.

2.2.8 Wet Oxidation

Wet oxidation is a hydrothermal treatment. It is the oxidation of dissolved or suspended components in sewage sludge by using oxygen as the oxidizer. It is also referred to wet air oxidation when air is used. The oxidation reactions occur in superheated water at a temperature above the normal boiling point of water which is 100 ° C, but below the critical point which is 374 ° C (Luck 1999). The general process of sludge wet oxidation is shown by Figure 8 (BERTRAMS 2014).

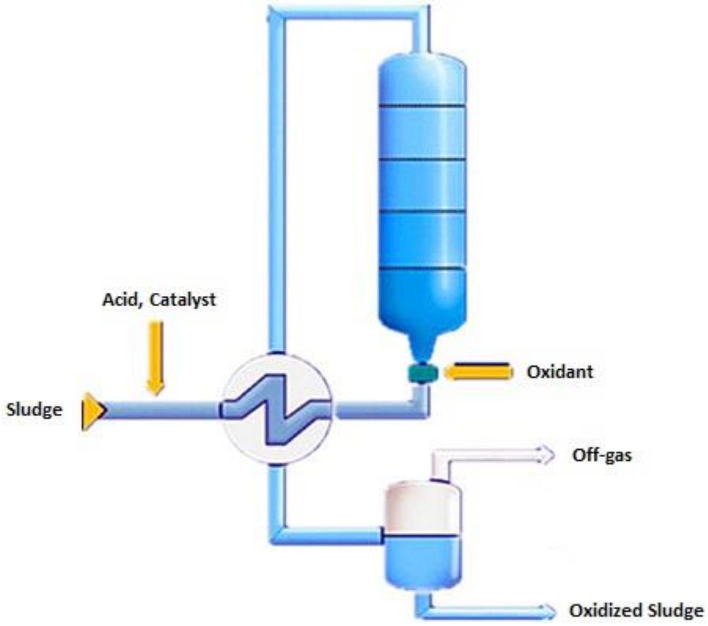

Figure 8: Process of wet oxidation

The organic components of sludge are oxidized in a specific reactor at temperatures of between 200 ℃ and 300 ℃ and at pressure levels of between 30 bar and 150 bar (Bresters 1997).

The main output of the process is oxidized sludge containing more than 95% of the original mineral components and less than 3% of the low-molecular organic substances (Baily 2009). The oxidized sludge can be dewatered and then recycled or landfilled. The filtration water is rich of ammonia, so it needs to be cleaned locally or sent to WWTP.

2.2.9 Land application

The purpose of using sludge on land is partly to utilize nutrients for plant growth, and partly to utilize organic substances for soil amending (Bresters 1997). Land application is a post-treatment of the sludge treatment system just like landfill, but the difference that it reuses the value of sludge, and it is usually in agriculture, forestry, urban green area and energy crops.

In theory, any type of sludge can be spread on land if it fulfils the quality requirements regarding heavy metals, pathogens, pretreatment, etc. Most often, the allowable amounts of sludge to be spread are controlled by explicit criteria according to their amount of nutrients and total amount of dry solids (Fytili and Zabaniotou 2008).

The advantage of land application that is it improves the resource recovery efficiency of a sludge treatment system by reusing the nutrients and organic components are contained in sludge.

2.2.10 Summary

A great advantage of drying sewage sludge is that it can greatly reduce the volume of sludge and simultaneously produce marketable products for land application such as fertilizers and soil conditioners. However, the use of dried sludge on land is restricted by legislation related to the content of harmful substances due to the concern of environment and public health. So for the time being, it is preferred as pre-treatment of SSRS.

Landfill is often considered as an economical method of handling sludge, so it is widely applied in developing countries. Nevertheless, it has become more and more expensive in developed countries, because of increasing legal restrictions and facilities investment recently.

Besides, the recycling value of sludge usually cannot be captured through landfilling unless it installs a gas collection system. Therefore landfilling sludge is given less and less priority in developed countries.

Incineration of sewage sludge can extremely reduce the volume of sludge and its harmful substances due to the high temperature in the incinerator. It also produces marketable product such as inert material for construction. However, the capital-intensive investment and the high energy cost compared to other techniques have become problems. Additionally, the high energy consumption also limits technologies like drying and wet oxidation.

The advantage of composting is that it produces a stable and marketable product for land application, due to the stabilization process. When compared to incineration, composting can utilize the nutritional value of sludge, and its products such as fertilizers and soil conditioner have a higher economic value than ash.

The advantage of anaerobic digestion mainly depends on its energy product – biogas, which is a product with high monetary value. Biogas can be directly used in CHP plant, the recovered heat and electricity then can replace the operation energy, or be integrated in the power grid. Another option is to upgrade biogas into biomethane for further use such as vehicle fuel. In addition, the digestate can be reused as fertilizers or soil conditioners just like compost, but their relative effects are different.

The advantage of gasification is that the high-temperature process refines out environmentally harmful substances and corrosive elements (e.g. chloride and potassium). However, the high-temperature requires more complex equipment and adds risk, and the produced syngas may be difficult to process due to its varying composition.

The advantage of land application is it reuses the nutritional value of sludge. But due to the heavy metal components are tend to accumulated in compost and digestate, land application is restrict by law, especially when it relates to agricultural application.

Depending on the features of technology (from resource and environmental perspectives), the rational and mature technology configurations for SSRS are drying, incineration, landfill, composting, anaerobic digestion and land application. The selection of sewage sludge treatment options is a comprehensive affair. Decision makers should consider multiple elements referring to actual conditions, not only the performance of technologies but also the development levels and the local legislation.

2.3 Sewage Sludge Management Worldwide

It is widely recognized that the management of sewage sludge has become one of the most important issues in wastewater management, due to the very fast increase in sludge generation as a result of sewerage extension, new installations and upgrading of facilities (Spinosa 2008). Sludge is generated under different social, economic and technical contexts, consequently the managements of sewage sludge differs throughout the world.

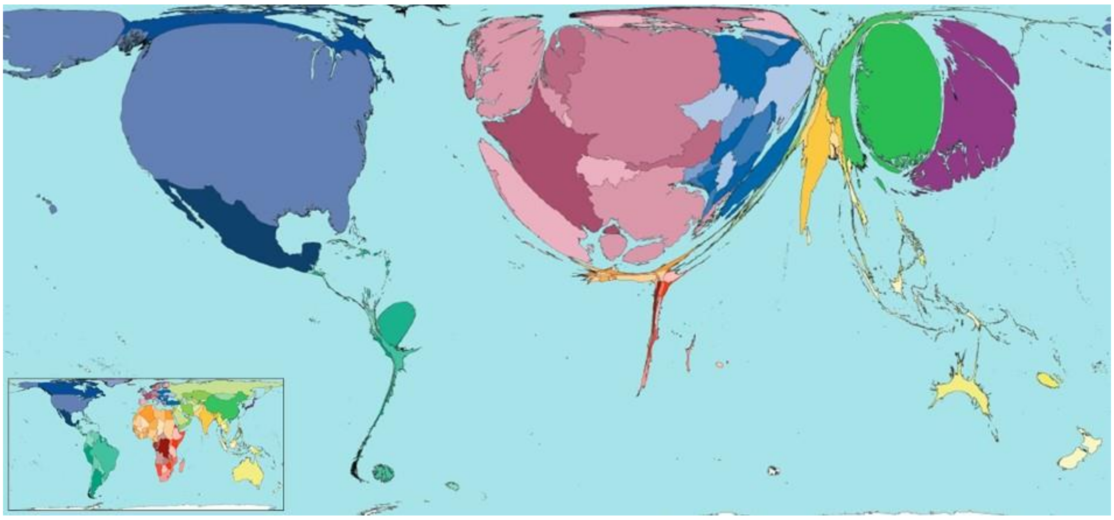

Figure 9: Distribution of global sludge production

The distribution of global sludge production is shown by Figure 9 (Poliakov 2005) which illustrates that sludge is primarily produced in 3 regions, Europe, North America and East Asia.

2.3.1 Africa

In this continent, with an exception of South Africa where sludge generated from over 900 WWTPs is treated by a variety of traditional technologies, and according to various guidelines and regulations (Spinosa 2008), there is lack of attention placed upon on sewage sludge management, even on wastewater management. This state is mostly due to lack of regulations and economic support. Sludge is often simply sent to landfill with municipal solid waste (MSW), or directly discharged to the environment.

A task of top priority for the most of African countries is to complete their wastewater treatment systems first, and then establish their sludge treatment systems as soon as possible afterwards.

2.3.2 South America

Brazil, Argentina, Peru and Colombia can be considered as four of the most representative countries on this continent, because they have the highest wastewater treatment coverage, and they are among the first countries to deal with challenge of sludge management (Spinosa 2011).

In Brazil as a result of democratization and the implementation of collection systems and treatment processes, a growing volume of complex residues has formed. Reflecting this fact, new management and disposal problems are slowly emerged. Although Brazil is one of the first countries to focus on this issue, only 27.2% of the collected sewage was treated in a suitable way. It means that Brazilians still have a long way to march, if they want to cover all sludge (Spinosa 2011). Argentina, Peru and Colombia are in the same situation with respect to sludge management (LeBlanc, Matthews et al. 2006).

All in all, the South American countries’ efforts on sanitation have concentrated on wastewater treatment, while little priority has been given to sewage sludge management in practice (Spinosa 2008). In fact, this is reflection of the shortage of legal bases and basic facilities. Hence, South American countries should put their efforts into developing adapted legislations and applying appropriate low cost methods to ensure full scope of sludge treatment. Based on the importance of agriculture in South America, as well as the degree of soil erosion, composting combined with land application may be considered as the best management option (Spinosa 2011).

2.3.3 Southeast Asia

In this region, the situation is highly differentiated. The range of population and development level for countries in Southeast Asia is wide. Consequently, approaches to sludge management extend over a similar range of extremes.

The existing sewerage system in Cambodia is in a poor situation of disrepair and is limited to the town area only. Specialized sludge treatment is rare in Cambodia (Spinosa 2011).

On the contrary, in this region Singapore is served by a well-designed centralized sewage treatment system. The sludge produced from WWTPs goes to anaerobic digesters and the biogas produced from the digestion is reused as fuel for thermal dryers to dry sludge. The dried sludge is currently incinerated and the ash is disposed of at Pulau Semakau Landfill Site (Spinosa 2011).

2.3.4 China

The land application is currently the favored option for sludge management in China, due to the disposal cost and environmental benefits. About 45% and 3.5% of sludge is applied to agriculture and gardening, after being treated by digestion and dewatering processes. For example, in Shanghai, the treated sludge is usually applied to the soils of the outskirts or of a neighboring province (He, Lv et al. 2007).

Land application is followed in preference by landfilling. Approximately 34.4% of sludge is disposed in landfill, the sludge is usually disposed with MSW (He, Lv et al. 2007). About 3.5% of sludge is treated by incineration. There is only one exclusive sludge incinerator located in the Shidongkou WWTP of Shanghai with capacity of 220 tons dried sludge per day, and the processes comprise thickening, dewatering, fluidized bed drying and then fluidized bed incineration (He, Lv et al. 2007).

In China, the development of wastewater sludge handling systems is unbalanced in different areas. Most of efforts to improve sludge treatment systems have concentrated in big cities. Nevertheless, a few attentions have been paid on cities in middle and small scale. Therefore, it seems that China should quickly balance its development of sludge treatment system in different areas, in order to cover all areas and prevent the negative impacts of unbalance such as pollution transportation.

2.3.5 Japan and South Korea

Japan and South Korea are two developed countries in East Asia, but despite being neighbors, they present a particularly major contrast in sewage sludge management.

In Japan approximately 70% of sludge is treated by incineration after being thickened and dewatered. Although landfill is a main disposal method, it has decreased in recent years. In a word, Japan opts for the highest technological approaches, but with problems of higher energy costs (Spinosa 2011).

On the other hand, South Korea had dumped most of its sludge (68.5%) into the ocean until 2012 when local legislation closed this disposal route (Spinosa 2008). Currently, the pressure of handing sludge mostly shifts from ocean dump to landfill and SSRS. About 53% of sludge ends up in landfill, 22.5% is incinerated, and the rest is treated by other recovery processes such as composting (Spinosa 2011).

2.3.6 Australia and New Zealand

Sludge management is referred to as biosolids management in this region. Australia is a highly urbanized nation, and produces approximately 300,000 tons of biosolids on a dry basis annually (Darvodelsky 2010). The most common use of biosolids is land application, furthermore water businesses throughout the country historically tended to stockpile sludge as a means of reducing costs. For example, Victoria State alone has a stockpile of 62,051 tons of dry biosolids annually (LeBlanc, Matthews et al. 2006). Landfilling is not considered a beneficial use of biosolids and only counts 3% of total biosolids treatment.

In New Zealand, most of domestic and commercial wastewater is treated at one of 320 WWTPs. In total 234,112 tons of sewage sludge are generated per year, of which, 116,380 tons are diverted to land application, 79,440 tons disposed of in landfill, 36,817 tons diverted to other beneficial use, 875 tons diverted to pond, and 600 tons diverted to forest (LeBlanc, Matthews et al. 2006).

2.3.7 USA

In USA, sludge management is referred as biosolids management as well. In 2004, about 6,514,000 tons (7,180,000 dry USA tons) of biosolids were beneficially used or disposed of in the fifty states according to data compiled from state regulatory agencies, approximately 55% of which was applied to soils for agronomic, land restoration and silviculture purposes, or was likely stored for such uses. The remaining 45% was disposed of in MSW landfills, surface disposal units, and incineration plants (NEBRA 2007).

The broad perspective on biosolids management has changed little in USA in recent years. The required biosolids treatment practices, processes, and properties are still essentially unchanged from the 1993's regulations part 258 (for landfill) and part 503 (for surface disposal, land application and incineration). The regulations designate three levels of pathogen treatment which are Exceptional Quality, Class A and Class B. Sludge classified as

Exceptional Quality and Class A can be used without restrictions; less strict requirement on sludge treatment apply to sludge classified as Class B, which must only be used on certain sites (Bresters 1997). For purposes of land application, the Exceptional Quality, Class A and Class B definitions are well established, in spite of ongoing controversy.

Future trend in USA biosolids management is toward greater public awareness and, of course, its consequences. The greater public awareness may lead to more stringent limits on some contaminants and the addition of others.

2.3.8 Norway

More than 90 % of Norwegian sludge is used for land application as a soil amendment product where about one-third goes to parks, sports fields, roadsides, the top cover of landfills, and other two-thirds goes to arable land within the agricultural sector (Eriksen 2009).

Applying sludge on arable land is considered by the Norwegian authority to be the most socioeconomically acceptable and cost effective utilization of the sludge. Although Norway uses a large portion of its sludge for agriculture, it has one of the strictest limitations on heavy metals in sludge products (Table 5), in order to ensure the health of public and environment.

Table 5: Different heavy metals limitations for sludge products

Item	Directive 86/278/EEC	France	Sweden	Norway
	(Range mg/kg DM)			
Zn	2500-4000	3000	800	150
Cu	1000-1750	1000	600	50
Ni	300-400	200	50	30
Cd	20-40	20	2	1
Pb	750-1200	800	100	50
Cr	-	1000	100	100
Hg	16-25	10	2.5	1

There are many ongoing experiments and pilots making synthetic fuel from sewage sludge and organic waste. In order to increase the production of biogas for energy purpose, it is becoming more common to co-digest sludge with other organic waste such as food. Co-digestion not only leads to a lower metal content, but also higher nutrient content, which may be more desirable for farmers (Eriksen 2009).

2.3.9 European Union

Legislation of the European Union (EU) does not usually operate directly in member states but set out standards and procedures that are then implemented by the member states via their own legislative systems. Sometimes the differences can be very distinctive, for example, sewage sludge use in agriculture varies from less than 10% in Sweden to approximately 70% in Spain (Spinosa 2008).

Land application seems to be the major option for western members of EU for many years. For example, in England and Wales disposal by dumping at sea, which previously accounted for about one quarter of production, was banned in 1998 (Inglezakis, Zorpas et al. 2012). Recycling to land application then became the main disposal option followed by incineration (Spinosa 2011). However, the declining public acceptance and more stringent limits are becoming a limiting factor of land application. In accordance with EU legislation such as Directive 86/278/EEC, members established limit values of certain heavy metals in sludge products to be used for land.

Landfilling of sewage sludge has significantly decreased in recent years and it is expected to continuously decline. A set of targets for the reduction of biodegradable municipal waste to be landfilled was introduced by EU legislation Directive 99/31/EC (EC 2001).

Nowadays, great attention is given to the recycling of biodegradable wastes within the ideas of “Productification” strategy. Increasingly, countries are showing interest in treatments like composting and anaerobic digestion, and some have already taken steps forward. The map of biogas production in EU is shown by Figure 10.

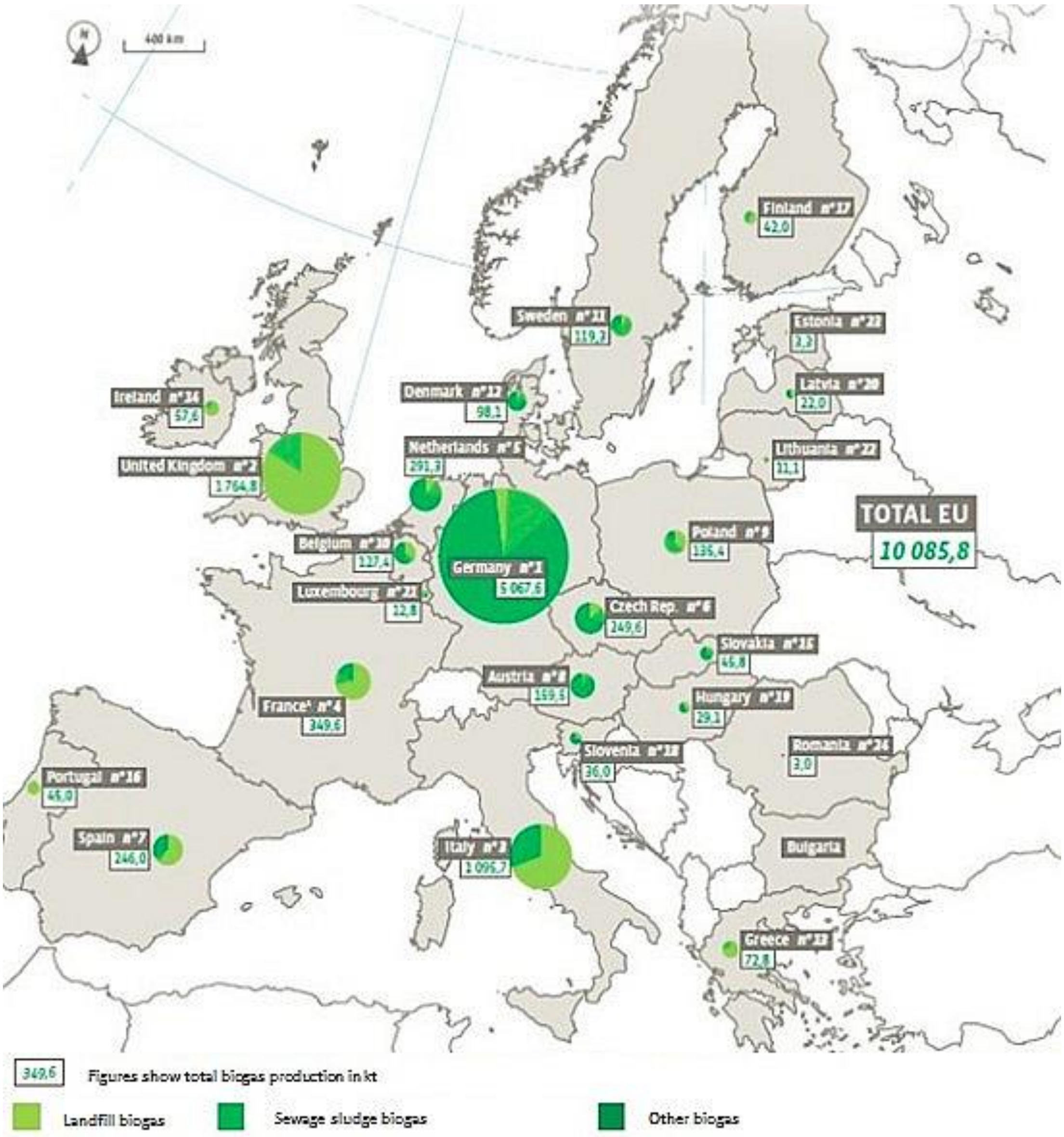

Figure 10: Primary energy production of biogas of EU in 2011 (ktoe)

Germany certainly leads the way in biogas production in Europe with a share of 61% of total production. This corresponded with more than 7,000 biogas plants in 2010. Of these plants, 84% are based on co-digestion of crops and slurry. 54 plants injected upgraded biomethane into the gas grid in 2010, and this number increased to 82 plants in 2011 (Rogers 2012). The total amount of German biogas production reached 5,067,000 toe in 2011, biogas generated from wastewater sludge contributed about one-sixth of total value (EurObserv'ER 2011).

Germany is followed by the United Kingdom with 1,764,000 toe of biogas production in 2011

(EurObserv'ER 2011). Landfill with gas collection is the main feedstock in the UK with a share of 84.6% of total production (Rogers 2012). Since 2008, the number of anaerobic digestion plants based on farm and food waste has shown a steep increase, but is still at an early stage.

In recent years, many eastern European countries have become members of the EU. In this area, sludge management is in a period of rapid change in line with the construction of WWTPs, because the new eastern members are obliged to harmonize their legislation and operational systems with the EU (Spinosa 2011). As a result of legislative changes, the amount of landfilled sludge in eastern counties will decrease, while a slow increase in the market share of recovery technologies, such as incineration or other biological treatment methods, can be expected.

For example, In Poland the total amount of sewage sludge production was 612,800 tons in 2010. The value is estimated to reach 706,700 tons by 2018 according to National Waste Management Plan (Werle and Wilk 2010). The dominant method for the disposal of sludge is storage and land application. But from January 2013, Polish legislation started to ban storage of low grade sludge, thus the sludge treatment route is going to gradually shift to other alternatives. The major consequence of this implementation is that large pressure has been put on the development of thermal treatment of sludge. Based on a forecast from the National Waste Management Plan, the proportion of thermal treatment in Polish sludge management will increase from 12% in 2010 to 59% by 2018 (Werle and Wilk 2010).

2.3.10 Summary

According to the review of global sewage sludge management, the sludge management basically can be classified in three different levels including undeveloped, developing and developed.

In most of Africa and parts of Asia and South America, wastewater treatment systems, are minimal or function poorly, sludge treatment systems barely exist, and basic sanitation is the focus.

In Eastern Europe, South America, and other areas, wastewater treatment has advanced, but wastewater sludge management is only now becoming increasingly important, and more complex regulatory structures are being developed.

In Europe, North America, Australia and Japan there is more focus on how to improve the management of sewage sludge or biosolids. In these places, wastewater is generally treated at the secondary level, in some cases at the tertiary level, and sludge recovery technologies and regulations are advanced. Especially in the EU, diverse professionals, engineers, scientists, agricultural experts, and government regulators are refining ways to improve efficiencies, maximize utilization of beneficial aspects, and reduce potential impacts of managing sludge.

All in all, the SSRS is mainly carried out by countries at a developed level, due to comprehensive reasons relating technology, economy and society.

2.4 Performance of sludge recovery system

The studies of sewage sludge treatment seem to focus on the research of environmental impacts. The studies on resource (nutrients and energy) efficiency of SSRS are relatively fewer. Especially for nutrients recovery efficiency, the available information is mainly the individually measured nutrient contents in sludge, composting or digestate, but there is lack of systematic analysis of nutrients recovery efficiency in SSRS.

2.4.1 Research results from previous studies

For nutrients recovery efficiency, Hospido, et al. concluded that thermal processes can be a good option for sludge recovery, but more efforts are needed to improve the valuable, and viable products, as nutrients are lost during the process (Hospido, Moreira et al. 2005).

Sommer has reported that most of the nitrogen loss in composting is due to hydro nitrogen volatilization. Additionally, he pointed out that the nutrients recovery efficiency of composting deep litter is about 41% for nitrogen, and 60% for phosphorus (Sommer 2001).

For energy recovery efficiency, Poschi, et al. reported that the primary energy input to output rate (energy recovery efficiency) corresponds to 34.1–55.0% for feedstock co-digestion in their study (Pöschl, Ward et al. 2010).

For environmental impacts, Suh and Rousseaux stated that the combination of anaerobic digestion and land application is the most environmentally friendly option in their study, and the most important substances contributed to HTP are heavy metals (Suh and Rousseaux 2002). Houillon and Jolliet found that approximately 100% of heavy metals are transferred to soil, water and air for their agricultural scenario, and thermic oxidation processes result in a heavy metals transfer of about 30% (Houillon and Jolliet 2005). Lundin, et al. concluded that agricultural application is a cost-effective solution that is beneficial to soil, but for large industrial cities where the quality of sludge is questionable, energy recovery combined with non-arable land ppplication is a better alternative (Lundin, 2004). Hong, et al. reported that digestion, landfill, drying and incineration processes have a high contribution to GWP; agricultural application, composting and drying have a high contribution to AP; agricultural application has the highest contribution to HTP which is corresponds to Suh and Rousseaux. Moreover, the economic benefit sequence of SSRS is of anaerobic digestion is larger than for composting, and composting is bigger than incineration (Hong, Hong et al. 2009). Righi and Oliviero summarized that transportation is largely the most impacting process for AP, GWP and POCP, and it also has a relevant contribution for EP and ODP in their study (Righi, Oliviero et al. 2013).

2.4.2 Summary from previous studies

The environmental impacts of sewage sludge treatment have been extensively studied using LCA.

Suh and Rousseaux had carried out an LCA comparing the environmental impacts of five alternative technologies including composting, anaerobic digestion, land application, incineration, and landfill (Suh and Rousseaux 2002). Nevertheless, they only focused on the relative environmental impacts. Houillon and Jolliet analyzed in detail the GWP of six technologies which were agricultural application, cement production, wet oxidation, incineration, melting of dried sludge and landfill (Houillon and Jolliet 2005). However, no other environmental impact is reported. Hospido, et al. reported a more detailed study, evaluating nearly all environmental impacts of three scenarios which were land application, incineration and melting of dried sludge (Hospido, Moreira et al. 2005). However, they did not include biochemical technologies like composting and anaerobic digestion, which are receive more and more attentions nowadays due to their marketable products. Similarly, Lundin, et al. reported four scenarios in detail, but they also did not any include biochemical technology in their study (Lundin, 2004). Hong, et al. went further, they reported an LCA estimating the environmental and economic impacts of six scenarios most often used in Japan, which are dewatering, composting, drying, incineration, incinerated ash melting and dewatered sludge melting (Hong, Hong et al. 2009). Although they add an economic analysis, they did not consider the situation that biogas can be upgraded to biomethane for vehicle use. In addition, none of them mentioned information related to nutrients recovery efficiency within the LCA; there is lack of information regarding comparison of energy recovery efficiency between technologies.

Accordingly, an improved assessment in this field requires that the following be addressed:

1) Biochemical technologies with recovery capacity (composting and anaerobic digestion) need to be focused on.
2) The scenario of anaerobic digestion combined with biogas upgrading needs to be described.
3) The analysis of nutrients recovery efficiency needs to be carried out.
4) The analysis of energy recovery efficiency needs to be carried out.

The comprehensive study with respect to resource recovery efficiency and environmental impacts is supposed to reflect the performances of SSRS better. Therefore, it is of value to carry out such an integrated MFA and LCA study for SSRS.

3 Methodology

3.1 Environmental system analysis

"A systems analysis commonly focuses on a problem arising from interactions among elements in society, enterprises and the environment; considers various responses to this problem; and supplies evidence about the consequences-good, bad and indifferent-of these responses" (Miser and Quade 1995).

A system analysis is a method used for studying the relations between elements within a system, and other elements or processes related to the system, in order to understand the system better. The purpose of a system analysis is to understand the systems' strengths and weaknesses, and find its improvement potential. System analysis is in most cases to estimate the effects of a certain change, as a basis for decision making, before doing large costly changes in real life (Øyen 2007). It is desirable that the simulation is as close to the real life situation as possible.

A waste management system usually includes the collection, transportation and treatment from waste, from where is produced to how it is treated and disposed of. A waste management system analysis is a way of researching the efficiency, impact and possibilities of handling waste, in order to find the optimal possible combination of the different parts of the system. The main challenge of carrying out such an analysis lies in the design of the system and the choice of performance indicators, for instance, efficient, environmental, and financial (Øyen 2007).

There are different tools for studying waste management. They vary with respect to how they emphasize different performance indicators, and also on design aspects like time, geographic boundaries, etc. Tools may also vary depending on their different purposes such as documentation, improvement, and decision making. It is essential to use a model that provides answers to the questions posed in a given study (Øyen 2007).

Two important system analysis tools for waste management applied in this study were:

1) Material Flows Analysis (MFA)
2) Life Cycle Assessment (LCA)

3.2 Material Flow Analysis

MFA is a systematic assessment of the flows and stocks within a system defined in space and time, it connects the sources, the pathways, and the intermediate and final sinks of material (Hendriks, Obernosterer et al. 2000). Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of a process. This feature of MFA makes it attractive as a decision-support tool in resource management, waste management, and environmental management.

An MFA delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. Through balancing inputs and outputs, the flows of wastes and environmental loadings become visible. The depletion or accumulation of material stocks is identified early enough either to take countermeasures or to promote further buildup and future utilization. Moreover, some important minor changes that are too small to be measured in short time scales but that could slowly lead to long-term damage become obvious through this method (Brunner and Rechberger 2004).

The procedure of MFA contains four main phases (Figure 11) which are problem definition, system definition, determination of flows and stocks, and illustration and interpretation (Brunner and Rechberger 2004).

In general, an MFA begins with the definition of the problem and of adequate goals. Then the system is defined by boundaries in space and time. The relevant processes, goods and substances are defined and linked. Next, mass flows of goods and substance concentrations in these flows are assessed. Substance flows and stocks are quantified, and uncertainties are considered. Finally, the results are presented in an appropriate way to visualize conclusions and to facilitate implementation of goal-oriented decisions (Hendriks, Obernosterer et al. 2000).

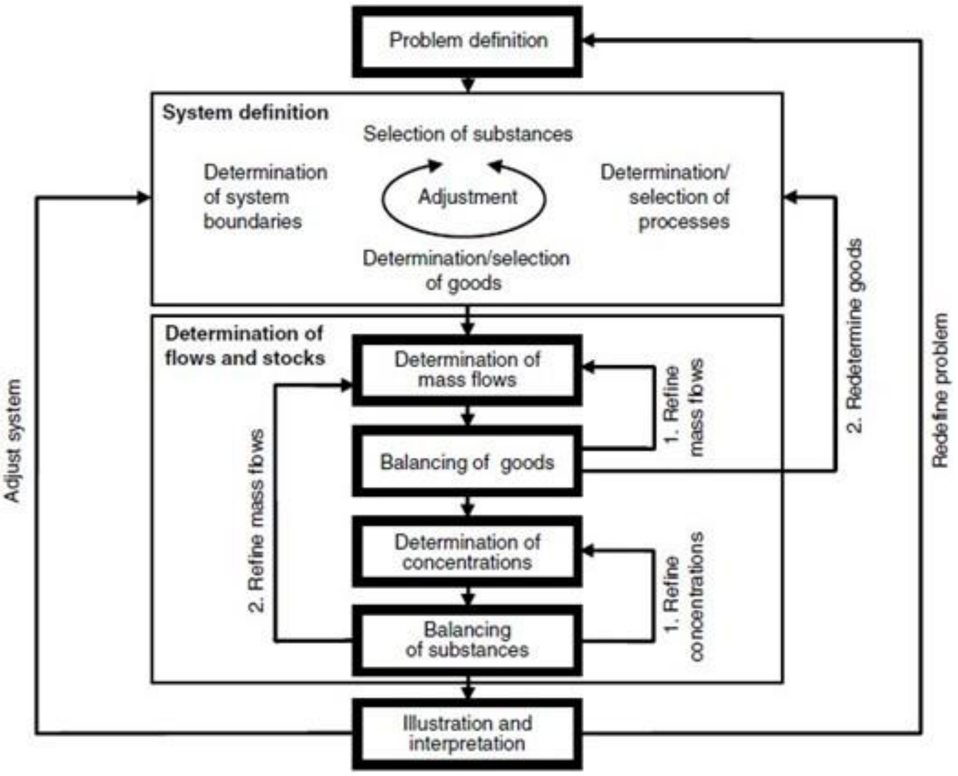

Figure 11: Procedure of MFA

It is significant to note that this procedure must not be executed in a strictly consecutive way. The procedure needs to be optimized iteratively. The provisions and selections that are taken during the course of the MFA need to be checked continuously. If necessary, they must be adapted to accommodate the objectives of the project. Generally, it is better to start with rough estimations and provisional data, and then to constantly improve and refine the system and data until the required quality has been achieved (Brunner and Rechberger 2004).

3.3 Life Cycle Assessment

LCA is defined, in ISO 14040, as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO 2010). It is a tool for the analysis of the environmental burden of product at all stages in its life cycle, from the extraction of resources, through the production of a product, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal (Guinée 2002). Like MFA, LCA is also an attractive decision-support tool in resource management, waste management, and environmental management.

The goal of an LCA is to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes and emissions released to the environment, and to evaluate opportunities to achieve environmental improvements (Schepelmann 2003).

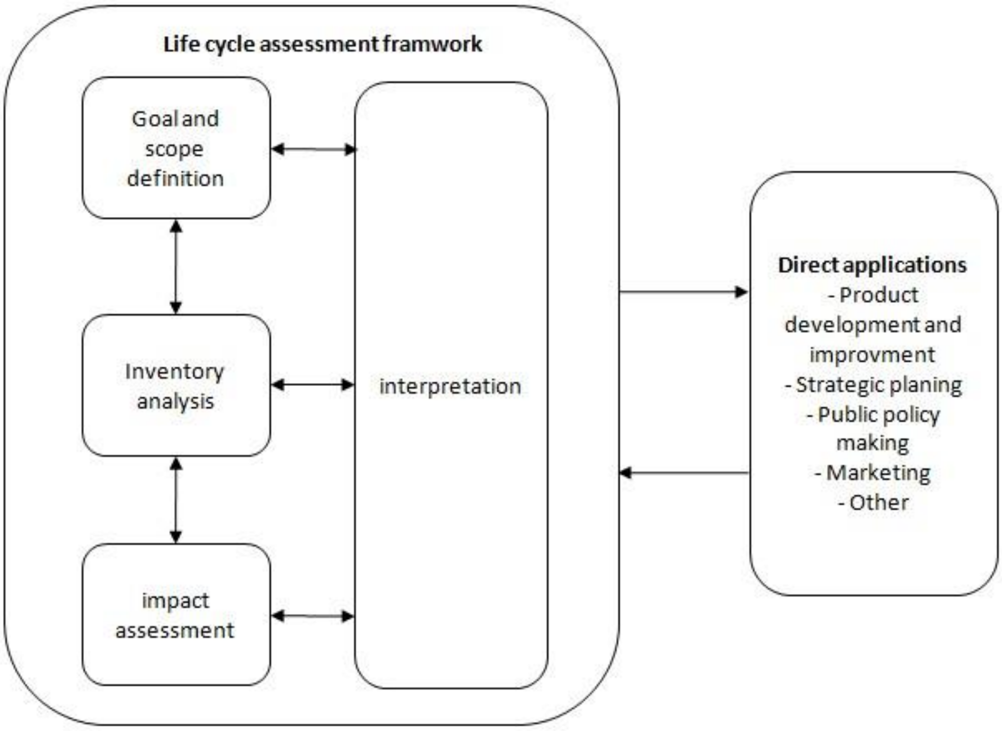

Figure 12: Framework of LCA

The framework of LCA contains 4 main stages (Figure 12) which are goal and scope definition, inventory analysis, impact assessment, and interpretation.

In order to start a LCA, it is important to know the purpose of the study. Goal and scope definition identifies the intended use, assumptions and limitations, the function of the product system and the functional unit (FU) (Guinée 2002). Then the inventory analysis need to be carried out through collection of data and calculations, in this stage all meaningful input and output factors from all the activities in the system are quantified (Schepelmann 2003). Next, understand and evaluate the results from inventory analysis by impact analysis which may involve classification, characterization, normalization, grouping and weighting (Gutierrez 2006). The last stage of the LCA is interpretation, in this stage the result from the inventory analysis and impact assessment is connected to the problem being addressed, in order to make conclusions and recommendations. Furthermore, the quality of the data needs to be revalued in a sensibility analysis, for the sake of ensuring the quality of result. (Øyen 2007).

It is important to note that for many substances there is little or no data available. An LCA often uses heterogeneous data from different sources. The necessary estimations and adjustment hold certain errors. Some large errors are possible in the classification of LCA results. Moreover, the valuation step is vague, due to being based on fuzzy models. Every model can leads to a different value. Thus a careful consideration of imprecision and uncertainties in LCA is necessary (Schepelmann 2003).

3.4 Principles for Generic Modelling of Sludge Recovery System

A generic model was built to analyse the profile and framework of SSRS. The model only focuses on qualitative analysis aiming to describe how the SSRS works without quantification.

In this model, important factors such as substances and processes were identified, and general system boundary was defined. Depending on the relationships and interactions between these factors, they can be connected orderly, forming a completely generic system.

According to the above literature study, SSRS can be divided into three sections (Figure 13), pre-treatment, main treatment and post-treatment.

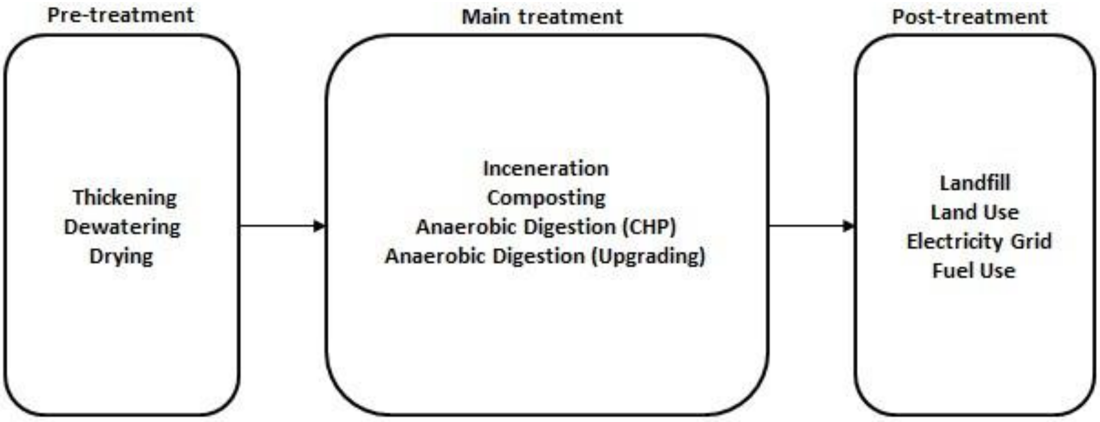

Figure 13: Different sections of sludge recovery system

The purpose of pre-treatment is to remove water from raw sludge which comes from WWTP. It usually concludes technologies like thickening, dewatering and drying. With an exception of thermally dried sludge, the thickened and dewatered sludge should not be directly used on land application and landfill, because they never go through any deep stabilization process, and they still contain many undecomposed substances which are harmful such as virus, bacterium, fungus and parasites. Therefore, unlike drying (pre-treatment, sometimes main treatment), thickening and dewatering are only preferred as pre-treatments of SSRS. Thickening and dewatering can reduce sludge’s water content to a certain degree, consequently the volume of sludge is reduced as well. For example, the water content of raw sludge is about 99%, after thickening and dewatering, it falls to 80% (Hong, Hong et al. 2009). That means sludge which contains 1 ton dry matter, after thickening and dewatering the total weight decreases from 100 tons to 5 tons, in total 95 tons of water is removed and sent to sewer. Hence, this water removal efficiency is enough to satisfy processes like composting and anaerobic digestion, and can reduce the difficulty and cost of later treatments.

As mentioned, to date the most applied and mature main treatments with obvious recovery capacities are incineration, composting and anaerobic digestion.

Among these technologies, incineration is the most efficient way for water removal, after this process the water content of incinerated ash and melted slag drops to nearly 0% (Hong, Hong et al. 2009). Moreover the solid residuals can be used as materials in construction (e.g. road and building). Incineration of organic waste including sludge is practiced in the EU and Japan. From an empirical perspective, the main disadvantages are negative impacts on the environment from airborne emissions, relatively high energy consumption in the operation phase (including drying of sludge) and high monetary investment (Suh and Rousseaux 2002).

Composting of sludge occurs in the presence of oxygen. Composting decomposes organic substances and stabilizes sludge by aerobic bacteria. Composting has many advantages such as reducing the fermentation cycle, high stabilization and easy mechanized operation, which make it be widely applied around the world. Furthermore, the solid product of composting can be sold as fertilizer or soil conditioner in open market. Composting not only reduces the total amount of waste that goes to final disposal, but also creates economic value by following a “Productification” strategy. However the heavy metals contained in compost may be the weak point of its utilization, due to the potential of bioaccumulation.

Anaerobic digestion of sludge occurs in the absence of oxygen. It is a technology to decompose organic substances and stabilize sludge by anaerobic bacteria. It produces two main products. One of them is solid product digestate that can be also used as fertilizer or soil conditioner like compost, another is biogas that can be used as a source of energy. Anaerobic digestion technology is used in many fields such as wastewater treatment, municipal solid waste treatment and new energy development. Countries like Germany have a lot of practical cases in this field.

In addition, there are two categories of configuration of biogas utilization. The first configuration is anaerobic digestion combed with CHP. In this option, the produced biogas from anaerobic digestion is used in an on-site CHP plant to generate heat and electricity, the total energy recovery efficiency can reach to 85% (SGC 2012). The generated heat can support the temperature demand of the plant, and the electricity can be used in the national grid. The second configuration is anaerobic digestion combined with biogas upgrading. The biogas generally contains 40% of carbon dioxide, 60% of methane (in volume), and nitrogen sometimes. The calorific value of biogas is about 5.9 kWh/kg, it is lower than vehicle fuel (e.g. diesel, 11.78 kWh/kg) (SGC 2012). So the biogas needs additional treatment to increase its calorific value, when it is used for vehicle. In fact, upgrading is the process which removes the carbon dioxide and sometimes nitrogen in biogas. After this process, the content of methane in biomethane increases to 97% (in volume), and the calorific value climbs to about 14.43 kWh/kg (SGC 2012). As a fuel, biomethane can be sold at a profitable price on open market compared to other fuels such as diesel. It seems that anaerobic digestion produces high economic value, but its solid product digestate may be also restricted by heavy metal components.

Post-treatment is the last phase of handing sludge, it often includes landfill, land application and energy use, and material use. Usually landfilling is used to dispose of undesirable solid waste from incineration. However in Singapore, there is no farmland and very limited green area due to its tiny territory. Therefore after anaerobic digestion, all digestate is disposed of in landfill. The case of Singapore is a special one. For other places, due to the products of SSRS have utilization value. Land application, energy use and material use should be considered in rational and appropriate ways in SSRS.

The establishment of a system boundary is based on the goal and scope and data of a research question. In this context, the boundary starts from raw sludge that is input into pre-treatment, through different main treatment, and ends at post-treatment. Furthermore, the geographic boundary can be at different levels such as global, national, regional and local level. But in this generic model, the geographic boundary is undefined.

Based on the important substances, processes and system boundary, the generic system is formed and connected (Figure 14).

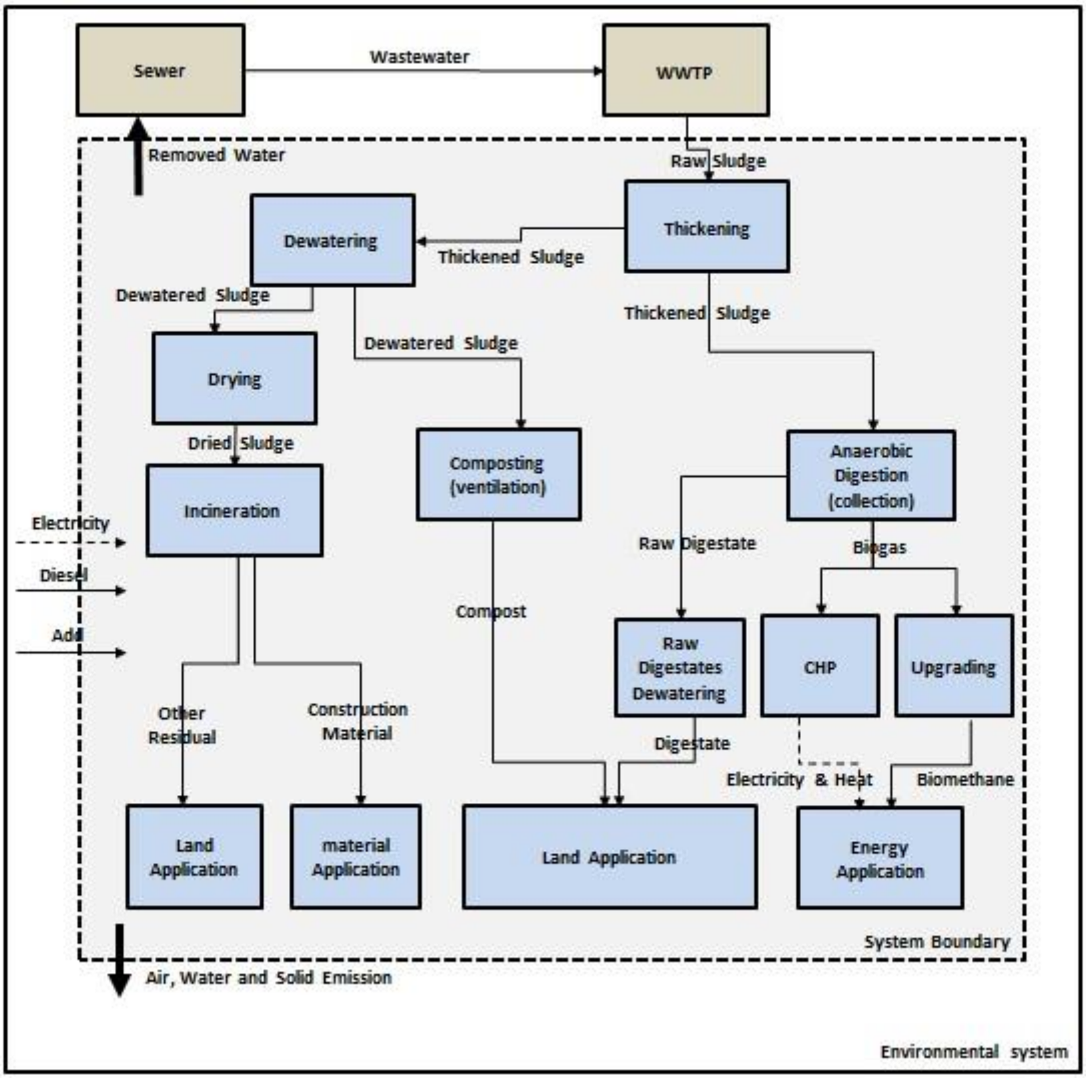

Figure 14: Generic model of sludge recovery system

4 Results from Specific Modeling of Sludge Recovery System

4.1 Case Study – The European Union (EU)

Due to the source availability and the quality of data, this study uses the EU as a case region. Following “Productification” strategy, sludge recovery technologies such as incineration, composting and anaerobic digestion have attracted more and more attention in sludge management. Nevertheless, the incineration of sludge is restricted by its capital-intensive investment and relatively high energy consumption due to the evaporation of water. For example, in main treatment phase, the energy consumption of incineration is about 3 times larger than composting, and 4 times larger than anaerobic digestion (Hospido, Moreira et al. 2005) (Suh and Rousseaux 2002). In order to avoid high energy consumption, EU countries have begun to prefer composting and anaerobic digestion. In recent years, plenty of theoretical research and practical experiments have been carried out to explore the potential of these natural methods. Composting and anaerobic digestion have gradually become the future trends of sludge management.

Furthermore, in order to remain in accordance with the purpose of BioTEnMaRe project, technologies like composting and anaerobic digestion should be the focus in this study. Therefore, excepting incineration, three scenarios are formed as follows:

1) Scenario 1 – the combination of composting and land application
2) Scenario 2 – the combination of anaerobic digestion, land application and CHP
3) Scenario 3 –the combination of anaerobic digestion, land application and biogas upgrading

4.2 Scenarios Descriptions

The first scenario, raw sludge coming from WWTP is inputted into pre-treatment, after thickening and dewatering the wet weight of sludge is greatly reduced to form dewatered sludge. Before the dewatered sludge goes to composting in windrow system, it should be mixed with bulking agent (e.g. woodchips) to increase the C/N ratio to around 30 (246, P. Kosobucki, 2000). Then the bulking agent is recycled in composting through screening process, the recycle rate is about 80% (Finstein, Cirell et al. 1980). In addition, ventilation is very important in composting, it provides ample oxygen for aerobic bacteria and ensures the normal operation runs smoothly. In the sludge composting process, leachate and air are generated; the leachate follows to the sewer send back to WWTP. The main components of the air are carbon dioxide and ammonia, they will directly go to the atmosphere in this scenario. The final output is compost that is comprised of nutrients such as nitrogen and phosphorus. Therefore, it is transported by truck (Euro 5 standard) to the post-treatment stage land application where it can enrich the as fertilizer or soil conditioner.

In Scenario 2, raw sludge is inputted into pre-treatment as well. However, the requirement on water content of anaerobic digestion is lower than composting, so sludge does not need to undergo dewatering. After thickening the water content of thickened sludge decreases to about 96% (Hong, Hong et al. 2009), and is then directly entered into anaerobic digestion. The products of anaerobic digestion are raw digstate and biogas. The raw digestate is sent to raw digestate dewatering to produce digestate for land application. The biogas is collected and sent to the on-site CHP plant for heat and electricity generation. To date the energy recovery rate of CHP plant can reach to about 85% as mentioned previously. The produced heat can support the temperature requirement of plant’s operation, moreover the produced electricity can be used in the national grid to replace traditional electricity source.

In Scenario 3, the processes are the same as Scenario 2 up until the treatment of biogas. Instead of being used in the CHP plant, biogas is sent to the on-site upgrading plant. The biogas generally contains about 60% of methane in volume. After biogas upgrading, the biogas is refined to biomethane, of which most of carbon dioxide, and sometimes nitrogen are removed, the methane content arises to approximately 97%. Due to the high methane content, the calorific value of biomethane is similar to petrol and diesel. Therefore it can be sold in market as a thermal engine fuel. The treatment of digestate in scenario 3 is the same as Scenario 2.

4.3 MFA Modelling

4.3.1 Problem Definition

An MFA usually starts with the definition of the problem and adequate goal. In this context, the problem is the analysis of SSRS. The goal is to calculate the nutrients and energy recovery efficiency of selected scenarios through the quantified systems.

4.3.2 System Definition

Table 6: Flows and stocks of different scenario in MFA

Item	Scenairo 1	Scenairo 2	Scenairo 3
Solid flow	Raw sludge Thickened sludge Dewatered sludge Compost Additive (composting) Polymer	Raw sludge Thickened sludge Dewatered digestat Digestate Polymer -	Raw sludge Thickened sludge Dewatered digestate Digestate Polymer -
Liquid flow	Untreatd Water	Untreatd Water	Untreatd Water
Air flow	Recation oxygen Carbon dioxied Ammonia Water vapour	Biogas Recation oxygen Carbon dioxied Water vapour	Biogas Carbon dioxied Biomethane -
Stock	Compost	Digestate	Digestate

The system should be chosen to be as simple and consistent as possible while still being broad enough to include all necessary processes and material flows. Firstly, the system boundary should be defined. The spatial system boundary is the geographic boundary of the EU in this study. The technical system begins with the raw sludge inflow at pre-treatment and end with the final product goes into post-treatment (including post-treatment). The technical system also separates SSRS from ambient environmental. The processes have been predefined in generic system, so in this stage the important thing is to identify and classify flows and stocks. The important flows and stocks are displayed in Table 6.

4.3.3 Quantification of MFA Mass Flows

The next phase is the determination of these flows and stocks through mass balance and model approach equations (Appendix A). In this stage, a flow chart is established for better understanding of a scenario. The number of processes in each scenario that are necessary to describe the system can be subdivided into sub-processes, or merged into a single process, depending on the situation. The complexity should depend on the goals of the study.

However, before the determination, several assumptions are made to keep the system as simple as possible, which are:

1) Assumption 1, the processes are perfect, there is no unknown substance loss within the processes or between the linkages of the processes.
2) Assumption 2, a few unimportant micro flows are omitted such as polymer in thickening and dewatering, nitrogen oxide and sulfur dioxide emission at CHP.
3) Assumption 3, in order to calculate the maximum nutrients recovery efficiency and energy recovery efficiency, scenarios assume that all compost and digestate are used as fertilizer or soil improver for agricultural purpose.

Based on the above hypothesizes, the system can be quantified, and in addition to the network of the system itself, the interactions between the system and the natural environment can be also visualized.

In Scenario 1, four processes are selected (Figure 15) which are thickening, dewatering, composting and land application respectively. 100,000kg of raw sludge from WWTP (1,000kg of dry mass (DM)) goes into the system, after pre-treatment 5,000kg dewatered sludge is formed and then sent to composting. As a main treatment process, composting requires 645kg of reaction oxygen and in total 1975kg woodchips as bulking agent which is comprised of 395kg raw woodchips and 1580 recycled woodchips. Composting produces 1,785kg compost as desired product, but it also produces undesired substances, for instance, 280kg removed water and 3,975kg air emission including 709kg carbon dioxide, 27kg ammonia and remaining water vapor. Finally the compost is transported to agricultural application and adds to stocks in soil.

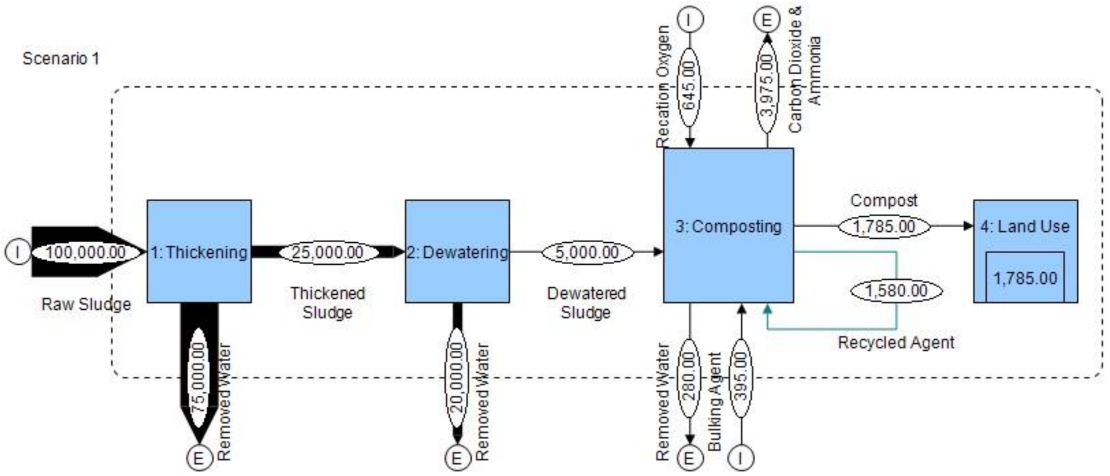

Figure 15: MFA model of Scenario 1

There are five processes be selected in Scenario 2 (Figure 16), they are dewatering, anaerobic digestion, digestate dewatering, land application and CHP.

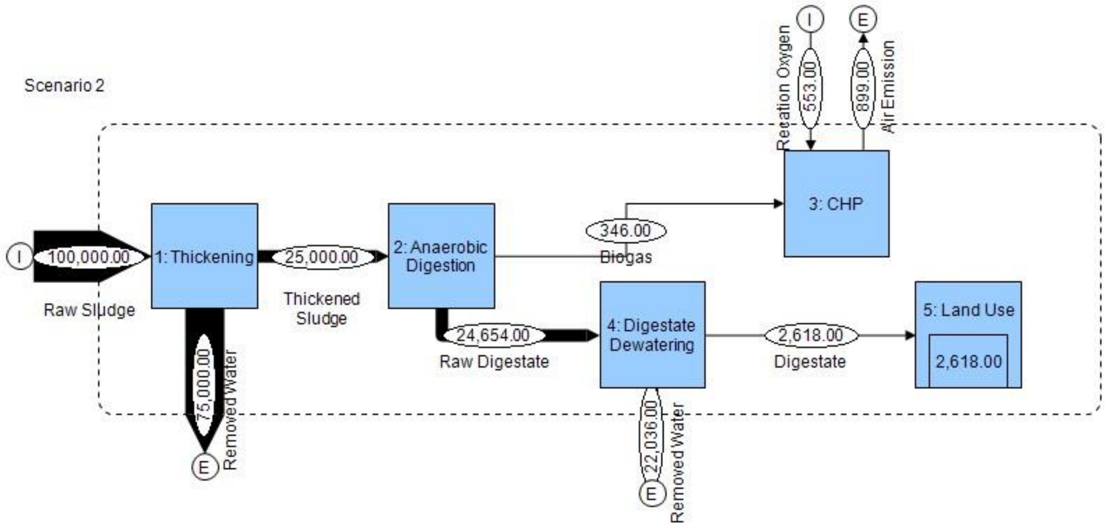

Figure 16: MFA model of Scenario 2

Similar to Scenario 1, there is 100,000kg of raw sludge that goes into pre-treatment. After removing 75,000kg water, 25,000kg thickened sludge is produced. Then it goes into anaerobic digestion and two main products are formed which are 24,654kg of raw digestate and 346kg of biogas. On one hand, raw digestate undergoes further dewatering and forms 2618kg of digestate which is transported and spread on agricultural land. On the other hand, biogas goes into a CHP for energy recovery. Moreover, the CHP produces 899kg of air emissions, mostly carbon dioxide and water vapor after reacting with 553kg oxygen.

Scenario 3 (Figure 17) comprises of six processes, the first four of which are the same as Scenario 2, the difference is that Scenario 3 treat biogas by biogas upgrading and energy use instead of CHP.

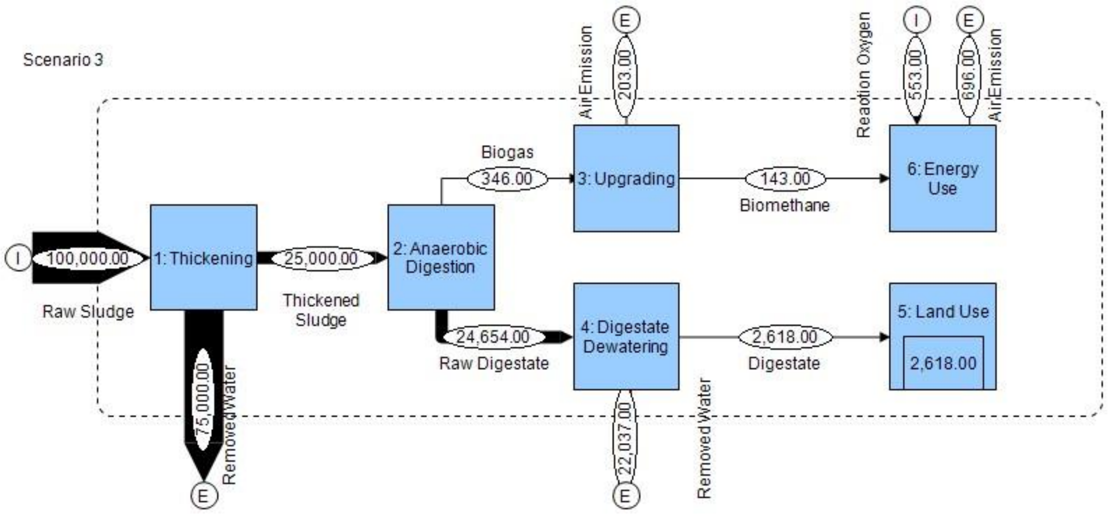

Figure 17: MFA model of Scenario 3

The difference from Scenario 2 is that biogas goes into an upgrading plant instead of CHP plant in Scenario 3. The 346kg of biogas is upgraded to 143kg of biomethane by removing 204kg of CO_2 out. Biomethane is then transported and utilized as vehicle fuel. 143kg of biomethane theoretically requires 553kg of oxygen for its own combustion, and it eventually transfers to 696kg of air emission, which is comprised by CO_2 and water vapor.

4.3.4 Quantification of Nutrients and Energy Recovery Efficiencies

According to the MFA results, the nutrients recovery efficiency and energy recovery efficiency can be calculated as follows:

$$NRE = \frac{NP}{NS} \tag{9}$$

$$ERE = \frac{EP}{ES + EO} \tag{10}$$

NRE represents nutrients recovery efficiency; NP and NS are nutrients in product for agricultural purposes and nutrients in raw sludge respectively. Additionally, ERE on behalf of energy recovery efficiency, EP, ES, and EO correspondingly represent energy content in product for energy use, energy content in raw sludge, and the energy consumption for process operations.

Nitrogen and phosphorus are two of the most common nutrients for plants. In this study, they are selected as indicators for nutrients efficiency. The nitrogen and phosphorus contents in sludge, compost and digestate are illustrated in Table 7 (Appendix A).

Table 7: Nutrients content in sludge, compost and digestate

Item (in DM)	Raw sludge	Compost	Digestate
Total N	3.26%	1.60%	4.00%
Total P	2.00%	1.00%	0.66%

Likewise, energy content in products for energy use and energy content in raw sludge are two important elements for the estimating of energy recovery efficiency. The energy contents in sludge, biogas and biomethane are shown in Table 8 (Appendix A).

Table 8: Energy content in sludge, biogas and biomethane

Item (kWh/kg)	sludge (DM)	Biogas	Biomethane
Energy content	5.32	5.91	13.43

In addition, process operation energy is also an important part in the calculation of energy recovery efficiency, so it should be taken into account. The process operational energy in the three scenarios is shown in Table 9 (Appendix A).

Table 9: Process operation energy of scenarios

Item (kWh/FU)	Scenario 1	Scenario 2	Scenario 3
Thickening	50.00	50.00	50.00
Dewatering	40.00	-	-
Composting	128.95	-	-
Anaerobic digestion	-	88.56	88.56
Digestate dewatering	-	49.09	49.09
Transport	53.40	78.32	82.59
Agricultural application	39.89	67.10	67.10
CHP	-	64.99	-
Upgrading	-		185.95

The benchmark in this study is to treat functional unit (FU) of sewage sludge which is determined as 1,000kg of sludge (in DM). According to FU, the nitrogen, phosphorus and energy recovery efficiency of scenarios are calculated (Figure 18) by using the above two equations.

Scenario 2 and 3 have exactly the same nitrogen and phosphorus efficiencies. This is because they share the same method of producing and using digestate. For nitrogen efficiency, anaerobic digestion reaches about 40% and composting is about 33%. Contrarily, composting has higher phosphorus efficiency which is about 34% compared to anaerobic digestion's 21%.

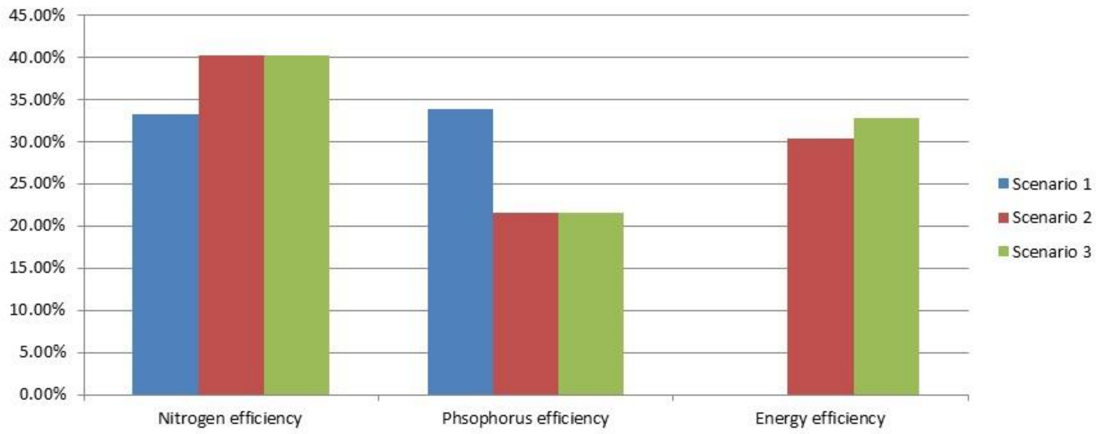

Figure 18: Resource recovery and energy recovery efficiency of scenarios

For energy recovery efficiency, because the only desirable product of composting is compost, it does not produce energy. The energy recovery efficiency of composting is zero. Scenario 3 has a little bit higher energy recovery efficiency which is about 33% compared to Scenario 2 which is about 30%.

4.4 LCA Modelling

The environmental profile and the comparative analysis can be performed using LCA methodology. As mentioned before, according to ISO 14040 LCA methodology comprises four phases, which are goal and scope definition, inventory analysis, impact assessment and interpretation.

4.4.1 Goal and Scope Definition

The goal of this assessment is to examine the three selected scenarios, in order to quantify and compare the environmental performance of SSRS. The FU is the unit of comparison in the Life Cycle Inventory (LCI). Besides, the FU of the LCA is defined as same as it is in the above MFA, which is to treat 1,000kg of sewage sludge in dry base. The scope is established as follows:

1) The construction of different sludge facilities, including machinery and electric

installation, is not considered and only the operation stage is taken into account for the analysis.

2) Since raw sludge is selected as the starting point of this study, the operation of the WWTP is not considered. The utilizations of final products are selected as the end points.
3) The spatial boundary is the territorial boundary of the EU.

In addition before the inventory analysis, in order to ensure the system is calculable, this LCA shares the same hypotheses as the previous MFA.

4.4.2 Inventory Analysis

An LCI analysis is concerned with the data collection and the calculation procedures necessary to complete the inventory (Appendix B). At first, the source of sewage sludge is generally considered as the WWTP with the secondary treatment system, in other words the start point, raw sludge actually is mixed sludge comprising primary sludge and secondary sludge. The material and energy flows for each individual process are based on what is needed treat 1,000kg dry mass (FU) of the input sludge.

For Scenario 1 (Figure 19), in pre-treatment dry mass rate of the sludge increases to about 20% (Hong, Hong et al. 2009), through the gravity belt thickening and pressure filter dewatering. In addition, 50kWh of electricity and 4kg of polymers are used in thickening, and 40kWh of electricity and 5kg of polymer are consumed in dewatering (Suh and Rousseaux 2002).

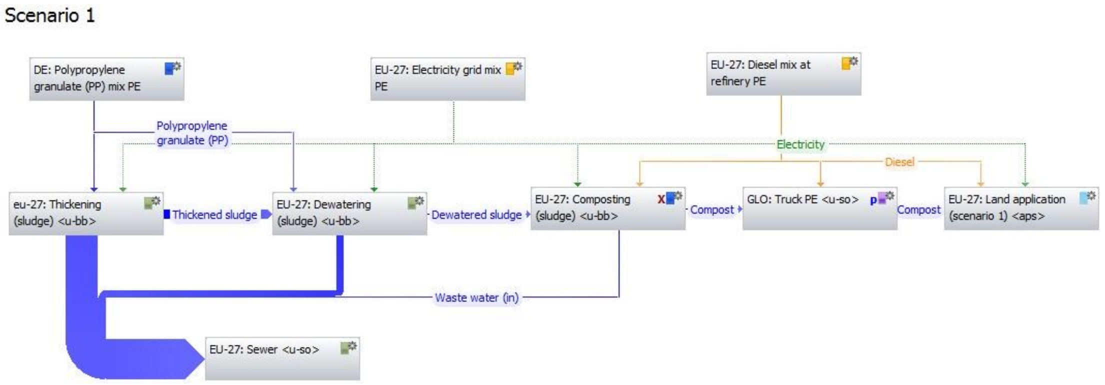

Figure 19: LCA system of Scenario 1

In main treatment composting, approximately 45% of volatile matter (VM) degrades into CO_2, H_2O and NH_3 during windrow composting (Suh and Rousseaux 2002). In the meantime, about 280kg of processing water are generated and removed via the sewer system (Righi, Oliviero et al. 2013). The ratio of dry mass in residue reaches about 60%. The energy consumption of composting is 30kWh of electricity for ventilation and 8.4kg of diesel for mobile equipments (Suh and Rousseaux 2002).

Transportation is also an important part which connects main treatment and post-treatment. Euro 5 standard diesel trucks with a load of 7.5 tons accomplish all transportation of products in this scenario. A distance of 40km is taken as an average transport distance to agricultural application.

In post-treatment, the potential harmful substances in agricultural application of compost are mostly heavy metals, because organic contaminants and pathogens are diminished by stabilization processes. Thus, this scenario takes into account only the impact of heavy metals. Every FU of sludge can produce 1785kg of compost (wet weight). This amount of compost contains 0.08kg of chromium, 0.19kg of copper, 0.33kg of lead and 1.51kg of zinc (Hospido, Moreira et al. 2005). The electricity consumption is on average 39.9kWh for using the compost, and diesel consumption is 0.5kg (Hospido, Moreira et al. 2005). Furthermore, compost contains nutrients, so 1785kg compost can provide soil with 10.82kg nitrogen and 6.76kg phosphorus which are equal to 67.6kg (16% of N) nitrogen fertilizer and 169kg (4% of P) of phosphorus fertilizer (FWG 2011).

For Scenario 2 (Figure 20), due to fact that anaerobic digestion requires less solid content of its input, so only the presence of gravity belt thickening is needed, the thickening process consumes 50kWh of electricity and 4kg of polymer (Suh and Rousseaux 2002).

The main treatment is anaerobic digestion. About 48% of VM degrades into gases during the digestion (Suh and Rousseaux 2002). The produced biogas is usually composed of 60% CH_4 and 40% CO_2 in volume (SGC 2012). Every FU of sludge can produce 346kg of biogas. After this process, the DM rate of sludge reduces to 25% to form raw sludge (Suh and Rousseaux 2002). About 88.56kWh electricity is used for agitation and pumping in anaerobic digestion (Hospido, Moreira et al. 2005).

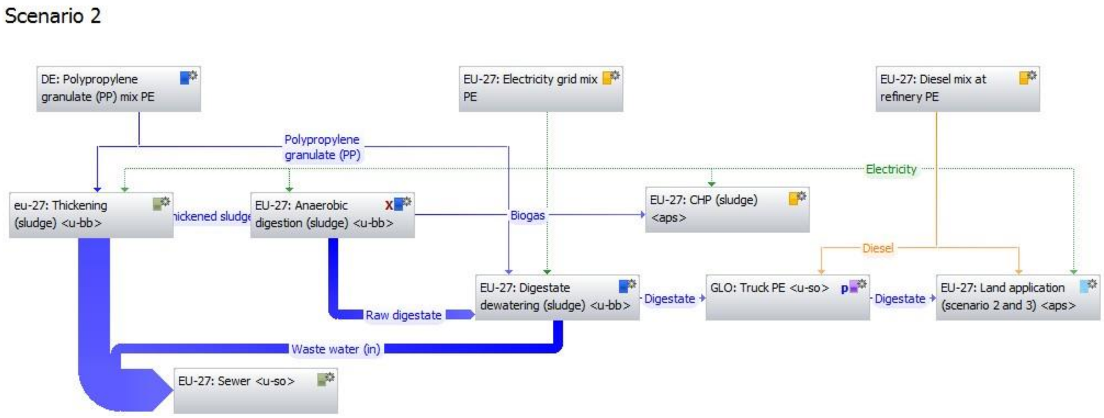

Figure 20: LCA system of Scenario 2

Next, the raw digestate goes to further dewatering. In this process, 49.09kWh electricity is consumed (Hospido, Moreira et al. 2005). On the other hand, the biogas goes to a CHP plant for heat and electricity generation. The CHP plant can recover about 85% of its energy combining heat and electricity, of which 35% is electricity (SGC 2012). About 65kWh of electricity is used in the CHP plant.

The post-treatment involves energy use and agricultural application. Heat is directly used on-site to support thermal processes and produce steam, and electricity added to the national grid. Anaerobic digestion produces 2618kg of digestate (wet weight) from every FU of sludge. This amount of digestate contains the same amount of heavy metals as 1785kg of compost, because the processes are assumed to be prefect processes, so there is no heavy metals loss, and they are accumulated in the final solid products. The electricity consumption is on average 58.5kWh for the agricultural application of digestate, and diesel consumption is 0.73kg. Moreover, digestate has a positive value; 2618kg digesate provides soil 13.09kg nitrogen and 4.32kg phosphorus which can replace 81.8kg (16% of N) nitrogen fertilizer and 108.0kg (4% of P) of phosphorus fertilizer.

For Scenario 3 (Figure 21), is very similar to Scenario 2 aside from the use of biogas. In this scenario, biogas goes to upgrading process instead of CHP plant, after upgrading the produced biomethane further goes to fuel use. In total 142kg of biomethane is produced, it contains to 1941kWh of calorific value which equals to about 162.42kg of diesel (SGC 2012).

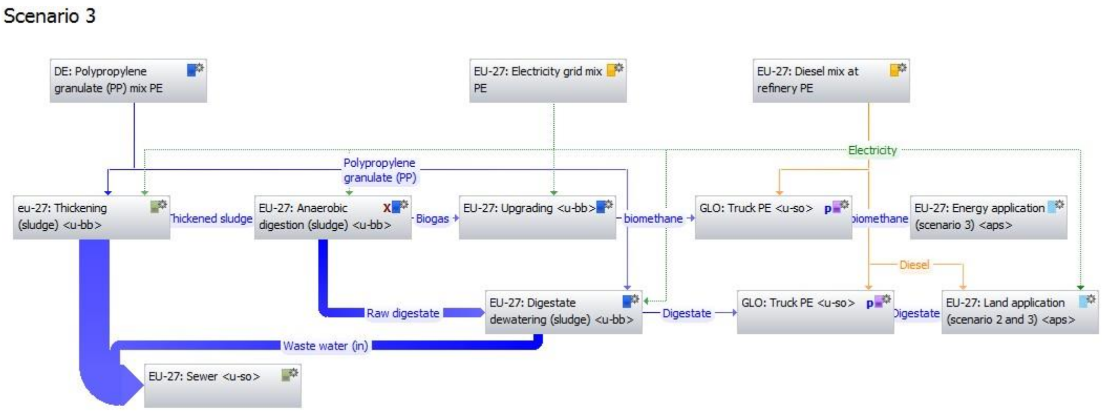

Figure 21: LCA system of Scenario 3

4.4.3 Life Cycle Impact Assessment (LCIA)

LCIA phase aims to examine the system from an environmental perspective using category indicators, derived from the LCI results. The LCIA phase also provides information for the interpretation phase.

This stage starts with the classification step, when the emissions and resources are sorted into different groups or impact categories according to their potential impact on the environment. Once classification is finished, characterization takes place in order to quantify the potential contribution of an input or an output to a specific impact, allowing aggregation into a single score. The classification and characterization are carried out by Gabi 6.0 with principle of CML 2001. The CML 2001 is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped into midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity). Eight categories of impacts were chosen in this phase which are:

1) Global warming potential (GWP 100)

2) Acidification potential (AP)

3) Eutrophication potential (EP)

4) Ozone depletion potential (ODP)

5) Abiotic depletion element potential (ADP element)

6) Abiotic depletion fossil (ADP fossil)

7) Human toxicity potential (HTP)

8) Photochemical oxidant formation potential (POFP)

The results are calculated through Gabi 6.0 (Appendix C) and shown by Figure 22.

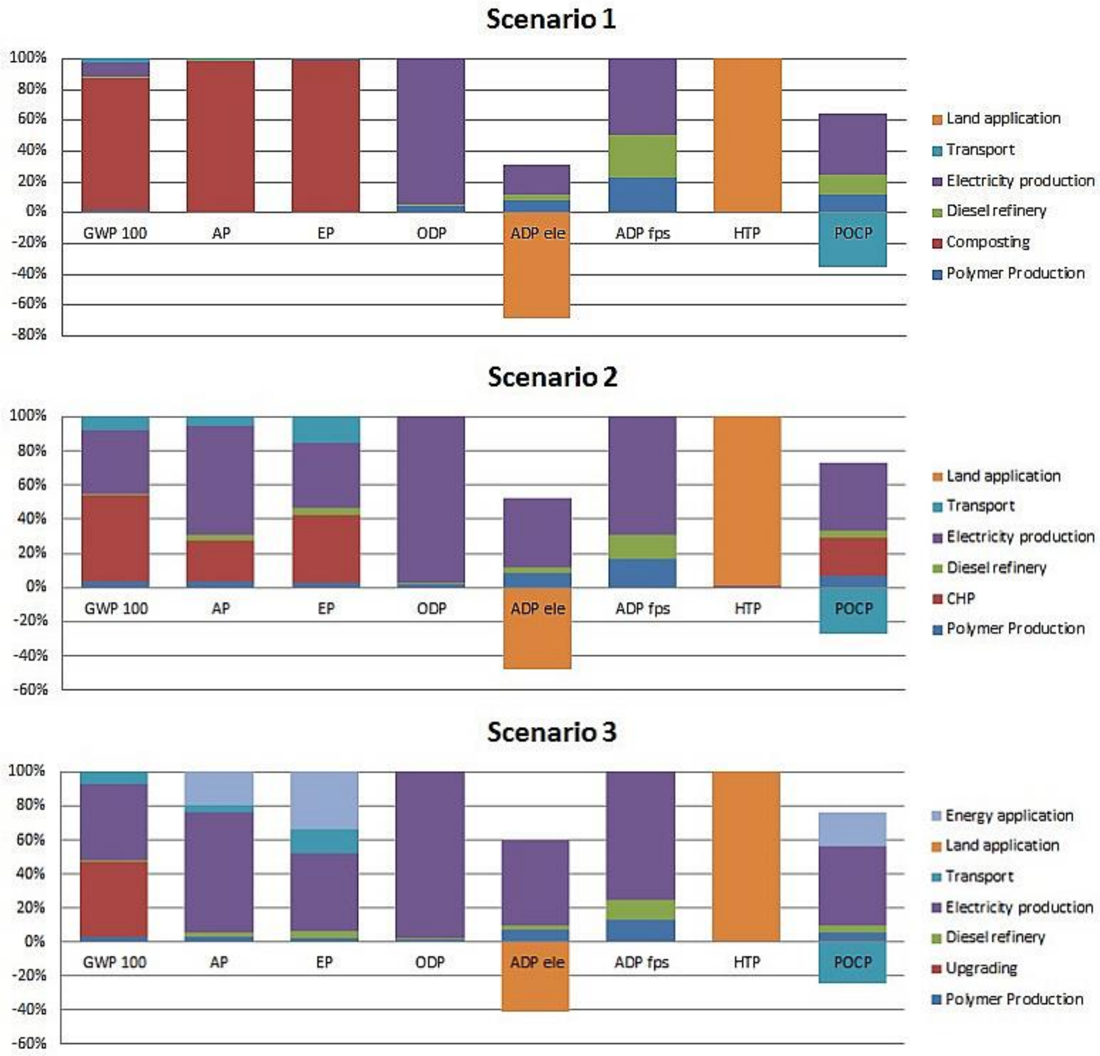

Figure 22: LCIA scenarios in each process and total without avoid impact

For Scenario 1, composting contributes the most to GWP 100, AP and EP. It is mainly due to its air emissions of carbon dioxide and ammonia. Electricity production dominates ODP, this maybe because a large portion of mixed electricity is produced via thermal power plant, and the air emissions (include chlorofluorocarbons or brominated substances) of thermal power plants harm the ozone layer. The solid product compost goes back to land, thus process land application brings positive impact to ADP element, and it also occupies the largest portion. ADP fossil is mainly influenced by electricity production, diesel refinery and polymer production. This is basically due to the fossil fuel consumption for their operation throughout the sludge treatment chain, and as background processes, they provide energy or substances to support foreground processes. Land application dominates HTP, because heavy metals cannot be effectively removed by sludge treatment processes, thus they tend to concentrate in compost which is used for agriculture. In addition, ADP, POCP is strongly influenced by electricity production, diesel refinery and polymer production. One thing to be noted is that transportation brings positive impact to POCP, due to one of its off-gases nitrogen monoxide having the ability to mitigate this impact.

For Scenario 2, GWP 100, AP and EP are greatly affected by CHP, electricity production and transportation, because the air emissions of these processes contain substances like carbon dioxide, nitrogen oxide and sulfur dioxide. Similar to Scenario 1, ODP is dominated by electricity production as well. Besides the followed impact such as ADP element, ADP fossil and HTP are also have the similar structures compared to Scenario 1. The POCP is mainly contributed by the background process electricity production and the foreground process CHP, and it is mitigated by transportation.

Scenario 3 and 2 are very similar in terms of their environmental performances. However there are some exceptions, the structures of GWP 100, AP, EP and POCP are different from Scenario 2. Upgrading becomes the biggest part referring GWP 100 due to removing large amount of carbon dioxide from biogas in order to form biomethane. For AP, EP and POCP, the difference is that energy use becomes one of the most important processes, as a result of its contaminative off-gas which generated in thermal engine.

Without taking the avoided impacts into account (Figure 24), Scenario 2 and 3 have less impact than Scenario 1 in GWP 100, due to carbon neutrality. The energy products of Scenario 2 and 3 contain methane which is generated from biogenic substances, therefore the carbon dioxide from methane is not take into account in GWP 100. Scenario 1 has higher impacts with respect to AP and EP as a result of ammonia which comes from composting. Additionally, Scenario 3 contributes the most to ODP, ADP element, ADP fossil and POCP, and it is followed by Scenario 2 and Scenario 1in order. That is because the total operation energy consumption of Scenario 3 is the highest one among the three scenarios.

However, final product of SSRS such as compost, digestate, biogas and biomethane can provide avoided impacts. By using them as resources in sludge treatment system and the extra amount can go to other systems such as manufacturing or household, they actually can reduce the total environmental impacts of anthroposphere. Since the avoided impacts benefits the environment in an extensive perspective, they should be taken into account in this study.

In addition, two additional assumptions are made in the analysis of avoided impacts. In Scenario 2a, the heat use in CHP plant is generated from EU's mix electricity grid. However, in Scenario 2b, the heat is produced from fossil fuel, and one of common fuel is hard coal, due to its low cost. An environmental impacts comparison between Scenario 2a and 2b is shown in Figure 23.

To date, using hard coal to produce heat is more environmentally friendly than using current mix electricity grid, according to Figure 23. Besides, producing heat by hard coal is generally cheaper than by mix electricity grid. Therefore, Scenario 2b should be the first option for CHP plant, unless the structure of mix electricity grid is changed in future, for instance, increase the sharing of renewable sources like hydro power, wind power and solar power to reducing the environmental impacts of heat generation by electricity.

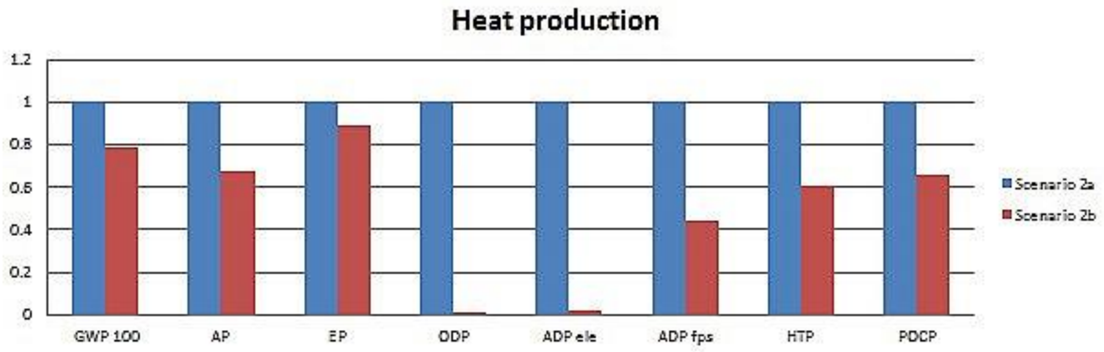

Figure 23: Environmental impacts comparison between Scenario 2a and 2b

Thus, Scenario 2b is chosen to represent Scenario 2 in the later avoided impacts analysis. The results of systems without and with avoided impacts are demonstrated by Figure 24.

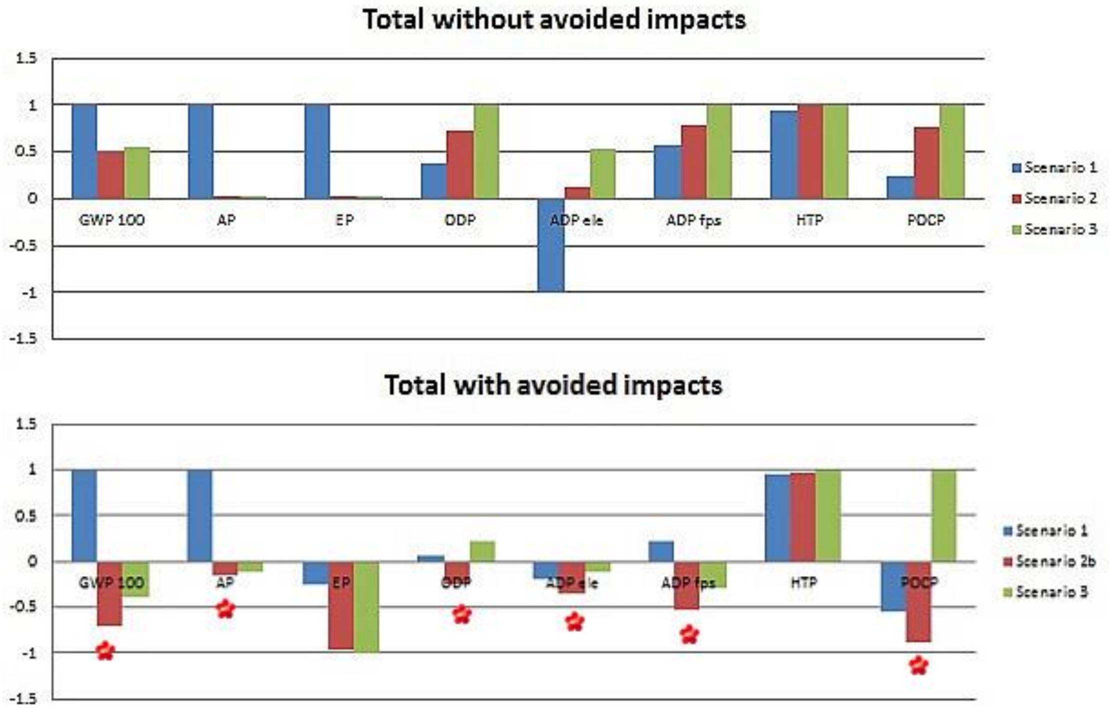

Figure 24: Impact of scenarios without and with avoid impact

SSRS has ability to recovery energy and substances. According to Figure 24, it is obvious that the environmental performance of the system with avoided impacts is much better than without avoided impacts, excepting HTP.

Anaerobic digestion combined with land application and CHP has the best performance in GWP 100, ODP, ADP element, ADP fossil and POCP. This is because it replaces heat and electricity generation, which can strongly contribute to these environmental impact categories. Anaerobic digestion combined with land application and biogas upgrading has the biggest contribution to POCP, because diesel is replaced by biomethane which does not form nitrogen monoxide (positive impact to POCP) during its combustion. Therefore the POCP increases instead of decreasing. For AP and EP the performances of Scenario 2 and 3 are similar, but both of them are much better than Scenario 1. For HTP, there is no obvious change, because the heavy metals are still accumulated in their solid products for agricultural purpose, which are compost and digestate.

Based on the perspective of environmental impacts, the anaerobic digestion combined with land application and CHP seems to be the best for environment. It is followed by anaerobic digestion combined with land application and upgrading, due to its relatively higher energy consumption in process operation. The last one is sludge composting system, the main reason is that it only recovers nutrients from sludge, but cannot reuse the energy content of sludge. Hence, its avoided impacts are much smaller than the other two scenarios.

4.5 Sensitivity analysis

A sensitivity analysis can be done in different ways. The idea of this analysis is to examine is how different assumptions and input values of model variables and parameters will change the results and affect the conclusions of the study.

The model should be as robust as possible, and the uncertainties in the system input information have to be evaluated and understood. It is undesirable for the model to have high uncertainties in important variables and parameters.

Therefore in this part, a robustness test of the calculations is provided by changing model assumptions and adjusting values in a systematic way. One common method of doing this is by using model variation, i.e. changing the input value of a variable one at a time, and keeping other variables unchanged (Appendix D). The important variables that affect results are listed in Table 10.

Table 10: Important variables in sensitivity analysis

Important input variables	Unit	Initial value	% change initial value	% Chane in result				
				Nit.RE	Pho.RE	ERE	GWP 100	HTP
Scenario 1								
Nitrogen content in raw sludge	-	3.26%	10%	-9.09%	0	-	-	−
Nitrogen content in compost	-	1.60%	10%	10%	0	-	-	−
Phosphorus content in raw sludge	-	2.00%	10%	0	-9.09	-	-	−
Phosphorus content in compost	-	1.00%	10%	0	10%	-	-	−
Air emission of Carbon Dioxide	kg	709	10%	−	−	-	10.53%	0.00%
Soil emission of Lead	kg	0.33	10%	−	−	-	0.00%	7.43%
Scenario 2								
Nitrogen content in raw sludge	-	3.26%	10%	-9.09%	0	0	-	-
Nitrogen content in digestate	-	2.00%	10%	10%	0	0	-	-
Phosphorus content in raw sludge	-	2.00%	10%	0	-9.09%	0	-	-
Phosphorus content in digestate	-	0.66%	10%	0	10%	0	-	-
Energy content in biogas	kWh/FU	5.9	10%	0	0	9.88%	-	-
Energy effciency of CHP	-	85.00%	10%	0	0	9.88%	-	-
Energy content in sludge	MJ/kg	19	10%	0	0	-8.51%	-	-
Avoided electricity, heat (S2 2b)	kWh	1733	10%	−	−	−	15.25%	-0.29%
Soil emission of Lead	kg	0.33	10%	−	−	−	0.00%	7.17%
Scenario 3								
Energy content in sludge	MJ/kg	19	10%	0	0	-8.35%	−	
Energy content in biomethane	kWh/FU	13.43	10%	0	0	10%	−	
electricity	kWh	432.15	10%	−	−	−	-7.89%	0.00%
Air emission of Carbon Dioxide	kg	204	10%	−	−	−	-7.52%	0.00%
Avoided diesel	kg	162.479	10%	−	−	−	22.18%	-0.09%
Soil emission of Lead	kg	0.33	10%	−	−	−	0.00%	7.04%

Nit.RE represents nitrogen recovery efficiency, Pho.RE represents phosphorus recovery efficiency, and ERE represents energy recovery efficiency.

For environmental impacts, because global warming is the most popular environmental topic, so it was chosen for sensitivity analysis. In addition, since HTP is the focus in SSRS as well, and the degree of HTP can influence the implement and development of SSRS, HTP was also chosen.

Among these important variables, some are suspicious (Table 11) and can be adjusted for a more accurate result. Unlike nutrients in sludge, there are less data about nutrients content in compost of digestate that comes from SSRS, so the relevant values should be modified. Moreover nutrients in compost and digestate may be lost in phases of transport or spreading, thus these values should be estimated to bea little bit smaller (5%) than the original values.

Table 11: Suspicious variables in sensitivity analysis

Suspicious Input variables	Unit	Initial value	% change initial value	Modified value
Scenario 1				
Nitrogen content in compost	-	1.60%	-5%	1.52%
Phosphorus content in compost	-	1.00%	-5%	0.95%
Air emission of Carbon Dioxide	kg	709.00	-10%	638.10
Soil emission of Lead	kg	0.33	-10%	0.30
Scenario 2				
Nitrogen content in digestate	-	2.00%	-5%	1.90%
Phosphorus content in digestate	-	0.66%	-5%	0.63%
Energy effciency of CHP	-	85.00%	-5%	80.75%
Avoided electricity, heat (S2 2b)	kWh	1733.00	10%	1906.30
Soil emission of Lead	kg	0.33	-10%	0.30
Scenario 3				
Air emission of Carbon Dioxide	kg	204.00	-5%	193.80
Avoided diesel	kg	162.48	-5%	154.35
Soil emission of Lead	kg	0.33	-10%	0.30

Some plants have installed on-site carbon capture facilities, but the accurate rate of captured carbon dioxide is hard to estimate due to the use of various methods, so the carbon dioxide emission may be less (10%).

In addition, lead is taken into plants in ion form. However, the solubility of lead is hard to tell in different circumstances, i.e. the plants cannot absorb solid lead. Thus the values of plant available lead are changed constantly, in this study it is assumed to be smaller (10%).

For Scenario 2, the total recovery rate in CHP plant can reach to 85%, but it i an optimistic number, so it should be smaller (5%). The initial heat sometimes comes from coal, sometimes from diesel, sometimes from electricity. In this study the heat is assumed all from coal, but if parts of it come from diesel or mix electricity grid, the avoided impacts then should be bigger, meaning more heat (10%) is produced by hard coal in CHP plant.

For Scenario 3, as a result of incomplete combustion sometimes in thermal engine, the carbon dioxide emission of vehicle may be smaller (5%), therefore, the substitution of diesel by biomethane is considered less (5%).

After adjustment, a probably more reliable result which describes the performance of system is achieved. The comparison of original and adjusted result is shown in Table 12.

Table 12: Comparison of unadjusted and adjusted result

Item	Nit. E	Pho. E	EE	GWP 100	HTP
Old S1	33.18%	33.80%	0	674	1481.2
New S1	31.51%	32.11%	0	757	1410
Old S2	40.15%	21.60%	30.31%	-472	1533.9
New S2	38.14%	20.52%	28.81%	-515	1507.7
Old S3	40.15%	21.60%	32.76%	-266	1563.5
New S3	38.14%	20.52%	32.76%	-249	1454.2

5. Discussion

5.1 Main finding

From the viewpoint of the nutritional value, compost as a product of Scenario 1 has a higher phosphorus content compared Scenario 2 and 3. After the adjustment of data by sensitivity analysis, the phosphorus content in compost is 32%, which is 1.5 times larger than digestate. However the digestate that comes from anaerobic digestion has the higher nitrogen content, because nitrogen is lost in the composting process as ammonia. After adjustment, the nitrogen content of digestate reaches 38% which is about 1.2 times bigger than compost. These results indicate that compost and digestate have their own strength on overall nutrients recovery efficiency.

However, if the relative volume is taken into account, compost then has an obvious advantage. Each FU of sludge has ability to produce 1785 kg compost or 2618kg digestate. The compost contains 10.82kg nitrogen and 6.76kg phosphorus, meanings that the relative content of nitrogen and phosphorus are 0.6 % and 0.4%. Nevertheless, the relative nitrogen content and phosphorus in digestate are only about 0.5 % and 0.2 % respectively. This shows that if a specific amount of fertilizing is required, the need of digestate is larger than compost (in volume). Compared to compost, applying digestate will undoubtedly increase the cost of transportation and spreading, due to its larger volume. Furthermore digestate has higher water content (75%) than compost (40%), so the use of digestate will also be more difficult than compost. Starting from the perspective of the relative nutrients efficiency and the degree of operation difficulty, compost should be considered as the better option, i.e. the combination of composting and agricultural application is the better option.

From the perspective of the energy recovery efficiency, Scenario 2 and Scenario 3 have absolutely dominant advantage. Scenario 1 cannot utilize the energy substances in the sludge. After adjustment by sensitivity analysis, Scenario 2 recovers about 29% of total energy from the FU of sludge, while Scenario 3 recovers 33% of total energy. Although Scenario 3 consumes more energy in its process operation, the upgraded biomethane has a higher calorific value (13.43kWh/kg). Therefore, Scenario 3 eventually perform better (5% higher) than Scenario 2 in terms of energy recovery. From the viewpoint of energy recovery efficiency, the combination of anaerobic digestion, agricultural application and biogas upgrading has the best performance.

From the perspective of the environmental impact, Scenario 2 is the one that performs excellently, with exceptions of EP and HTP, Scenario 2 performs slightly inferior compared to its opponents. It has better performances in the other six categories of environmental impacts. Especially related to GWP, ODP and POCP, Scenario 2 is significantly higher than the second rank. Thus, from the viewpoint of environmental impact, a conclusion can be made that the combination of anaerobic digestion, agricultural application and CHP has the best average environmental performance. In addition, for the EP, the combination of anaerobic digestion, agricultural application and biogas upgrading has the best performance; for HTP, the combination of composting and agricultural application is the superior one.

The MFA combined with LCA is an appropriate way of analyzing SSRS. MFA serves LCA. By performing an MFA, flows and substances in system can be quantified. The quantified data can contribute to the construction of LCA’s inventory which is very important to the accuracy of an LCA. For example, in the case of lacking of information or existing some unmeasured data, MFA results can be utilized to build LCA’s inventory. In addition, in the situation of having available data, MFA results can also be used to double check the data, in case of error data. If the quantified data from MFA is greatly different from measured data, it indirectly indicates that the model may have a defect, or the data may be wrong. Then a review needs to be carried out in order to repair the incorrect spot and optimize the study.

In the analysis of MFA combined with LCA, it is better to share FU, by doing this to avoid inconvenience of unit transformation and to simplify operations. In addition the system is better to have a consistent system boundary in both methods, in order to avoid the errors causing by different geography or processes.

5.2 Comparison with literature

In this study, the conclusion is basically consistent with the literatures. In Scenario 3 the combination of anaerobic digestion, agricultural application and biogas upgrading has a calculated 33% of energy recovery efficiency. This result is similar to the energy recovery efficiency of organic mixture in Poschi's study which is around 34.1-55 %. Sommer reports that the nutrient efficiencies of composting deep litter are about 41% for nitrogen and 60% for phosphorus. The nitrogen and phosphorus efficiency of Scenario 1 are 31.51% and 32.11% respectively. As it can be seen that the results are different, it is because using different organic sources can result in different consequences. Parts of nutrients in sludge are often lost with the filtrate during processing. Suh and Rousseaux report the combination of anaerobic digestion and land application is the most environmentally friendly way, our result is basically the same as their result, but at more specific level. We find the combination of anaerobic digestion, agriculture use and CHP to be the best option for environment. Land application dominates the HTP in all three scenarios, this is in accordance with the conclusion of Houillon and Jolliet.

However, we also find a difference compared to literature, Righi summarizes transportation occupies a large section of AP, GWP and POCP. But in our study transportation only contributes a lot to POCP. It does not contribute much to AP and GWP, and it is only a small part in both AP and GWP. The different result between Righi and our study could be caused by different way of constructing scenarios or designing models. However, the similar conclusion as what is reported by Righi is not found in other literatures so far.

5.3 Strength and weakness

This study uses three indicators to reflect the performance of SSRS, they are nutritional efficiency, energy recovery efficiency and environmental impacts. Through such a multi-angle analysis, the limitation (incomprehensive thinking) of an analysis only with single indicator is reduced. The scenarios were well selected based on the global situation; the model was rationally designed which combining MFA and LCA, an MFA was carried out at first and an LCA was then processed relying on the results of the MFA. From nutrients recovery efficiency to energy recovery efficiency, then to environmental impacts, the linear structure made the analysis simple and efficient. The introduction of Gabi 6.0 database in this study ensured the quality of background data and improved the accuracy of results. Therefore, we have great confidence in our results.

But in the quantificaiton of specific models, some hypothetical conditions and individual estimated data will affect the accuracy of the final result and increase the uncertainty. In order to avoid such effects, a sensitivity analysis was carried out in the end of the analysis to minimize the data uncertainty by identifying the important system variables and adjusting them.

In addition, this study was mainly conducted broadly over the EU. The data was derived from many different members of the EU. Therefore the main function of result is to reflect the overall development trend and performance of SSRS. However, if a study is held in a more specific level such as a country, a city, it requires the use of more specific data which could be the actual measured data in local level. This study is a part of BioTEnMaRe project of researching the methods of analysis. Surely, the future research of BioTEnMaRe project needs to rely on more specific and more accurate data support to determine the merits of the different system configurations at a specific level.

Furthermore, this study mainly concentrated on the functional performance, but economic and social factors can also be very important indicators for decision makers. If economic and social benefit and cost are added into the study, it can be further improved.

6. Conclusion & recommendation

Among the three scenarios, the product of Scenario 1, compost has the highest relative nutrients recovery efficiency due to its small volume and low water content compared to digestate. However, composting is restricted by the condition of itself, because it cannot reuse the energy content in sludge, therefore its energy recovery efficiency is zero. This certainly is the biggest drawback of composting. By contrast, the performance of anaerobic digestion technology is more comprehensive, although its relative nutrients recovery efficiency is lower than composting technology, it is more energy efficient and has less environmental impacts. Scenario 2 and 3 have similar energy recovery efficiency, but Scenario 2 performs better than scenario 3 in perspective of environmental impacts. Hence, according to the comprehensive viewpoint, among these three scenarios, the combination of anaerobic digestion, agricultural application and CHP should be the best option with the best overall performance.

The electricity consumption of SSRS does not directly contribute to environmental impacts, according to our result. However, intensive electricity consumption requires the support of electricity production process which greatly contributes to environmental impacts as background process, for instance, in GWP, AP and ADP. The possible way to improve the system is to increase the sharing of cleaner electricity sources in mixed electricity grid, such as hydro, wind or solar power.

Carbon dioxide emission makes a large contribution to GWP, therefor it should be reduced as much as possible to mitigate the current global warming trend globally. To achieve this, the carbon dioxide capture rate of SSRS must be maximized. The possible way is to increase the rate of using carbon dioxide capture facility in plant, and maybe develop new carbon dioxide storage, for instance, Norway has cases of storing carbon dioxide emission in the underground.

In addition, reducing HTP is obviously still a challenge faced in SSRS. The present research focuses on how to extract heavy metal from sludge. Nevertheless none of them has been unreservedly accepted by the scientific community. To date, one possible solution is to use compost and digestate as much as possible on urban green area or other non-arable lands, and put agricultural application as the second choice.

LCA has been extensively applied to the waste management system including sludge management. However, most of previous studies focus on analyzing environmental impact. In this context, the MFA and LCA combined method can reflect the nutrients efficiency, energy recovery efficiency and environmental impacts of a system. This method provides a more comprehensive perspective and consequently results in a more comprehensive analysis. In summary, it makes the results more scientifically reliable.

Additionally, if data is available, it is of value to add an economic factor in analysis, or even extend the analysis to include a social factor, because the use of SSRS may potentially result in high economic or social costs.

Reference

Baily, R. E. (2009). Sludge Types, Treatment, Process and Disposal. USA, NOVA.

BERTRAMS (2014). "Nassoxidation." from http://www.bertrams.ch/index.php?id=15.

BioTEnMaRe (2014). " BioTEnMaRe." from http://www.biotenmare.com/.

Bresters, A. R. (1997). Sludge Treatment and Disposal Management Approaches and Experiences. Netherland, ISWA.

Brunner, P. and H. Rechberger (2004). "Practical handbook of material flow analysis." The International Journal of Life Cycle Assessment **9**(5): 337-338.

Darvodelsky, P. (2010). "Biogas - The Big Issue." Australian Water Association: 2-4.

DEFRA (2012). Waste Water Treatment in the United Kingdom-2012. Implementation of the European Union Urban Waste Water Treatment Directive. UK, Department for Environment, Food and Rural Affairs, UK**:** 2-41.

EC (2001). "Landfill of Waste." from
http://ec.europa.eu/environment/waste/landfill_index.htm.

Eriksen, G. S. (2009). Risk assessment of contaminants in sewage sludge applied on Norwegian soils. Opinion of the Panel on Contaminants in the Norwegian Scientific Committee for Food Safety. Norway, VKM.

EurObserv'ER (2011). Biogas electricity production
growth in 2011. biogas barometer. France, EurObserv'ER.

Finstein, M. S., et al. (1980). Engineering Principles of Sludge Composting. USA, Water Pollution Control Federation.

FWG (2011). National Code of Practice for Fertilizer Description & Labelling. Australia, Fertilizer Working Group.

Fytili, D. and A. Zabaniotou (2008). "Utilization of sewage sludge in EU application of old and new methods—A review." Renewable and Sustainable Energy Reviews **12**(1): 116-140.

Guinée, J. B. (2002). Handbook on Life Cycle Assessment. USA, KLUWER ACADEMIC PUBLISHERS.

Gutierrez, S. (2006). Life Cycle Assessment: Principles and Practice. USA, National Risk

Management Research Laboratory.

Halls, S. (2000). Environmentally Sound Technologies for Wastewater and Stormwater Management. Japan, Newsletter and Technical Publications.

He, P. J., et al. (2007). Sewage Sludge in China: Challenges Toward a Sustainable Future. China, IWA Publishing.

Hendriks, C., et al. (2000). "Material Flow Analysis: A tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands." Local Environment **5**(3): 311-328.

Henley, L. and G. Barker (2011). A Commitment to Increasing Energy from Waste through Anaerobic Digestion. Anaerobic Digestion Strategy and Action Plan. UK, Department for Environment, Food and Rural Affairs**:** 1-51.

Hong, J., et al. (2009). "Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan." Waste Management **29**(2): 696-703.

Hospido, A., et al. (2005). "Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes (10 pp)." The International Journal of Life Cycle Assessment **10**(5): 336-345.

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

Inglezakis, V. J., et al. (2012). European Union legislation on sewage sludge management. Romania, SC European Focus Consulting srl
Aristotle University of Thessaloniki**:** 475-480.

ISO (2010). "ISO 14040 Life cycle assessment - Principles and framework." Environmental management. from http://www.iso.org/iso/catalogue_detail?csnumber=37456.

LeBlanc, R. J., et al. (2006). Moving Forward the Sustainable and Welcome Uses of a Global Resource, United Nations.

Luck, F. (1999). "Wet air oxidation: past, present and future." Catalysis Today **53**(1): 81-91.

Lundin, M., et al. (2004). "Environmental and Economic Assessment of Sewage Sludge Handling Options." Resource, Conservation and Recycling **41**(4): 255-278.

Miser, H. J. and E. S. Quade (1995). Handbook of system analysis. UK, Handbook of system analysis.

NEBRA (2007). A National Biosolids Regulation, Quality, End Use & Disposal Survey. USA, North East Biosolids and Residduals Association.

Øyen, K. P. R. (2007). ORWARE Systems Analyses of Alternative Treatment Strategies for Organic Household Waste for Oslo. Department of Energy and Process Engineering, Norwegian Univiersity of Science and Technology. **Master**.

Pöschl, M., et al. (2010). "Evaluation of energy efficiency of various biogas production and utilization pathways." Applied Energy **87**(11): 3305-3321.

Poliakov, O. (2005). "Sewage Sludge." from http://www.worldmapper.org/posters/worldmapper_map306_ver5.pdf.

Righi, S., et al. (2013). "Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches." Journal of Cleaner Production **44**(0): 8-17.

Rogers, H. (2012). Perspectives for Biogas in Europe. UK, Oxford Institute for Energy Studies.

Schepelmann, P. (2003). Life cycle assessment (LCA). P. Schepelmann. Germany, Wuppertal Institute for Climate, Environment and Energy.

SEAGATEFILTERA (2014). "Waste Water Treatment." Xtreme Bio Media for Waste Water Treatment. from http://www.seagatefilters.com/Waste-Water-Treatment-c-44.html.

SGC (2012). Basic Data on Biogas. Sweden, Svenskt Gastekniskt Center AB.

Sommer, S. G. (2001). "Effect of composting on nutrient loss and nitrogen availability of cattle deep litter." European Journal of Agronomy **14**(2): 123-133.

SOUL (2012). "Citizens Initiative for saving water bodies in Hyderabad." from http://www.soulhyd.org/intro-stp.html.

Spinosa, L. (2008). Status and Perspectives of Sludge Management. UK, CNR.

Spinosa, L. (2011). Wastewater Sludge A Global Overview of The Current Status and Future Prospects. UK, IWA Publishing.

Suh, Y.-J. and P. Rousseaux (2002). "An LCA of alternative wastewater sludge treatment scenarios." Resources, Conservation and Recycling **35**(3): 191-200.

Tokich, S. H. (2004). Wastewater Management Strategy: Centralized v. Decentralized

Technologies for Small Communities Netherlands, The Center for Clean Technology and Environmental Policy, University of Twente**:** 1-27.

Werle, S. and R. K. Wilk (2010). "A review of methods for the thermal utilization of sewage sludge: The Polish perspective." Renewable Energy **35**(9): 1914-1919.

Williams, P. T. (2005). Waste Treatment and Disposal. UK, John Wiley & Sons.

Yao, J. L. (2010). The Assessment of Municipal Sewage Sludge Treatment and Disposal Technologies. Department of Environmental Science. China, Chinese Research Academy of Environmental Sciences. **Master:** 104.

Appendix

Appendix A

The date for MFA quantification

Parameter	Name	Unit	Source 1	2	3	4	5	6	7	8	9	10	11	12	13	14	Other	Chosen
F	Functional unit (dry mass DM in sludge)	kg																1000
WC1	Water content of raw sludge	-		99%														99%
WC2	Water content of thickened sludge	-		96%	94%-95%													96%
WC3	Water content of dewatered sludge	-	74%	80%		75.50%												80%
P1	Percent of VM in sludge (DM)	-	72%			73.50%												72%
P2	Percent of VM loss in composting	-	45%															45%
D1	Density of O2	kg/m3															1.429	1.429
D2	Density of atmosphere	kg/m3															1.2	1.2
P3	Percent of O2 in air (volume)	-															21%	21%
C1	Content of DM In compost	-	60%															60%
WC4	Water content of mix sludge (include recycling)	-					60%											60%
P4	Percent of reacted air in total air	-				10%												10%
CC1	Organic carbon content in raw sludge (DM)	-									31%	36.15%						31%
CC2	Organic carbon content in compost (DM)	-									23%							23%
CC3	Organic carbon content in digestates (DM)	-									24%							24%
NC1	Nitrogen content in raw sludge (DM)	-									3.80%	3.26%	2%					3.26%
NC2	Nitrogen content in compost (DM)	-									1.60%							1.60%
NC3	Nitrogen content in digestates (DM)	-						2%			2.30%		0.3%-0.8%				4.27% (sour	2%
PC1	Phosphorus content in raw sludge (DM)	-						2%			1.50%		1.50%					2%
PC2	Phosphorus content in compost (DM)	-									1%							1%
PC3	Phosphorus content in digestates (DM)	-									2.20%						0.66 (source	0.66%
EC1	Energy content in compost (DM)	MJ/kg											14					14
EC2	Energy content in sludge (DM)	MJ/kg											19					19
EU1	Energy use in thickening	kWh/FU	50															50
EU2	Energy use in dewatering	kWh/FU	40															40
DU1	Diesel use in composting	kg/FU	8.4															8.4
EC3	Energy content in diesel	kWh/kg								11.78								11.78
EU3	energy use in ventilation	Kwh/FU	30															30
DU2	Diesel used in transport per km	kg/WT	0.064															0.0635
T	Transport distance to land application	km	40															40
P5	Percent of VM loss in AD	-	48%															48%
SC	Solid content in dewatered digestates	-	25%		25%-35%													25%
MC1	methane content in biogas (weight)	-							39%-40%									40%
MC2	methane content in biomethane	-			5%-10%					97%								97%
EC4	Energy content in biogas	kWh/FU								5.9								5.9
EE	Energy effciency of CHP	-													85%			85%
EU4	Energy use in AD including collection	kWh/FU			50-100			88.6										88.56
EU5	Energy use in dewatering digestates	kWh/FU						49.1										49.09
R1	Rate of energy input & output of CHP	-												3.75%				3.75%
R2	Rate of kWh to MJ	-															0.28	0.28
EC5	Energy content in biomethane	kWh/FU								13.43								13.43
EU6	Energy use in upgrading biogas	kWh/kg								0.537								0.537
VW	Volume of woodchips	m3				1.69												1.69
D3	Density of woodchips	kg/m3				233.8												233.8
WR	Watwe removed from composting															280		280
RR	Rate of recycled agent						80%											80%
EU7	Energy use in land application	kWh/kg																64.63

The sources of the data for MFA quantification

Number	Title	Writer
1	An LCA of alternative wastewater sludge treatment scenarios	Suh and Rousseaux
2	Environmental and economic LCA for sewage sludge treatment processes in Japan	Hong, et al.
3	Principle and potential of AD of waste-activated sludge	Appels and Baeyens
4	Materials balance in composting of wastewater sludge as affected by process control strategy	Miller and Finstein
5	Engineering principle of sludge composting	Haug, et al.
6	Environmental evaluation of different treatment processes for sludge from urban wastewater treatment	Hospidp, et al.
7	Calculating the Heating Value of Biogas	Ludington, et al.
8	Basic data on biogas	SGC
9	composting sewage sludge for land application	Parr, et al.
10	Chemical evaluation of sewage sludge composting as a mature indicator for composting process	Li, et al.
11	Sustainable approach to energy recovery from sewage sludge	Cao, et al.
12	Evaluation of energy effciency of various biogas production and utilization pathways	poschl and Ward
13	Perspectives for Biogas in Europe	Oxford
14	Life cycle assessment of management systems for sewage sludge and food waste	Righi, et al.

DM quantification in MFA (for Figure 15, 16 and 17)

Mass balance equation (scenario 1):			**Result (scenario 1):**	
Number	Process	Equation	Flow	value (kg)
1	System	X0,1+X0,3a+X0,3b=X1,0+X2,0+X3,0a+X3,0b+S4	X0,1	100000
2	Process 1	X0,1=X1,0+X1,2	X1,2	25000
3	Process 2	X1,2=X2,0+X2,3	X2,3	5000
4	Process 3	X2,3+X3,3+X0,3a+X0,3b=X3,0a+X3,0b+X3,4+X3,3	X1,0	75000
5	Process 4	S4=X3,4	X2,0	20000
			X0,3a	645
Model approch equation (scenario 1):			X3,4	1785
Number	Flow	Equation	X3,0a	3975
1	X0,1	X0,1=FU/(1-WC1)=1/(1-99%)	X0,3b	395
2	X1,2	X1,2=FU/(1-WC2)=1/(1-96%)	X3,0b	280
3	X2,3	X1,2=FU/(1-WC3)=1/(1-80%)	X3,3	1580
4	X0,3a	X0,3a=W2 (PE NO.2)	S4	1785
5	X3,4	X3,4=(FU-W1+X0,3b)/C1=(1-324+395)/60%		
6	X3,0b	X3,0b=VW		
7	X0,3b	X0,3b=(X2,3*VW*D3/1000)-X3,3		
8	X3,3	X3,3=RR*(X2,3*VW*D3/1000)		
Mass balance equation (scenario 2):			**Result (scenario 2):**	
Number	Process	Equation	Flow	value (kg)
1	System	X0,1+X0,7=X1,0+X5,0+X6,0+X7,0	X0,1	100000
2	Process 1	X0,1=X1,0+X1,2	X1,2	25000
3	Process 2	X1,2=X2,4+X2,3	X1,0	75000
4	Process 4	X2,4=X4,0+X4,5	X2,3	346
5	Process 5	S5=X4,5	X2,4	24654
6	Process 3	X2,3+X0,3=X3,0	X4,5	2618
			X4,0	22037
Model approch equation (scenario 2):			S5	2618
Number	Flow	Equation	X0,3	553
1	X0,1	X0,1=FU/(1-WC1)=1/(1-99%)	X3,0	899
2	X1,2	X1,2=FU/(1-WC2)=1/(1-96%)		
3	X2,3	X2,3=FU*P1*P5=1*72%*48%		
4	X4,5	X4,5=X2,3(VM)/SC=(FU-X2,3)/SC=(1000-346)/25%		
5	X0,3	X0,3=W7		
Mass balance equation (scenairo 3):			**Result (scenario 3):**	
Number	Process	Equation	Flow	value (kg)
1	System	X0,1=X1,0+X5,0+X6,0+X8,0+X9,0	X0,1	100000
2	Process 1	X0,1=X1,0+X1,2	X1,2	25000
3	Process 2	X1,2=X2,4+X2,3	X1,0	75000
4	Process 4	X2,4=X4,0+X4,5	X2,3	346
5	Process 5	S5=X4,5	X2,4	24654
6	Process 3	X2,3=X3,0+X3,6	X4,5	2618
7	Process 6	X3,6+X6,0=X0,6	X4,0	22037
			S5	2618
Model approch equation (scenario 3):			X3,6	143
Number	Flow	Equation	X3,0	203
1	X0,1	X0,1=FU/(1-WC1)=1/(1-99%)	X6,0	553
2	X1,2	X1,2=FU/(1-WC2)=1/(1-96%)	X0,6	695
3	X2,3	X2,3=FU*P1*P5=1*72%*48%		
4	X4,5	X4,5=X2,4(VM)/SC=(FU-X5,8)/SC=(1000-346)/25%		
5	X3,6	X3,6=WCO2+WCH4=4+138		

Appendix B

Inventory in LCA (for Figure 19, 20 and 21)

Scenario 1 (Scenario * per FU = 1000 kg DM sludge)	Direction	Unit	Amount	Source
Thickening				
Electricity	Input	kWh	50	Literature
Polymer	Input	kg	4	Literature
Raw sludge (1000 DM)	Input	kg	100000	Calculated
Thickened Sludge (1000 DM)	Output	kg	25000	Calculated
Removed water	Output	kg	75000	Calculated
Dewatering				
Electricity	Input	kWh	40	Literature
Polymer	Input	kg	5	Literature
Thickened sludge (1000 DM)	Input	kg	25000	Calculated
Dewatered Sludge (1000 DM)	Output	kg	5000	Calculated
Removed water	Output	kg	20000	Calculated
Composting				
Electricity (ventilation)	Input	kWh	30	Literature
Diesel	Input	kg	8.4	Literature
Recation Oxygen (O_2)	Input	kg	645	Calculated
Dewatered Sludge (1000 DM)	Input	kg	5000	Calculated
Compost	Output	kg	1785	Calculated
Air emission of Carbon Dioxide (CO_2)	Output	kg	709	Calculated
Air emission of Ammonia (NH_3)	Output	kg	27	Calculated
Air emission of Water (vapour)	Output	kg	3239	Calculated
Removed water	Output	kg	280	Literature
Transport (Truck)				
Distance (diesel)	Input	km	40	Literature
Land Use				
Compost	Output	kg	1785	Calculated
Electricity	Input	kWh	39.89	Calculated
Diesel	Input	kg	0.50	Calculated
Soil emission of Chromium (Cr)	Output	kg	0.08	Estimated
Soil emission of Copper (Cu)	Output	kg	0.19	Estimated
Soil emission of Lead (Pb)	Output	kg	0.33	Estimated
Soil emission of Zinc (Zn)	Output	kg	1.51	Estimated
N avoid	Output	kg	10.82	Calculated
P avoid	Output	kg	6.76	Calculated
N-fertilizer avoid	Output	kg	67.6	Calculated
P-fertilizer avoid	Output	kg	169	Calculated

Scenario 2 (Scenario * per FU = 1000 kg DM sludge)	Direction	Unit	Amount	Source
Thickening				
Electricity	Input	kWh	50	Literature
Polymer	Input	kg	4	Literature
Raw sludge (1000 DM)	Input	kg	100000	Calculated
Thickened Sludge (1000 DM)	Output	kg	25000(2501	Calculated
Removed water	Output	kg	75000	Calculated
Anaerobic Digestion				
Electricity	Input	kWh	88.56	Literature
Thickened Sludge (1000 DM)	Input	kg	25000	Calculated
Biogas (CO_2 and CH_4 138kg)	Output	kg	346	Calculated
Raw Digestate	Output	kg	24654	Calculated
Raw Digestates Dewatering				
Electricity	Input	kWh	49.09	Literature
Raw Digestate	Input	kg	24654	Calculated
Polymer	Input	kg	5.5	Literature
Digestates	Output	kg	2618	Calculated
Removed water	Output	kg	22036	Calculated
Transport (Truck)				
Distance (diesel)	Input	km	40	Literature
Land Use				
Digestate	Output	kg	2618	Calculated
Electricity	Input	kWh	58.5	Literature
Diesel	Input	kg	0.73	Literature
Soil emission of Chromium (Cr)	Output	kg	0.08	Literature
Soil emission of Copper (Cu)	Output	kg	0.19	Literature
Soil emission of Lead (Pb)	Output	kg	0.33	Literature
Soil emission of Zinc (Zn)	Output	kg	1.51	Literature
N avoid	Output	kg	13.09	Calculated
P avoid	Output	kg	4.32	Calculated
N-fertilizer avoid	Output	kg	81.8	Calculated
P-fertilizer avoid	Output	kg	107.975	Calculated
CHP				
Electricity	Input	kWh	65	Calculated
Recation Oxygen (O_2)	Input	kg	553	Calculated
Biogas (CO_2 and CH_4 138kg)	Input	kg	346	Calculated
Air emission of Carbon Dioxide (CO_2)	Output	kg	204	Calculated
Air emission of Water (vapour)	Output	kg	311	Calculated
Air emission of Carbon Monoxide (CO)	Output	kg	0.4	Estimated
Air emission of Nitrogen Oxide (NO)	Output	kg	0.3	Estimated
Air emission of Sulphur Dioxide (SO_2)	Output	kg	0.1	Estimated
Aviod electricity	Output	kWh	606.55	Calculated
Avoid coal produced heat	Output	kWh	1126.45	Calculated

Scenario 3 (Scenario * per FU = 1000 kg DM sludge)	Direction	Unit	Amount	Source
Thickening				
Electricity	Input	kWh	50	Literature
Polymer	Input	kg	4	Literature
Raw sludge (1000 DM)	Input	kg	100000	Calculated
Thickened Sludge (1000 DM)	Output	kg	25000(2501	Calculated
Removed water	Output	kg	75000	Calculated
Anaerobic Digestion				
Electricity	Input	kWh	88.56	Literature
Thickened Sludge (1000 DM)	Input	kg	25000(2501	Calculated
Biogas (CO2 and CH4 138kg)	Output	kg	346	Calculated
Raw Digestates	Output	kg	24654	Calculated
Raw Digestates Dewatering				
Electricity	Input	kWh	49.09	Literature
Raw Digestates	Input	kg	24654	Calculated
Polymer	Input	kg	5.5	Literature
Digestates	Output	kg	2618	Calculated
Removed water	Output	kg	22036	Calculated
Transport (Truck)				
Distance (diesel)	Input	km	40	Literature
Land Use				
Electricity	Input	kWh	58.5	Literature
Diesel	Input	kg	0.73	Literature
Soil emission of Chromium (Cr)	Output	kg	0.08	Literature
Soil emission of Copper (Cu)	Output	kg	0.19	Literature
Soil emission of Lead (Pb)	Output	kg	0.33	Literature
Soil emission of Zinc (Zn)	Output	kg	1.51	Literature
N avoid	Output	kg	13.09	Calculated
P avoid	Output	kg	4.32	Calculated
N-fertilizer avoid	Output	kg	81.8	Calculated
P-fertilizer avoid	Output	kg	107.975	Calculated
Upgrading (remove other air emission)				
Electricity	Input	kWh	186	Calculated
Biogas (CO2 and CH4 138kg)	Input	kg	346	Calculated
Air emission of Carbon Dioxide (CO2)	Output	kg	204	Calculated
Biomethane (CO2 and CH4 138kg)	Output	kg	142	Calculated
Transport (Pipe)				
Distance (Electricity)	Input	km	40	Estimated
Biomethane USE (vehicle)				
Biomethane (CO2 and CH4 138kg)	Input	kg	142	Calculated
Recation Oxygen (O2)	Input	kg	553	Calculated
Air emission of Carbon Dioxide (CO2)	Output	kg	204	Calculated
Air emission of Water (vapour)	Output	kg	311	Calculated
Air emission of Carbon Monoxide (CO)	Output	kg	0.4	Estimated
Air emission of Nitrogen Oxide (NO)	Output	kg	0.3	Estimated
Air emission of Sulphur Dioxide (SO2)	Output	kg	0.1	Estimated
Total energy	Output	kWh	1914	Calculated
Fuel aviod	Output	kg	162.48	Calculated

Appendix C

Gabi 6.0 result in LCA (for Figure 22, 23 and 24), per FU = 1000 kg DM sludge

Scenario 1	Polymer Production	Composting	Diesel refinery	Electricity production	Transport	Land use	
GWP 100	15.30	709.00	5.04	77.50	21.40		
AP	0.04	43.20	0.06	0.37	0.04		
EP	0.00	9.45	0.01	0.02	0.01		
ODP	2.93E-09		9.57E-10	6.91E-08			
ADP ele	4.24E-06		2.04E-06	1.06E-05		-3.73E-05	
ADP fps	619.00		759.00	1360.00			
HTP	0.35	2.70	1.13	5.39	0.02	1510.00	
POCP	0.01		0.01	0.02	-0.02		
Scenario 2	Polymer Production	CHP	Diesel refinery	Electricity production	Transport	Land use	
GWP 100	16.10	204.00	3.41	150.00	31.30		
AP	0.04	0.27	0.04	0.71	0.06		
EP	0.00	0.04	0.00	0.04	0.02		
ODP	3.09E-09		6.47E-10	1.35E-07			
ADP ele	4.47E-06		1.38E-06	2.06E-05		-2.38E-05	
ADP fps	654.00		513.00	2640.00			
HTP	0.37	0.37	0.76	10.50	0.03	1610.00	
POCP	0.01	0.02	0.00	0.04	-0.03		
Scenario 3	Polymer Production	Upgrading	Diesel refinery	Electricity production	Transport	Land use	Energy use
GWP 100	16.10	204.00	3.58	208.00	33.00		
AP	0.04		0.04	0.99	0.06		0.27
EP	0.00		0.00	0.05	0.02		0.04
ODP	3.09E-09		6.80E-10	1.87E-07			
ADP ele	4.47E-06		1.45E-06	2.87E-05		-2.38E-05	
ADP fps	654.00		539.00	3660.00			
HTP	0.37		0.80	14.60	0.04	1610.00	0.37
POCP	0.01		0.00	0.06	-0.03		0.02

Appendix D

Sensitivity analysis of all variables for all environmental impact category

Item	Unit	Initial value	The % increase	The % chane in result							
				GWP	AP	EP	ODP	ADP ele	ADP fos	**HTP**	POCP
Scenario 1											
electricity	kWh	159.89	10.00%	**1.04%**	0.00%	0.00%	17.42%	-4.46%	5.66%	**0.00%**	-1.10%
polymer	kg	9.00	10.00%	**0.15%**	0.00%	0.00%	0.76%	-1.78%	2.83%	**0.00%**	-0.31%
diesel	kg	8.90	10.00%	**0.00%**	0.00%	0.00%	0.25%	-0.45%	2.02%	**0.00%**	-0.21%
Air emissio	kg	709.00	10.00%	**10.53%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**	0.00%
Air emissio	kg	27.00	10.00%	**0.00%**	11.02%	-47.64%	0.00%	0.00%	0.00%	**0.00%**	0.00%
Distance (tr	km	40.00	10.00%	**0.30%**	0.00%	0.00%	0.00%	-0.45%	1.62%	**0.00%**	0.84%
Soil emissio	kg	0.08	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**2.70%**	0.00%
Soil emissio	kg	0.19	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.12%**	0.00%
Soil emissio	kg	0.33	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**7.43%**	0.00%
Soil emissio	kg	1.51	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.68%**	0.00%
N in compo	%	1.60	10.00%	**-1.63%**	-0.36%	0.00%	-5.30%	0.09%	-0.12%	**-0.22%**	3.66%
P in compos	%	1.00	10.00%	**-0.74%**	-0.82%	62.83%	-2.78%	0.80%	-0.93%	**-0.05%**	7.31%
Scenario 2											
electricity	kWh	311.15	10.00%	**-3.18%**	-1.20%	-0.06%	-8.54%	-5.12%	-4.69%	**0.00%**	-1.38%
polymer	kg	9.50	10.00%	**-0.21%**	-0.17%	0.00%	-0.61%	-1.09%	-1.22%	**0.00%**	-0.23%
diesel	kg	0.73	10.00%	**0.00%**	0.00%	0.00%	0.00%	-0.02%	-0.17%	**0.00%**	0.00%
Air emissio	kg	204.00	10.00%	**-4.24%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**	0.00%
Distance (tr	km	40.00	10.00%	**-0.64%**	-0.17%	-0.03%	0.00%	-0.32%	-0.87%	**0.00%**	0.79%
Soil emissio	kg	0.08	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**2.61%**	0.00%
Soil emissio	kg	0.19	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.12%**	0.00%
Soil emissio	kg	0.33	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**7.17%**	0.00%
Soil emissio	kg	1.51	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.65%**	0.00%
Air emissio	kg	0.40	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**	-0.36%
Air emissio	kg	0.30	10.00%	**0.00%**	-0.34%	-0.06%	0.00%	0.00%	0.00%	**0.00%**	-0.30%
Air emissio	kg	0.10	10.00%	**0.00%**	-0.17%	0.00%	0.00%	0.00%	0.00%	**0.00%**	-0.16%
N in digesta	%	2.00	10.00%	**2.75%**	3.09%	0.13%	1.59%	0.07%	0.05%	**-0.25%**	2.96%
P in digesta	%	2.20	10.00%	**0.85%**	3.61%	9.82%	0.49%	0.27%	0.24%	**-0.03%**	2.96%
Avoided ele	kWh	1733.00	10.00%	**15.25%**	5.33%	0.27%	16.24%	10.26%	16.34%	**-0.29%**	5.91%
Scenario 3											
electricity	kWh	432.15	10.00%	**-7.89%**	-2.29%	-0.08%	12.21%	-24.33%	-11.24%	**0.00%**	1.68%
polymer	kg	9.50	10.00%	**-0.75%**	-0.23%	-0.01%	0.00%	-4.19%	-1.87%	**0.00%**	0.20%
diesel	kg	0.73	10.00%	**0.00%**	0.00%	0.00%	0.00%	-0.84%	-0.12%	**0.00%**	0.00%
Air emissio	kg	204.00	10.00%	**-7.52%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**	0.00%
Distance (tr	km	40.00	10.00%	**-1.50%**	-0.23%	-0.03%	0.00%	-1.68%	-1.56%	**0.00%**	-0.72%
Soil emissio	kg	0.08	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**2.56%**	0.00%
Soil emissio	kg	0.19	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.11%**	0.00%
Soil emissio	kg	0.33	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**7.04%**	0.00%
Soil emissio	kg	1.51	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.64%**	0.00%
Air emissio	kg	0.40	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**	0.32%
Air emissio	kg	0.30	10.00%	**0.00%**	-0.46%	-0.05%	0.00%	0.00%	0.00%	**0.00%**	0.23%
Air emissio	kg	0.10	10.00%	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.00%	**0.64%**	0.00%
N in digesta	%	2.00	10.00%	**4.89%**	4.13%	0.13%	-1.76%	0.25%	0.09%	**-0.24%**	-2.60%
P in digesta	%	2.20	10.00%	**1.50%**	4.82%	9.54%	-0.54%	0.92%	0.44%	**-0.03%**	-2.60%
Avoided die	kg	162.48	10.00%	**22.18%**	4.59%	0.59%	-0.72%	18.46%	25.30%	**-0.09%**	13.58%