A Life Cycle Assessment of Sewage Sludge Treatment Options

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ABSTRACT

The enactment of the EU water directive resulted in the production of huge amounts of sewage sludge from waste water treatment plants; consequently it becomes necessary that this excess sludge be managed in an economically and environmentally acceptable way. This study is focused on the use of Life cycle assessment to compare different options for the treatment of sewage sludge so as to determine which method is more environmentally friendly. Four treatment options are analysed and they include cement kiln incineration, agricultural land application of digested sludge, composting and finally fluidised bed incineration. The Life Cycle Assessment tool used for evaluating the environmental performance of these treatment options is based on the ISO14040 series which defines LCA as the compilation and f evaluation of the inputs, outputs and potential environmental impacts of a system throughout its life cycle; from the production of raw materials t the disposal of the waste generated. This study uses data from existing sewage sludge treatment and thermal treatment facilities.

According to the results of the study, As far as composting and agricultural application of sewage sludge is concerned, much research needs to be carried out to establish the exact amount of heavy metals that is effectively take up by plants and crops as well as the amount transferred to another phase like leachate. (Hospido et al 2005). Also, though thermal processes such as incineration in cement kilns and fluidised bed incineration prove to be promising technologies vis-à-vis global warming and energy recovery, more efforts are still needed to improve the valuable, viable products as nutrients are lost during the process. Moreover, these conclusions are base only on one impact category and since it is the subject of current debates and research, it is not surprising that most researchers use only this impact category to make their conclusions. It is worth noting that an evaluation of the environmental impacts of sewage sludge treatment should be based on an analysis of the effect of the treatment options on the different impact categories so as to be able to get a clear picture of the consequences of using these technologies. As indicated by the study, the thermal treatment scenarios show the best results only for the impact category of global warming. This is however not true for the other two impact categories Acidification and Eutrophication. An inclusion of other impact categories shows composting to be the bets scenario so far (see appendix); it is thus necessary when analysing the effects of sludge treatment systems to analyse the effects on all impact categories

Keywords: life cycle assessment, sewage sludge, green house gas emissions, global warming, energy, fertilisers

PREFACE

This report presents a comparative analysis of four treatment options for sewage sludge with focus on their environmental impacts in terms of global warming, acidification and eutrophication.

The study is conducted by Ngelah Sendoh Akwo, as master thesis for the study programme Environmental Management at the department of Development and Planning, Aalborg University.

The method of reference is according to the Chicago style where the author's surname and year of publication is referred to. In the case of two or three authors all surnames are noted whereas in the case of more than three authors the primary authors surname is given along with 'et al'. For a publication where no author is given, the organisation behind the publication is noted. If the year of publication is not stated, it will be referred to as 'n.d' which is an abbreviation for no date. Figures and tables are numbered according to the number of the chapter and a continuous number. The appendices of the report are available at the end of the report.

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CHAPTER ONE
INTRODUCTION

Huge amounts of sewage sludge that need to be handled are generated all over the world from waste water treatment plants. Its management in an economically and environmentally acceptable way has become a matter of increasing importance during the last few years (Hospido et al 2005).

1.1 General Overview

1.1.1 Current situation

Several factors contribute to the existing trends in waste generation and include economic activity, demographic changes, technological innovations, life style and patterns of production and consumption. Hence in order to achieve a successful management of waste generated, these factors also have to be taken into consideration. The generation of waste reflects a loss of materials and energy thus imposing economic and environmental costs on society for its collection treatment and disposal. How waste impacts on the environment is largely dependent on its quantity, nature and the waste management option chosen for its treatment. The quantity of waste is an indicator of the material efficiency of a society, since excess amounts of waste imply an enormous loss of resources in the form of material and energy. High quantities of waste can result from inefficient production processes, poor durability of goods and unsustainable consumption patterns.

It can be said that, the more civilised a society becomes, the more problems with waste management arises. A permanent and efficient handling of increasing and more hazardous quantity of waste material has become an issue of global concern. Each material quantity, even the most minor one, and its uncontrollable return to nature, represents handing down one and the same problem to generations to come. Interest in environmental issues is constantly increasing and at the same time, environmental issues have gradually been expanded with concepts such as sustainable development which includes in economic and social as well as ecological responsibilities. A far more complex problem now, is the management of sewage sludge which is one of the most significant challenges in waste management. Recently, it has become a matter of public health concern in the EU and the world at large. The EU directives and guidelines are increasingly promoting wastewater treatment and subsequently, sewage sludge generation in EU countries hence despite the use of wastewater treatment plants; the generated sewage sludge has to be properly managed (Ristic 2005, Fytili & Zabaniotou 2006).

Sewage sludge is formed during waste water treatment; waste water , which is a combination of the liquid or water-carried wastes removed from residential, institutional, commercial and industrial establishments contain certain components such as organic, inorganic and toxic substances as well as pathogenic or disease causing microorganisms. In its untreated form, waste water is not fit for disposal because first, the biological decomposition of organic materials in the waste water consumes oxygen thus reducing the quantity available in the receiving waters for aquatic life. The decomposition produces large amounts of malodorous gas. Secondly, there are numerous pathogenic microorganisms in untreated wastewater which are health hazards to humans. Thirdly, its toxic components especially heavy metals can be dangerous to both plants and animals. Finally, also present are the elements phosphate and nitrogen which may lead to uncontrolled growth of aquatic plants. All these components reside in the sewage sludge obtained from wastewater treatment; hence it is necessary to manage these organic components, nitrogen, phosphorous, toxic compounds and also to destroy the pathogenic microorganisms from the sludge. Consequently, the handling of sewage sludge must be such that it meets the requirements for efficient recycling of resources without supplying harmful substances to humans or the environment (Werther & Ogada, 1997).

Historically, most of the sludge was disposed by landfilling or applied directly or indirectly to agricultural land. Agricultural land application of sewage sludge is a predominant method for sludge disposal in the EU because sludge contains nitrogen and phosphorous for which gives it unique fertilising benefits, however its use is characterised by increasing problems related to increased input of organic contaminants, heavy metals and pathogens into the soil and food chain associated with arable land. In addition, there is increasing public apprehension and an ongoing debate in the EU on whether to promote sludge use in agriculture (Fytili & Zabaniotou 2006). The percentage of sludge going for agriculture in Denmark has greatly reduced when compared to previous years. From 1995 to 2001, the relative fraction of sewage sludge used as fertiliser decreased from 70% to 60% as a result of increasing quality requirements for sludge with municipalities demanding stable and long term solutions. New regulations on the use of sludge in agriculture have been set (Statutory order no. 49 of January 20, 2000 on the Application of Waste Products for Agricultural Purposes) and these are considered sufficiently strict to reduce risks to an acceptable level (Jensen & Jepsen 2004).

In the EU, dry weight per capita production of sewage sludge resulting from primary, secondary and tertiary treatment is in average 90g per person per day. The problems related of sludge management can be attributed to two factors;

- increase in volumes of sewage sludge produced by urban waste water treatment plants (Council Directive 91/271/EEC, *concerning urban waste water treatment*)
- reduction in the amount of biodegradable waste going to landfills (Council Directive 1999/31/EC, *on landfill of waste*)

The implementation of the Urban Wastewater treatment directive 91/27/EEC led to 50% increase in sludge production by the year 2005 that is 10 million tons annually. This directive was introduced so as to improve the aqueous environment through treating municipal wastewater before releasing it, which at the same time, avoids possible adverse effects where such discharges occur. In addition, with the enactment of the EU Landfill Directive 99/13/EC, it is obligatory to reduce the amount of biodegradable wastes deposits to landfills by the end of 2010 to 75% of production starting in the year 1995. This implies there is pressure for reducing the share of sewage sludge going to landfilling. With the above mentioned arguments it can be concluded that, there will be a significant increase in sludge production and this is the main drawback which takes further the issue of sludge handling. This is because it now becomes necessary to find appropriate disposal or recycling routes for sewage sludge produced (Fytili & Zabaniotou 2006).

Notwithstanding, sewage sludge represents a source of material, energy and nutrients, it is possible to utilise it as raw material for industrial production, energy production and soil amendment. There exist several processes through which sewage sludge can be converted into useful output and this includes co-incineration and mono-incineration with energy recovery, anaerobic digestion with biogas production and aerobic composting, pyrolysis, gasification and wet oxidation processes (to name a few). The choice of a sludge management technology from the available options should be based on their environmental effect that is which technology produces less impact on the environment. At first, decisions related to choice of the most efficient sludge management strategy were made with main focus on economic, technological and societal constraints; however, assessment of the overall sustainability of sludge management is now becoming an important aspect in decision-making. As the publics' interest on the environmental effects of the management options chosen for sludge treatment increases, industries are beginning to adopt the clean technology approach and assessment of environmental impacts of alternative processes, in process evaluation (Poulsen & Hansen 2003).

1.1.2 EU Legislation concerning Sewage Sludge

Waste management as one of the key priorities of the EU environmental policy, has undergone a lot of changes over the past years; waste minimisation and recycling/reuse policies have been introduced so as to reduce the amount of waste generated and alternative waste management strategies are being exploited, to reduce the environmental impacts of waste management (IPCC 2006). The Sixth Environmental Action Programme (2002-2012) called for a decoupling of environmental pressures from economic growth followed by a significant reduction in

- volumes of waste generated
- quantity of waste going to disposal (landfill and incineration with no or low rates of energy recovery)
- volumes of hazardous waste produced

The European Commission further proposed its Thematic Strategy on Prevention and Recycling (2005) where it states that 'the long term goal for the EU is to become a recycling society that seeks to avoid waste and uses waste as a resource'. As a result of these, Europe's leadership on policies to tackle climate change has increased and there is a growing awareness among policy makers and scientists on the interface between waste management policies and policy to tackle climate change (EEA Briefing No.1 2008).

EU waste policy is currently based on the waste hierarchy which was first introduced into European waste policy in the European Union's Waste framework Directive of 1975. Taking its point of departure from the precautionary principle, it prioritizes the prevention and reduction of waste, its reuse, recycling and finally optimisation of its final disposal. This hierarchy is fundamental in designing national policies to reduce dependence on the use of landfills as a waste management option. The waste hierarchy can be regarded as a general guiding principle, for a more flexible approach to develop strategies for improvements. The options recycling and recovery are usually chosen over those that do not result in the recovery of energy or material resources, while the options at the bottom of the hierarchy are considered essential for obtaining a balanced strategy. This interpretation is an essential element in the concept of integrated waste management. (SITA 2004)

The main legislation of concern here is the EU directive on Urban Waste water treatment (91/271/EEC) and the Sewage Sludge Directive 86/278/EEC. The former is primarily aimed at minimising pollution from sewage by requiring that sewage discharge should undergo some treatment before being discharged. This directive also banned the disposal of sewage sludge into the sea (a practice which originally accounted for 30% of sewage sludge disposal) by the end of 1998. The directive stipulates that sewage sludge be reused whenever possible and the environmental impacts from the chosen disposal option be minimised. The challenge now faced by the members of the EU is how to a) maintain cost effective and environmentally secure methods for sewage sludge disposal and b) increase public confidence in the option chosen. The latter seeks to encourage the use of sewage sludge in agriculture. At the same tome, it regulates its use in such a way that any potential harmful effect on soil, vegetation, animals and human beings is prevented. According to the above principle, use of untreated sludge in agriculture is prohibited, unless it is injected or incorporated into the soil. Moreover, the term treated sludge is defined as sewage sludge which has undergone biological, chemical or heat term, long term storage or any other appropriate process so as to significantly reduce its ferment ability and the health hazards resulting from its use.

The EU waste management policy exploits the principle of sustainable development through the use of the waste hierarchy which supports policy in this area. To ensure an efficient choice of a waste management system, the use of specific tools is necessary; in order to attain a sustainable waste management, a society's waste has to be treated in a way that is environmentally efficient, economically affordable and socially acceptable. Assessing such sustainability requires the use of tools capable of predicting the likely environmental burdens of any waste management system. Life Cycle Assessment (LCA) can be applied to waste management systems to assess their overall environmental burdens (Coleman et al 2003).

1.2 Problem Formulation

Waste is a resource and the future challenge is to limit the amount of resource lost as much as possible in an environmentally efficient and economically viable way. The Danish government, in its waste policy, outlines its strategies based on three fundamental elements:

- prevention of resource and environmental load associated with waste
- decoupling the increase in the amount of waste from economic growth
- The greatest environmental benefit for investment through improved waste management quality and a more effective waste sector.

The Danish waste strategy for 2005-2008 outlines the guidelines for the Governments waste policy. This waste strategy is a continuation of waste 21(1998-2004) and it implements the national waste management initiatives compulsory for all EU member states. In Denmark, there exists a close interplay between EU regulation and national regulations on waste. In Waste 21, the governments plan for the Danish waste is a change of focus so as to attain environmental improvement of waste management in Denmark. Focus was primarily on the quantitative aspect of waste management but recently, it is increasingly based on qualitative targets: increasing the quality of waste treatment so as to promote less impact from environmental contaminants and better resource utilisation (Danish EPA 1999).

Recently in the EU, increasing quantities of waste water is being treated to reduce the outlet of eutrophying substances into the aquatic environment. This has led to an increased production of sewage sludge. Total production of sludge increased in Denmark since the beginning of the 1980s following the initiation of large investments in the construction of waste water treatment plants. The subsequent years have been characterised by a stabilisation of sludge production between 150,000 and 160,000 tons d.m per year with a drop to 140,000 ton d.m in 2002. Historically, Danish sludge has been end-deposited in 3 major ways; used as fertiliser on agricultural land, disposed on controlled dumpsites or incinerated internally at waste water treatment plants (WWTP) or externally at large incineration plants. From 1995 to 2001, the fraction of sewage sludge used as fertiliser by farmers, decreased from 70% to 60% following legislation with increasing requirements for the use of sludge and a demand from the municipality for a stable and long term solution. It is the responsibility of the municipalities to dispose the sludge and the have to make a choice among the available options. Hence, for this to be possible there is a need for a better understanding of the implications associated with each given option (Jensen and Jepsen 2004).

The main focus of this study is to assess the effectiveness of alternative waste management systems for sewage sludge treatment in Denmark, more specifically Aalborg municipality, vis-à-vis their environmental impacts, so as to determine which option is better and if it can be optimised for better efficiency. Environmental impacts associated with the chosen treatment technologies would be analysed and these impacts include green house gas emissions, heavy metal emissions as well as resource use and energy used. Sewage sludge treatment contributes to several impact categories but the primary focus of this study would be on global warming and non-renewable resources (nutrients and fossil fuels), acidification as well as eutrophication.

The research question is formulated as thus;

How environmentally efficient is the treatment of sewage sludge, in the Aalborg municipality?

The following sub-research questions will serve as guide in answering the above question;

- To what extent do green house gas emissions from the existing sludge treatment options, contribute to global warming
- What other environmental impacts are associated with these treatment options,
- Which of the alternative sludge treatment options is more environmentally efficient in Aalborg and globally
- What existing policies are in place in EU and Denmark as concerns sludge management and how effective are they in ensuring the choice of an environmentally efficient sludge management system.

This study is a comparative analysis of the sewage sludge treatment options practised in Denmark more specifically, the Aalborg municipality as concerns technology used, so as to determine which is most environmentally efficient. Also the study will try to decipher why policy makers maximise on certain options and what aspects of sustainability are taken into consideration when making these policies. The Life Cycle Assessment methodology according to ISO14040 would be the main tool used in this study and the computer software tool used for analysis of impacts is SimaPro.

1.3 Content of Chapters

Chapter One gives a general overview on sewage sludge and also the directives set by the EU vis-à-vis sludge management. It also embodies the statement of the problem and the research questions formulated as an attempt to decipher the problem. Finally, it gives an insight into the contents of the different chapters.

Chapter Two reveals the methodology used to carry out the research as well as the concepts/tools that would serve as backbone to fulfilling the demands posed by the study questions. Life Cycle Assessment and Integrated solid waste management are the main concepts adopted for this study

Chapter Three gives an overview of the existing policies and legislations on waste management in Denmark and how effective they are in ensuring the implementation of effective waste management systems.

Chapter Four is primarily focused on the goal and scope definition of the study. It describes the goal of the study and intended application as well as the scope of the study in terms of system boundary and technologies included.

Chapter Five gives a detailed presentation of the scenarios considered in this study and this includes the use of articulate flow diagrams linking the different processes considered.

Chapter Six is a life cycle inventory of each scenario. This is a representation of the inputs and outputs of all the processes considered in the chosen scenarios.

Chapter Seven gives the life cycle impact assessment methods, impact categories and characterisation factors used in the comparative analysis of the different scenarios chosen. It also embodies the Interpretation phase (last phase) of the Life Cycle assessment used in this study, and represents an analysis of the findings obtained from the developments made in the computer software SimaPro.

Chapter Eight is a conclusive chapter in that it provides a summary on the findings obtained in the study and as well provides recommendations as concerns optimisation of existing technologies as well as possible adjustments in existing waste policies so as to promote sustainable waste management practices as far as sewage sludge management is concerned.

CHAPTER TWO

This chapter gives an overview of the methodological framework as well as the theories and concepts and tools used to carry out this study and this includes a description of the Life Cycle Assessment tool and the SimaPro computer software used.

2.1 Life Cycle Assessment

Due to an increased awareness of the importance of environmental protection and the possible impacts associated with product systems, there has been an increased interest in the development of methods to better understand and address these impacts. As defined in ISO14040 (2005), Life cycle assessment is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system or service throughout its life cycle. LCA takes into consideration the environmental aspects throughout a products life cycle starting from raw material acquisition through production, use, end of life treatment, recycling and final disposal. LCA is very efficient in identifying opportunities to improve the environmental performance of products at various points of their life cycle; inform decision makers in industry, government etc. in relation to strategic planning, priority setting, to name a few. It can also assist in the selection of indicators of environmental performance including measurement techniques and marketing.

The application of LCA to product and services is thus becoming a useful tool in decision making, processes and system performance documentation. There is increasing interest in the use of LCA in the waste management sector, as the problem of waste management is increasingly becoming a pertinent issue. The application of LCA in a waste management perspective is specifically targeted towards;

- Identifying the most environmentally significant processes occurring during waste treatment
- Identifying the most significant environmental burdens during a waste treatment scenario
- Identifying whether improvement proposals result in local optimisation or if they are environmentally better for the whole waste management system.
- Assessing the environmental performance of a waste management scenario in a life cycle perspective. Here, the assessment of several scenarios can be used to compare the performance of alternative systems (Bjarnadottir et al 2002).
-

2.1.1 Methodological Framework for Life Cycle Assessment

LCA is conducted in accordance with the principles and framework described in the ISO14040 series. LCA is made up of four phases which is described in the ISO 14040 - 43 standard series. They include ISO 14041 – Goal and Scope Definition; ISO 14041 – Life Cycle Inventory (LCI); ISO 14042 – Life

Cycle Impact Assessment (LCIA) and ISO 14043 – Life Cycle Interpretation. The concept of life cycle methodology is depicted on figure 2.1

2.1.1.1 Goal and Scope definition

The goal and scope of and LCA must be clearly defined and be consistent with the intended application. Since LCA is an iterative process, this phase may be revisited and readjusted during the study.

1. *Goal of study*

During goal definition in LCA, the following must be clearly stated;

- the intended application
- the reasons for carrying out the study
- the intended audience
- Whether the results would be used in comparative assertions with the aim of disclosing to the public.

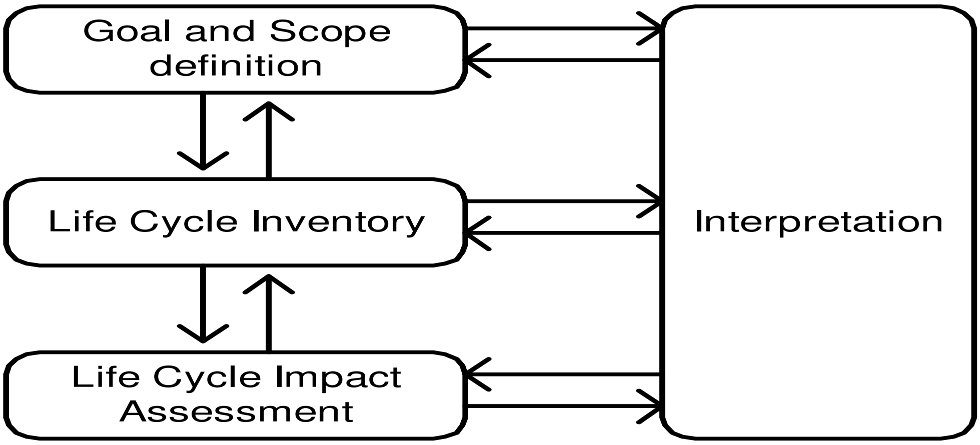

Figure 2.1: The Phases of LCA according to ISO 14040

2. *Scope of study*

The scope of a study defines the system, boundaries, data requirements, assumptions and limitations. The scope should be defined in detail to ensure that the whole analysis is compatible with and sufficient to address the stated purpose. All data boundaries, methodology, data categories and assumption should be clearly stated and should include geographical extent (local, national, regional, continental and global) and time (product life, tome horizon of processes and impacts).

- Product system, Function and Functional unit

The product or service system must be clearly stated as well as the performance characteristics of the system being studied. The functional unit must be consistent with the goal and scope of the study. The primary purpose of the functional unit is to provide a reference to which input and output data can be normalised. Comparison between systems must be made on the basis of the same function(s) quantified by the same functional unit(s) in the form of reference flows. By definition, a reference flow is a measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

- System boundary

The system boundary determines the unit processes included within the LCA. System boundaries selected must be consistent with the goal of the study. Also, the criteria used in establishing the system boundary have to be identified and explained. The omission of certain life cycle stages, processes or outputs is permissible only if it does not significantly change the overall conclusions of the study and explanations must be provided. The system can be described using a process flow diagram showing the unit processes and their interrelationship. The cut-off criteria for initial inclusion of inputs and outputs and the assumptions on which the cut-off criteria are established must be clearly defined. Several cut-off criteria are used in LCA so as to decide which inputs to include such as mass, energy and environmental significance. In a case where the study is intended to be used in comparative assertions intended to be disclosed to the public, the final sensitivity analysis of the inputs and outputs data shall include the mass, energy and environmental significance criteria so that all inputs that cumulatively contribute more than a defined amount (e.g. percentage) to the total are included in the study (ISO14040 2005).

- LCIA Methodology and Types of Impacts

The impact categories have to be determined as well as defining category indicators and characterisation models. The selection of these, in the Life cycle impact assessment phase must be consistent with the goal of the study.

- Types and Sources of Data

Selected data are dependent on the goal and scope of the study and these data may be collected from the production site associated with the unit process within the system boundary or they can be obtained or calculated from other sources. Source of data may include measured, calculated or estimated data.

- Data Quality Requirements

Data in LCA is defined as the degree of confidence in individual input and output data set as a whole. Data quality requirement should take into consideration aspects such as time related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility as well as the source of data.

2.1.1.2 Life Cycle Inventory

According to SETAC(1993) the LCI phase is an objective data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste and other environmental releases incurred throughout the life cycle of a product, process or activity. This is carried out through direct measurements, theoretical data, energy balances or statistics from databases and publications. This assessment is carried out through out the entire life cycle and the quality of data used is of primary concern due to the broad scope of the study. Aspects of the LCI phase include

- Defining systems and system boundaries: systems are defined not only in terms of their functions but also vis-à-vis geographical boundaries and technosphere and nature.
- Data collection: detailed data in the form of input (material and energy) and outputs (product releases to air, water and land), data variability, uncertainty and sensitivity analysis. Sensitivity analysis is carried out to test the effects of the results and possible limitations on the conclusions
- Allocation Procedures: when one or more useful output is produced in a subsystem, there arises the need for a consistent way to identify those inputs and outputs attributed to the system of interest in the study.

2.1.1.3 Life Cycle Impact Assessment

This is a technical, quantitative/qualitative process to characterise and assess the effects of the environmental burdens identified in the LCI phase. This includes the following elements;

- selection of impact categories, category indicators and characterisation models
- Assignment of LCI results to the selected impact categories (classification).
- Calculation of category indicator results (characterisation)

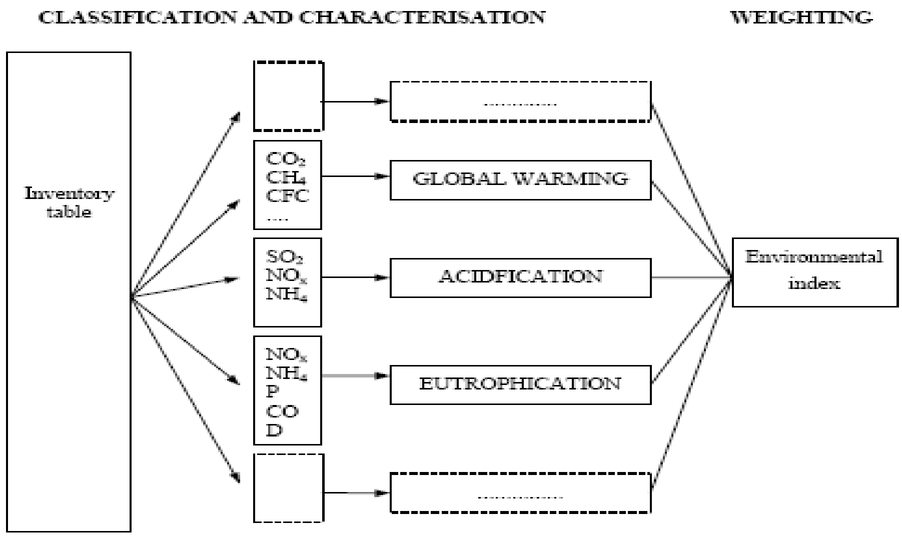

Figure 2.2 An overview of the steps followed in LCIA (Finnveden et al. 2000,19)

Classification involves grouping of data in an inventory table into different impact categories, while characterisation is the quantification, aggregation and analysis of impact data within the impact categories (Welford 1997). An impact category is a class representing environmental issues of concern to which LCI results may be assigned (ISO14044 2006). The selection process of the impact categories, category indicators and characterization models shall be both justified and consistent with the goal and scope of the LCA. A category indicator is a quantifiable representation of an impact category (ISO 14044 2006). Characterisation models according the ISO14044 (2006) reflect the environmental mechanism by describing the relationship between the LCI results, category indicators and in some cases category endpoint(s). It is used to derive the characterization factors. The environmental mechanism is the total of environmental processes related to the characterization of the impacts. An example of the terms used the characterisation process is presented in table 2.1.

Table 2.1: Example of terms in characterisation process (ISO 14044 2006, 26

Terms	Example
Impact Category	Climate Change
LCI Results	Amount of GHG emission per functional unit
Characterisation Model	Baseline model of 100 years of the Intergovernmental Panel on Climate Change
Category Indicator	Infrared radiative forcing (W/m^2)
Characterisation Factor	GWP100 for each GHG ($kgCO_2$-equivalents per functional unit)
Category indicator result	kg of CO_2-equivalents per functional unit

Valuation involves the processes of normalisation and weighting. Both processes of valuation are optional elements according to the ISO 14042 (2000). Normalisation "*provides a basis for comparing impact categories by dividing the scores to 'something' we can relate to – a normalisation reference)*12" (Thrane and Schmidt 2005, 231). Weighting helps to evaluate the significance of each impact category using weighting factors. The assigning of weighing factors to the different impact categories eases the purpose of comparison based on perceived importance.

2.1.1.4 Interpretation

This is the last phase of an LCA and consists of the following;

- Identification of the significant issues based on the results of the LCI and LCIA phases of LCA
- Evaluation to analyse completeness, sensitivity and consistency checks
- Conclusions, limitations and recommendations

The goal and scope definition and interpretation phases of an LCA frame the study while the LCI and LCIA phases provide information on the product system studied. Some of the major flaws associated with LCA as presented in the ISO 14040 (2006) are firstly, the nature of the choices and assumptions made in LCA, e.g. system boundaries and data selection may be subjective and value laden. Also, models used to assess the environmental impacts are limited by their assumptions and may not be available for all potential impacts or applications. Thirdly, the accuracy of LCA studies may be limited by accessibility or availability of relevant data or by data quality e.g. types of data, site-specificity and aggregation. Lastly, the lack of spatio-temporal dimensions in the inventory data used for impact assessment introduces uncertainty in impact results. However, it is claimed that information developed in an LCA study should be used as part of a much more comprehensive decision process or used to understand the broad or general tradeoffs (ISO 14040 2006).

2.1.2 LCA Methodology

2.1.2.1 Allocation Procedures in Consequential LCA

In many subsystems, more than one useful output or product is produced; treatment of pollutants from several subsystems may take place in a single unit operation, a system may have an open-loop recycling element. According to ISO14040, processes that are shared with other product systems have to be identified and dealt with using any of the following procedures:

1. Whenever possible, allocation should be avoided by
    - dividing the unit processes to be allocated in two or more sub-processes and collecting the input and output data related to these sub-processes
    - Expanding the product system to include the additional functions related to the co-products.
2. In cases where allocation cannot be avoided, the inputs and outputs of the system should be shared between the different products or functions in a way that reflects the underlying physical relationship between them.
3. Where it is impossible to establish physical relationship or use it as a basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them (ISO14040)

A consequential LCA models the causal relationship originating at the decision at hand or the decision maker that the LCA is intended to inform that is to say, it includes activities within and outside the life cycle that are affected by a change within the life cycle of the product under investigation. On the contrary, attributional LCA applies to situations where no specific change is planned e.g. hotspot identification, for setting priorities that do not immediately involve a change. The consequential LCA model requires the use of marginal data and that allocation be avoided by system expansion.

1. Allocation for Multifunctional Processes

It is relevant to note that different approaches to allocation are relevant to different situations. This section deals with allocation for multifunctional processes which is quite different from allocation for open-loop recycling because different methodological descriptions apply for the two cases. Figure 2.2 gives an illustration of a theoretical multifunctional process.

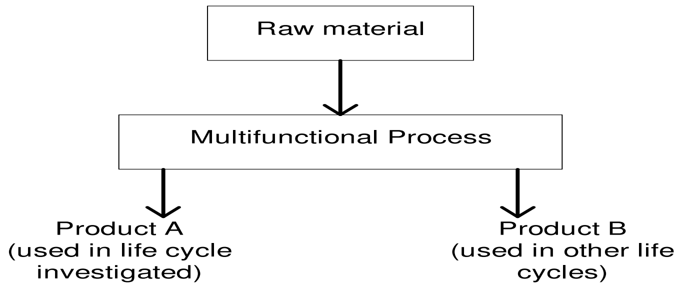

Fig. 2.2 Illustration of a Theoretical Multifunctional Process (Ekvall and Weidema 2004)

In order to give an example of how allocation is carried out for multifunctional processes, the case taken into consideration is a situation where the production of B depends on the production of A. here it is clear that any action would have a significant effect on the production of both products since the production volume of A and B is determined by the demand for A. an increase in the production or demand for A would result in an additional amount of B which is likely to replace another product fulfilling this function. In this case, all the environmental burdens from the multifunctional process in the system investigated must be taken into consideration. This solution is justified by the fact that the objective of a consequential LCA is to include what is affected by a change in the use of product A (Ekvall and Weidema 2004).

2. Allocation for Open-loop Recycling

Open-loop recycling is the recycling of material from one product system into another. Here, the problem of allocation arises when material is recycled from the system investigated as well as when material is recycled into it. Usually, when material is recycled from the system investigated, it replaces other material recycled or virgin new products. The effect of this might be that less recycled material is used in other product systems or that landfill or waste incineration is reduced. According to the consequential LCA model, the system under study should be expanded to include the unit processes that are actually affected by an increase or reduction in the flow to/from the life cycle under investigation.

2.1.2.2 Time Aspects in Landfill Modelling

An important question in Landfilling is how the future emissions shall be handled in LCA, based on the fact that a landfill may give emissions for thousands or millions of years (Sundqvist 1999). This problem has been solved by a group of experts who assert that different time frames should be used depending on the aim and scope of the study. Sundqvist (1999) summarised the time period into two categories:

- *A Short Time Period (Surveyable Time Period)*: Defined as the time period until the landfill reaches some kind of pseudo-steady-state. It includes: specific time as 15, 50, or 100years; or responsible time (which usually should be 15-30years); or processes.

- *A Long Time period (Hypothetical, Infinite Period)*: when all Land filled materials has been released to the environment. It is also a worst-case scenario. It includes: specific time (e.g. 1 million years); a period until the emission reached an “acceptable” level; or a “background” level; or the infinite time.

2.2 SimaPro

SimaPro 7 is the computer software tool used to calculate and identify the pertinent environmental impacts associated with the sludge treatment technologies proposed in this study. This serves as a tool for managing and storing data, making calculations and sensitivity tests. The LCA phases are structured in SimaPro in accordance with ISO14040 and ISO14044 LCA standards.

2.2.1 Goal and Scope definition in SimaPro

A special section is available for a description of the goal and scope for each project. There exist three sections and these include;

- Text fields into which a description of the different aspects of the goal and scope definition can be made. Text entered here can be later copied and pasted into the report.
- A libraries section in which it is possible to predefine which libraries with standard data are considered relevant for the project to be run. For example, for LCA studies relevant to Europe, it is possible to switch off the USA-IO database and this avoids accidental inclusions of unwanted data.
- Data quality section where data characteristics can be predefined. (Pre Consultants 2006)

2.2.2 Inventory in SimaPro

In SimaPro process and product stages are easily accessible and system boundaries are used as additional documentation in some processes. Also, waste types are noted when handling materials in waste scenarios. This tool is well advanced in modelling the end of life phase, in modelling the end of life in SimaPro, two distinctions are made; waste scenarios and disposal scenarios. Waste scenarios refer to material flow without observing any product characteristics. In this category, information on how the product is split up into different components (sub assemblies) is lost while only information on the materials is maintained.

2.2.3 Impact Assessment in SimaPro

There exist a wide variety of impact assessment methods available in SimaPro. The basic structure of impact assessment methods in SimaPro is characterisation, damage assessment, normalisation and weighting. The last three steps are optional according to the ISO standards.

2.2.4 Interpretations in SimaPro

This is designed as a checklist which covers the relevant issues mentioned in the ISO standards used. As suggested by Pre Consultants (2006), observations are filled in when the LCA study is about to be completed and conclusions made.

CHAPTER THREE

This chapter gives an overview of waste management policies vis-à-vis sewage sludge disposal in Europe and more specifically, Denmark. The aim is to show how the overall sustainability of waste management is making its way into decision making and how clean technology approaches can be introduced so as to obtain an optimised waste management system.

3.1 General Overview

Waste can be considered a loss of both material and energy resources because an increase in its production results from inefficient production processes, low durability of goods and unsustainable consumption patterns which serve as an indicator of how efficiently society uses raw materials. As earlier mentioned, the EU uses the waste hierarchy as framework when developing its waste policies or legislation. This waste hierarchy is a conceptual framework which acts as a guideline to waste management. It sets out optimal ways for dealing with waste in a preferential order. It aims to encourage individuals and businesses to produce less waste in the first place and thereafter, consider how value can be best recovered through its treatment. Disposal is considered a last resort.

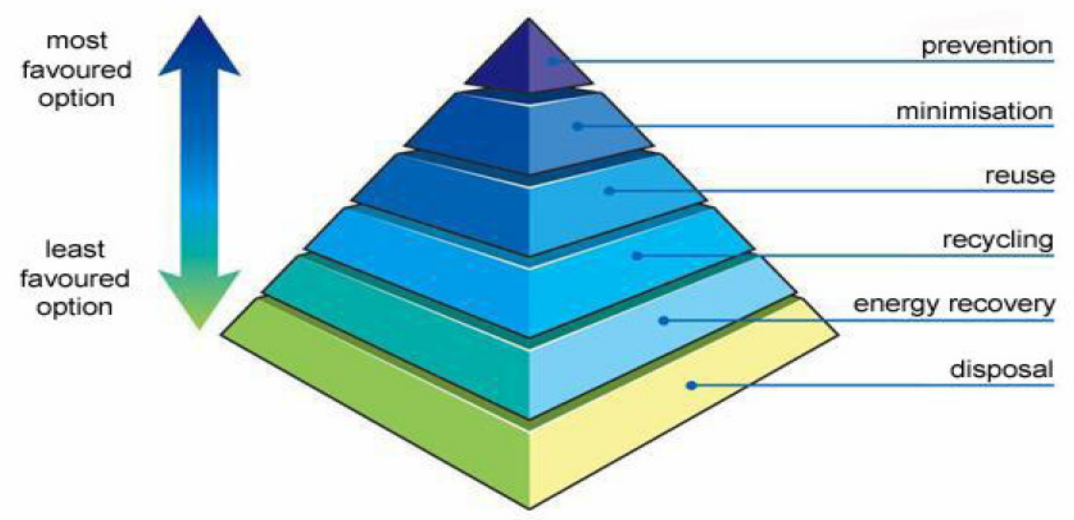

Figure 3.1: The Waste Hierarchy

The prevention and minimisation of waste is given the highest priority as stated in the EU council directive 75/442/EEC on waste;

'*Member states shall take appropriate steps to encourage firstly the prevention or reduction of waste production and its harmfulness'*

Thus the EU waste hierarchy defines the priorities in waste treatment and gives preference firstly to waste prevention then to recycling , followed by energy recovery and finally to disposal (EEA 2002). According to the Sixth Environmental Action Programme, waste management is one of the main priorities of EU environmental policy. However the framework put in place for waste management only acts as a backbone of waste management practice. There is the need for complementary action by member states and local authorities in order for the Waste Framework Directive to be efficient. Each member state is allowed to set up policies depending on its particular situation; it geography, governance, geology, public opinion and the existing waste facilities and infrastructure. The waste hierarchy is an environmental concept which is implemented in different ways in different countries working towards optimal waste management strategies. The concept of the waste hierarchy is expected to be further strengthened by the amended Waste Framework Directive whose final adoption is expected by the end of 2009.

3.2 EU Waste Policies (Directives on Waste)

The 6th Environmental Action programme provides overall guidelines to EU policy on environmental issues in general. It initiates different thematic strategies of which two of the strategies relates directly to waste and resource management: Taking sustainable use of resources forward: A thematic Strategy on the prevention and recycling of waste COM (2005) and Thematic Strategy on the Sustainable Use of Natural Resources COM (2005).The Landfill Directive (Directive 1999/31/EC on landfill of waste) is one of the most important waste policies in the EU and has as aim to reduce as much as possible the negative impacts associated with landfilling of waste. Landfilling of untreated waste is considered the worse option for the environment due to its emissions of CH_4, long term emissions to soil and water and groundwater as well as the loss of resources it entails. The landfill directive introduces stringent requirements for landfills and is aimed at diverting biodegradable municipal waste from landfills. Thus with the increasing quantity of biodegradable waste generated and the stringent targets set in the landfill directives, the EU member states are faced with a big challenge. However, though landfilling is the most prevalent method for waste disposal within the EU, there is a significant difference in how dependent member states are on this waste management option. Countries like Denmark, Netherlands, Sweden and Belgium, focus more on incineration and material recovery.

Another major set of directives, which are of major importance to this study (in that they regulate sewage sludge and have the strongest impacts on the production, disposal and recycling of sludge) are the Urban Waste Treatment Directive 91/271/EEC and the Sewage Sludge Directive 86/278/EEC. The first one focuses on the gathering of waste water and thus sets targets for its treatment while the second one ensures that sewage sludge is not a threat to neither health nor the environment when used in agriculture. Sewage sludge, besides being used in agriculture, can also be incinerated, and thus, the Incineration Directive 2000/76/EC (which regulates incineration of different wastes including sewage sludge) is also applicable (EEA 2007).

3.3 Waste Management in Denmark

In order to fulfil targets provided by the related directives on waste, member states have the obligation to set up national strategies for reducing the amount biodegradable waste going to landfills. The Landfill directive is expected to exert a major effect on the waste management system vis-à-vis waste recovery and waste prevention.

3.3.1 National Legislative Framework

The Danish environmental Protection Act and Associated Statutory Orders and circulars, give the legal framework which stipulates the obligation of local authorities to manage waste. Under the terms of the Danish EPA and the Statutory Order on waste, the local councils are given duties vis-à-vis waste management and these include;

- Ensuring that waste management is carried out in accordance with the waste hierarchy;
- Preparing both short and long term waste management plans covering 4 and 12 years respectively
- Establishing schemes to ensure an environmentally efficient management of waste generated.

Table 3.1 National Acts/Laws on waste management

Reference	Main features
Environmental Protection Act Consolidated Act No. 753 of 25 August 2001 (as amended)	Defines the responsibility of the local council in establishing capacity for waste management and for providing information on how to dispose of the waste It defines that new landfills must be owned by public authorities, and that whoever operates a landfill site must ensure that all costs related to establishment and operation
Statutory Order No 619 of 27 June 2000 on Waste (as amended	The most important Statutory Order on waste is Statutory Order on Waste No. 619 of 27 June 2000

3.3.2 National Policies on Waste

In Denmark, there is a close interplay between EU regulation and national regulations on waste. The overall framework is determined by the former while the Danish Folketing decides on organisation and legislation in the area of waste.

Table 3.2 National Waste Management Plans

Period of Implementation	Main Features
Waste Strategy 2005 - 2008	The Government's waste policy builds upon three fundamental elements: • Prevent the loss of resources and environmental impact from waste. • Decouple growth in waste from economic growth. • Ensure the improved cost-effectiveness of environmental policies through: • Improved quality in waste treatment. • An efficient waste management sector
Waste Management Plan 1998 - 2004	The future challenges are: • Stabilise total waste amounts • To improve quality in waste treatment, i.e. • Reduce environmental impact from environmental contaminants in waste. • Ensure better resource recovery.

3.3.2.1 Policy Instruments

The Danish waste model is based on traditional administrative instruments (act, orders, and circulars) and several economic instruments which cover taxes and charges and also includes subsidy schemes and agreements, and packaging deposit return systems. There exists a general tax on waste and this tax varies in that it is most expensive to landfill waste, cheaper to incinerate it and tax is exempt for recycling. State subsidy schemes are established for projects on cleaner technology that aim at reducing the environmental impacts from products in a life cycle perspective. Subsidies may also be assigned to projects that aim at solving waste problems such as developing new forms of treatment.

3.3.2.2 Sewage Sludge Management in Denmark

Waste can be differentiated into different categories and sludge falls in the category of waste coming from waste water treatment plants. Sludge resulting from wastewater treatment is very rich in fertiliser and energy content though it also contains a high degree of contaminants such as heavy metals and pathogens that are harmful to both human and the environment. Sewage sludge is to some extent, not fully utilised in Denmark. Historically, Danish sludge has been treated in one of three major ways;

- used as fertilizer on agricultural land

- deposited in controlled dumpsites (landfills)
- incinerated either internally at the WWTP or externally at large incineration plants

The use of sewage sludge as fertiliser on agricultural land was at first the most favoured waste management option but problems began to arise in relation in relation to eutrophication of streams, lakes and in seas thus resulting in a call for political action to reduce the amount of phosphorous and nitrogen leaching to the aquatic environment. Consequently a number of regulations were set up controlling the use and handling of sludge.

From 1995 to 2001, the fraction of sewage sludge used as fertilisers decreased from 70% to 60% as a result of increasing quality requirements for the sludge and municipalities demanding stable and long term solutions. New regulations were set up in Denmark on the use of sewage sludge in agriculture (Statutory Order no. 49 of January 2000 on the Application of Waste Products for Agricultural Purposes). The following years were characterised by a decrease in the amount of sludge used for agricultural land application and the implementation of alternative treatment methods. The debate on sludge recycling and disposal has been the target of growing interest and this can be attributed to expressed concerns about the potential risks of the agricultural use of sludge for health and the environment. There are doubts on the safety of products on the markets and the ability of existing regulations and controls to minimise human exposure to potential risks. A comparison with national legal requirements shows that *tight* legal constraints (such as low limit values for pollutants in sludge) do not necessarily imply a greater acceptance of the use of sludge for agriculture.

Some main positions vis-à-vis sewage sludge use for agriculture can be summarised as follows;

- The interest of farmers on the use of sludge for agriculture is mainly due to the supply of organic fertiliser at low cost. Here, difficulties arise from customers like food industries or retailers, who have specific quality requirements. In an increasing number of cases, these quality requirements include restrictions on and sometimes the prohibition of the use of sludge for agriculture. Consequently, farmers associated with the use of sludge in agriculture could face a reduction in their market share and a drop in profits. As a result, the said farmers (in countries where the debate is heated), insist that a guarantee system be set up which would cover them against possible risks in order to continue using sludge.
- Agri-food industries are mostly concerned wit marketing and public health. The brand image which is its most valuable asset must be protected from being tarnished. The industries' attitude is mainly influenced by the way in which the general public perceives the potential risks of using sludge in agriculture.
- National authorities have implemented policies which support the use of sludge in agriculture as a method of dealing with the increasing quantities of sludge. They are seeking to increase confidence in the quality and safety of products cultivated on sludge fertilised soils.

Summarily, the main areas of consensus on sludge disposal and recycling are that the increasing quantities of sludge have to be treated in such a way as to ensure that both environmental and economic costs are as low as possible. Also, improving practices as regards the treatment and use of sludge is considered very essential. The evolution of the debate on sludge disposal and recycling in Europe is an indicator of how the relationship between farmers and their customers (food industries and retailers) is crucial for the acceptance of use of sludge in agriculture.

3.4 Synthesis - What remains to be done

Environmental policy makers have to take into cognisance the impacts posed by pollutants that accumulate in the environment. Usually goals for regulation of these damages involve keeping long-term emissions below a level considered to be dangerous or banning certain products or practices and subsidization of more *green* alternatives. A number of directives have been drawn up to guide waste management in the EU so as to control the amount of pollution resulting from the waste sector and as earlier mentioned, each country further sets its national policies which aids them in meeting up with the demands of the directive. What is of importance now is whether the type of technologies used in meeting up these targets is the best available and most efficient as far as the environment is concerned.

Firstly, the choice of technology for sewage sludge management should be based on the stipulations of the waste hierarchy. Although national policies have been set up in Denmark to serve as framework for sludge management, it is the municipality concerned that determines which waste management system /technology to implement for sludge treatment. In order to ensure an effective sludge management system, the decision to go for a particular option should be based on fitness of purpose and on fair and economic evaluations that are not distorted by subsidies, for example. The waste hierarchy should be used to aid in determining the optimal management option for sewage sludge. However, this hierarchy should be applied flexibly to avoid maximisation of certain options such as reuse and recycling. The choice of which option to apply should be based on strict environmental and economic considerations taken as a case-by-case basis (cepi 2007).

Conclusively, the use of the waste hierarchy must be accompanied by flexible rules on how it should be applied. Where necessary, life cycle assessments and cost-benefit analysis should be carried out. In each case though, environmental, economic and social impacts have to be considered equally. The next chapter is characterised by the use of the life cycle assessment tool to evaluate the environmental impacts associated with the current sludge management option chosen by the municipality of Aalborg (two municipalities in Denmark – Aalborg and Randers).

CHAPTER FOUR

This chapter deals with the goal and scope definition phase of the LCA. It entails a definition of why the study is being carried out and a description of the system boundaries of the study, scenarios that would be analysed as well as the functional unit.

4.1 Goal and Scope Definition

4.1.1 Objective

The aim of this study is to assess the environmental performance of different methods of sludge treatment so as to identify the most efficient system for wastewater sludge disposal. This is carried out with the use of the Life Cycle Assessment approach as stipulated by ISO14040-44 and also with the aid of the computer software SimaPro. The case study area is Aalborg municipality which currently has two wastewater treatment plants. The results of the study is expected to serve as useful information to the decision makers in the said municipality, in relation to choosing the most promising waste management system and technology for treating wastewater sludge.

4.1.2 Functional unit

The system studied is wastewater sludge management and the function of the system is the treatment of sludge resulting from the municipal wastewater treatment plant in the Aalborg municipality. This study focuses on mixed sludge (raw sludge). The functional unit which is the base for the comparison of the treatment systems is taken as 1 ton of mixed sludge in dry basis (1td.m).

4.1.3 Characteristics of Sludge

Sewage sludge can be distinguished into four different categories; primary sludge from the primary settling tank or chemical precipitation; secondary sludge(activated sludge) from biological treatment tank; mixed, which is a mixture of primary and secondary sludge and; tertiary from tertiary waste water treatment.

Table 4.1: Sludge composition in Aalborg municipality (Poulsen & Hansen 2003).

Parameter	Value	Unit
Sludge production (28%) at WWTP	0.24	Ton d.m/ton COD
Sludge ash content	15	% w/w (d.m)
Raw sludge N content	4.8	% w/w (d.m)
Raw sludge P content	3.3	% w/w (d.m)
Sludge Energy content	22,000	MJ/ton d.m

Table 4.2 gives an overview of the concentration of heavy metals in Danish sludge and the cut-off values for EU and Denmark. Median values are used for concentration of metals in Danish sludge.

Table 4.2: Concentration of heavy metals in Danish Sludge mg/kg d.m (Jensen & Jepsen 2004)

Heavy metals	Cut-off value		Amount in Danish sludge (2002)
	EU	**DK**	
Pb	750 - 1200	120	50
Cd	20 - 40	0.8	1.3
Cu	1000 - 1750	1000	243
Hg	16 - 25	0.8	1.1
Zn	2500 - 4000	4000	700
Ni	300 - 400	30	20
Cr	-	100	21

4.1.4 Cut-off criteria

The cut-off-criteria is a method of delimiting the processes and materials that are available otherwise the process tree will grow indefinitely (Mikkel and Schmidt 2005). There have been actually no cut off in the study except for the capital good which is left out when modelling anaerobic digestion due to data limitation. The processes and products that have a small contribution to the impact potential less than 0.01% are left out in the study. Also, a cut-off-criteria was considered in relation to data obtained from databases in SimaPro; fewer data bases were used in order to avoid inconsistencies.

4.1.5 System Boundaries

Incoming waste water from both municipal and industrial source is treated at the wastewater treatment plant. The resulting sludge is pre-treated after which is subjected through different stabilisation/ treatment alternatives. The system boundary for the study starts at the point where raw sludge is released from the pre-treatment processes. This sludge is not digested and comes from the thickening system of the municipal wastewater treatment plant.

Table 4.2 An overview of the sludge management options considered and the products that would be analysed.

Sludge management option	Important Products
Incineration in Cement kilns	- Energy recovery from anaerobic digestion process used for heat and power production
composting	- Windrow system - Compost for fertilizer
Fluidised-bed incineration	- energy recovery (heat and power)

Four different scenarios are analysed in this study with the first scenario depicting the existing situation in Aalborg municipality while the remaining scenarios are alternatives to the existing one. The environmental impacts of these scenarios would be analysed and compared to determine which of them is the most favourable vis-à-vis avoided environmental impacts. The rationale behind the choice of these scenarios can be explained as follows;

- these, scenarios can offer sustainable means for treating municipal solid waste as there is the possibility to exploit the nutrient and energy content of sludge as well as reducing pollutant emissions: that is to say, possibilities of valorisation of sludge can be obtained through incineration or combustion with energy recovery or by anaerobic digestion with energy recovery from the methane produced in that process. Both are sources of renewable energy.
- Also, a lot of studies have been carried out on sewage sludge treatment processes with most of them are not LCA based and also the technologies considered are quite different. Houillon and Jolliet performed a very detailed LCA study but focus was only on energy and emissions contributing to global warming. This study encompasses additional impact categories such as aquatic acidification and aquatic eutrophication as well as non-renewable resources.
- Moreover, the scenarios have been chosen based on available technologies in Aalborg municipality (specifically) and Denmark (in general) which makes their application look more realistic. With the LCA approach, it would be possible to identify the best system to treat wastewater sludge together with the key parameters influencing their environmental impacts.

The scenarios are listed as follows;

1. Incineration of digested sludge in cement kilns (baseline scenario)
2. Agricultural Land application of digested sludge
3. Composting of raw followed by agricultural land application
4. Incineration of digested sludge in a fluidised bed and finally landfilling of residues

The sludge treatment options considered in this study produce useful products such as materials, fertilisers, fuels, heat or electricity, which replace the same product produced in a different way. This is taken into account in this study.

Table 4.3: Scenarios and the recovered products

Scenarios	Recovered products
Incineration in Cement kilns	Heat and power production
Agricultural application of digested sludge	Fertilizer production, energy
Composting followed by agricultural application	Fertilizer production
Fluidised bed incineration of sludge	Heat and power production

Processes analysed include;

- raw material input and output and emissions
- distribution and transportation
- production and use of fuel, electricity and heat
- substitutions in terms of energy and fertilizers

Figure 4.1 depicts the general system boundary of the study

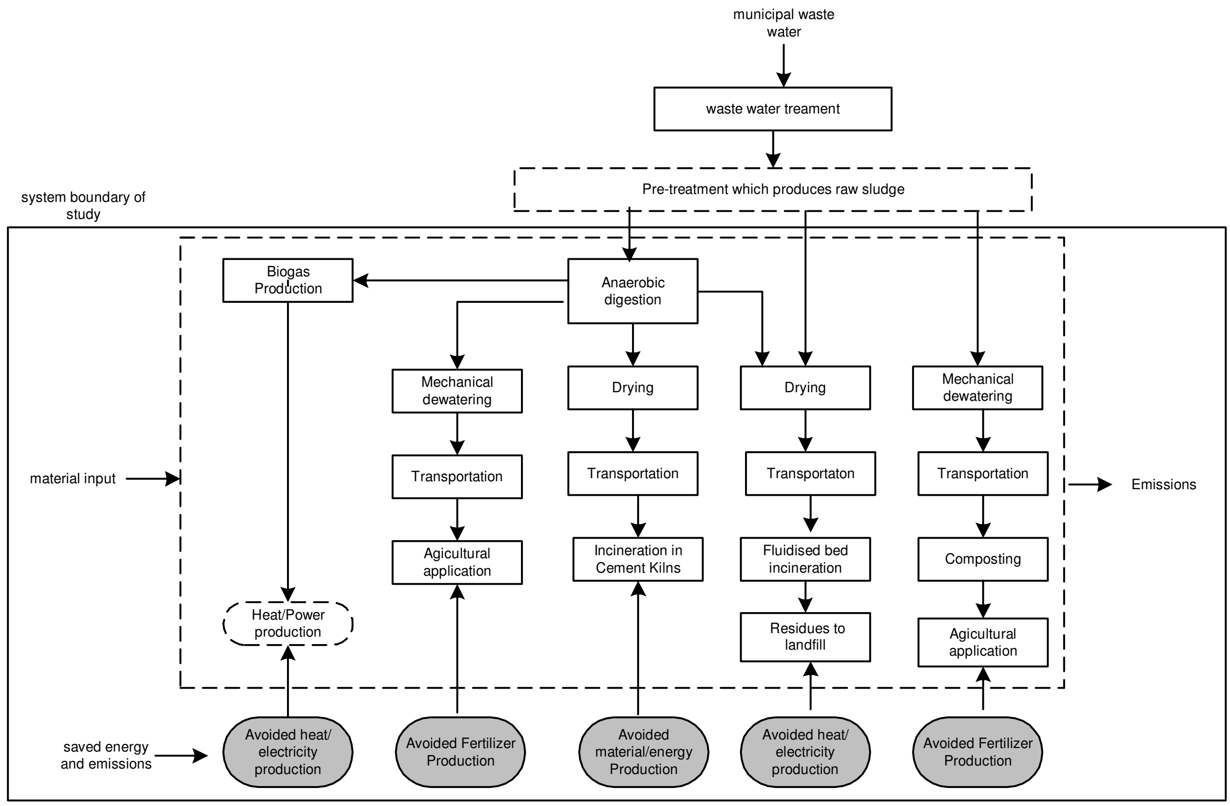

Figure 4.1 System boundary of Study

4.1.6 Technological Description

1. Municipal wastewater treatment at WWTP

Treatment of wastewater in wastewater treatment plants (WWTP) produces sludge. The first step in waste water treatment process is the pre-treatment process which consists of screening to remove large solids. In the next step the wastewater undergoes primary treatment which involves the use of clarifiers and sedimentation tanks to settle particulates in the wastewater. During this treatment about 50-60% of the suspended solids and 30-40% of the BOD is removed and the resulting sludge is mostly organic matter and highly putrescible. Next, the wastewater is subjected to a secondary treatment where aerobic microorganisms are introduced to biologically remove the remaining BOD and suspended solids. This effluent is passed through a secondary clarifier and the out coming sludge is 90% organic matter. Mixed sludge from primary and secondary treatment are combined and undergo another form of treatment which involves thickening using gravity or flotation, removing as much water as possible and reducing the raw sludge to about half of its volume. This process is depicted in figure 4.2

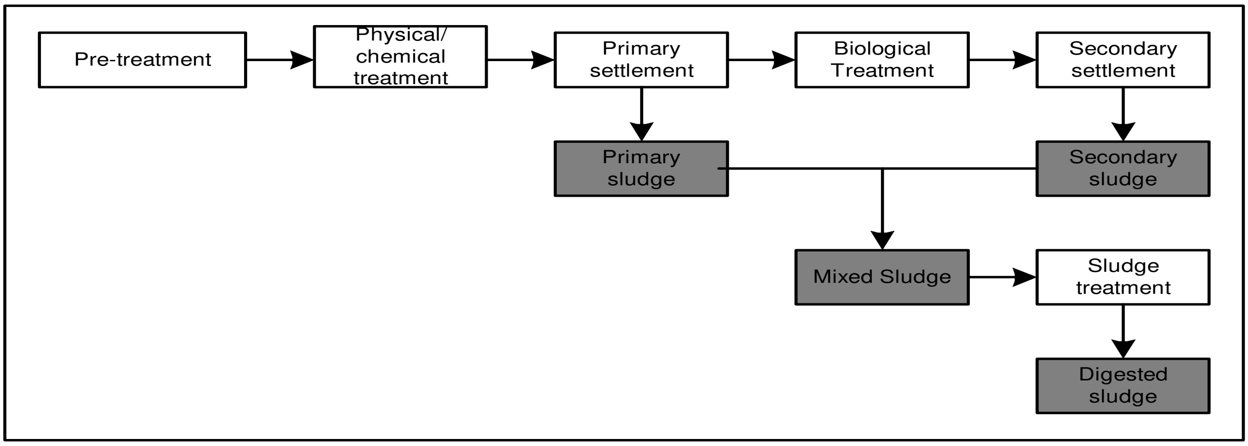

Fig 4.2: A conventional wastewater treatment plant and sludge generation (Hospido et al 2005)

2. Anaerobic Digestion

This is a naturally occurring process of decomposition during which organic matter is degraded to simpler chemical components under anaerobic conditions. Sewage sludge is fed to an enclosed reaction tank where naturally occurring bacteria degrade the organic material. The enclosed tank has an attached heating and mixing system. The digester can also be equipped with a floating roof for gas collection or a separate gas holder. Anaerobic digestion occurs in three main stages:

- Hydrolysis: fermentative bacteria convert the insoluble complex organic matter in sludge (e.g cellulose) into soluble molecules such as fatty acids, amino acids and sugars. This hydrolytic activity is very significant for wastes with high organic content. Chemicals can be added during this step in order to decrease the digestion time and provide a higher methane yield.

- Acidogenesis: Acetogenic bacteria then convert the products from the first stage into simple organic acids, carbondioxide and hydrogen.
- Methanogenesis: here, methanogenic bacteria convert these simple organic acids into carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen.

The efficiency of the anaerobic digestion process is dependent on total solid content of incoming sludge, temperature, retention time, pH, C:N ratio (where a high C:N ratio indicates a rapid consumption of nitrogen by methanogenic bacteria, which results in lower gas production, while lower C:N ratio causes accumulation of ammonia and pH values exceeding 8.5 which is toxic to methanogenic bacteria), mixing within digester improves contact between microorganisms and substrate. The end product of this process is biogas and stabilised sludge (Monet 2003).

3. *Cement Kiln Incineration*

Cement production processes can be divided into five stages: first the raw material (limestone, clay etc) are dried, crushed and milled so as to reduce the diameter of the materials (90um). In the second stage, the prepared material are carried in an air suspension with the flue gas and separated in an electro-filter. In the third stage, the separated material is carried in dust gas suspension to a battery of cyclones where it is pre-heated to 800-850^oC before entering the rotary kiln where cement formation takes place at peak gas temperatures of 1800-2000^oC. The formed cement is then cooled with incoming combustion air preheated at 850^oC. Two separate firings may be used, main firing and secondary firing. The former provides the energy necessary for the rotary kiln, whereas secondary firing may be required to provide sufficient gas temperature at the entrance of the cyclone pre-heaters. Pre-dried sludge can be co-fired with coal in main firing or secondary firing stages. Maximal sewage sludge feed rate should not exceed 5% of the clinker production capacity of the cement plant. This implies that for a 2000ton/day cement kiln, a maximum of 100ton/day sludge should be used (Werther & Ogada 1999).

4. *Fluidised Bed Incineration*

Fluidised bed incinerators consist of a vertically oriented outer shell constructed of steel and lined with refractory. Nozzles designed to deliver blasts of air are located at the base of the furnace within a refractory lined grid. A bed of sand which is approximately 0.75metres thick rests upon the grid. The digested sludge is fed into the lower portion of the furnace and air is injected through the nozzles at pressures of 20 to 35vkilopascals and this simultaneously fluidises the bed and the incoming sludge. Temperatures of 750 to 925^oC are maintained in the bed and residence time is between 2 to 5 seconds. During incineration, fine ash particles are carried out at the top of the furnace. Some sand is also removed in the air steam. Sludge combustion occurs in two zones; within the bed itself (zone 1) where evaporation of the water and pyrolysis of the organic materials occur. In the second zone (free board area), the remaining free carbon and combustible gases are burned.

Fluidisation allows for an almost ideal mixing between the sludge and the combustion air and the turbulence facilitates transfer of heat from the hot sand to the sludge. Flue gases resulting from combustion process are at very high temperature and some of this heat is recovered by passing through a waste heat recovery unit. An abatement system comprising two stages of gas treatment is needed and includes an electrostatic precipitation for particulate control and wet scrubbing for acid gas control.

5. ***Agricultural Application of Sewage sludge***

This represents the use of sludge as fertilizer on agricultural land. Before land application, the sludge is first stored for at least nine months and specific requirements have to be met before the sludge is fit for use. Sludge has to be sampled and checked for contaminants (pathogens, heavy metals etc) and the frequency of sampling and analysis depends on the production and quality of the sludge. Once the sludge has been tested and approved for land application, two methods are available for its application: in each method, the dry sludge is mixed with water to facilitate its application. Firstly, the sludge can be applied through direct spraying where a large truck with spray and pump capabilities travels over the land and applies the sludge directly to the soil surface. The sludge is then mixed with the top soil through discing by a tractor. In another method, a truck uses special soil intrusive adaptations that pump the sludge into the soil (injection) about 6 to 10inches below the surface (Lowe & Min 1996).

6. ***Composting***

This process consists of mixing sludge with bulking agent to ensure that the mixture can be aerated so as to allow for an accelerated aerobic degradation process. A high amount of energy is usually required for this process. After sludge is dewatered to approximately 35% d.m content, it is then mixed with structural elements (bulking agents) in a suitable proportion to obtain a C:N ratio of 30:1 in the compost. Examples of structural elements that can be used include sawdust, wood shavings, bark, straw, leaf litter. The composting process is dependent on certain parameters which are indicated in table 4.4

Table 4.4 parameters affecting the Composting process

Determination	**Unit**	**Value**
Temperature of composting	^{o}C	55 - 60
Moisture (W%) composting masses	%	40% <W< 60%
Aeration	m3/t.h	90 - 160
Time of composting	weeks	< 4
Time of ripening	months	< 6

There are several methods existing for composting and these include;

- Traditional windrow
- Aerated Static pile
- Oxygenic composting in reactors

This study adopts the use of the traditional windrow system for composting. This involves heaping up sludge piles mixed with structural materials and periodically turning these piles to aerate (Kosobucki et al 2000).

4.1.7 Geographical Boundaries

The study is mainly focused on Denmark though some data would be obtained from other areas in Europe applicable to the study

4.1.8 Data Quality Requirements

Data used in this project have been obtained from the following sources

1. existing literature on related LCA studies
2. existing installations in Aalborg municipality and other municipalities
3. A few estimations have been made due to lack of more accurate data

4.1.9 Substitutions

It is necessary to quantify the products and energy avoided so as to be able to compare between the different scenarios proposed. The following calculations are made:

- Fertilisers avoided; the fertilising value of the sludge when applied to agricultural land are determined based on the nitrogen (N) and phosphorus (P) content and the availability of these nutrients.
- Energy Avoided; the anaerobic digestion process produces biogas which is converted to energy, also the sludge drying and incineration processes produce energy (heat) which is used for district heating thus saving coal and natural gas. Hence the avoided production of energy is considered.

4.1.10 Impact Assessment Methods

The impact assessment method used to translate the inventory results of the three waste management scenarios into potential contributions to various impacts is the EDIP method (Environmental Design of Industrial Products, in Danish UMIP)(Wenzel, Hauschild & Alting 1997). This study does not progress to the normalisation phase; it ends at the characterisation step. Impact assessment includes the assessment of the global warming impact, the assessment of other emissions impacts and the impact on the energy resources. The impact categories selected include global warming (GWP100year), acidification and eutrophication.

4.1.11 General Assumptions of Study

- Heat Production: from incineration and biogas from anaerobic digestion is assumed to replace heat produced from other sources. The marginal source is taken as natural gas (Finnveden et al, 2000).
- Electricity Production: According to Weidema et al (1999), the trend for electricity use in Europe is increasing and the marginal technology (technology with the lowest long-term production cost) would thus be the most preferred technology. They conclude that hard coal is the EU marginal power source. Hence electricity from incineration and biogas is assumed to replace electricity from coal-fired power plants which is taken as marginal source.
- Since the operation of the waste water treatment plant is shared by all the scenarios, it will not be considered and also because thickened mixed sludge is selected as the starting point of this study. (Hospido et al 2005)
- Residues from anaerobic digestion and composting replace artificial fertiliser with similar contents of nitrogen and phosphorus.

4.1.12 Limitations of Study

- The impacts associated with the pre-treatment process of sludge that is thickening and dewatering would not be considered since they are similar for all scenarios.
- The study does not include all the impact categories of the EDIP97 methods: only three impact categories are considered, those not considered also include human toxicity water and soil, bulk waste, hazardous waste, radioactive waste and resources. These impact categories were left out of the analysis because it is assumed that their contributions to the LCIA results are insignificant in providing answers to the study.
- Uncertainty, which can affect the results of the LCIA as discussed in section on Consistency checks.

CHAPTER FIVE

This chapter embodies a detailed description of the different scenarios considered in the study and it is made explicit by the inclusion of process diagrams depicting the input and output parameters of the systems studied.

5.1 Scenario One: Baseline Scenario – Anaerobic Digestion + Cement Kiln Incineration

The baseline scenario represents the actual system practised in the wastewater treatment plants in Aalborg. According to Poulsen & Hansen (2003), the plant located in the west receives 78% of waste water produced by Aalborg municipality. The plant employs anaerobic sludge digestion and biogas production and part of the biogas produced is used for heat and electricity production. During sludge digestion, the raw sludge goes through a three step process during which ethane and other gases are produced. The first step is characterised by the hydrolysis of lipids, cellulose and protein by extracellular enzymes produced by inhabiting bacteria, breaking down these macromolecules into smaller more digestible forms. In the second step, these molecules are decomposed to fatty acids by facultative and anaerobic bacteria. Finally methanogenic bacteria digest the fatty acids releasing methane gas. Electricity consumption for this process is directly related to the moisture content of the sludge. High moisture sludge uses more heat but requires less electricity to circulate the fluid digestate (EC 2001).

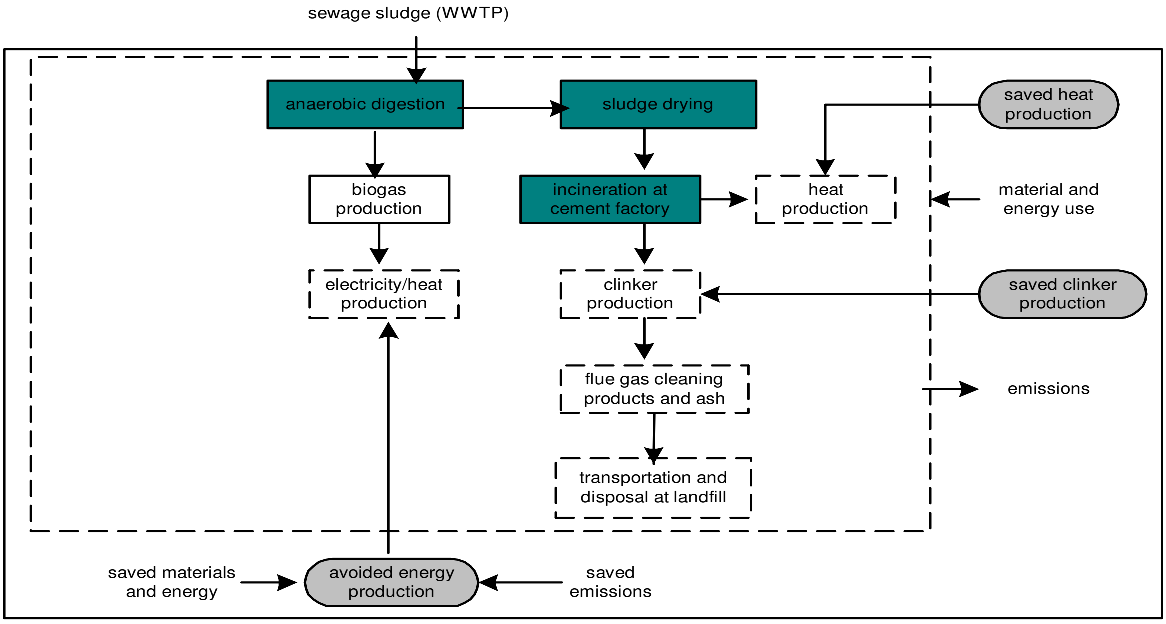

Fig. 5.1 Process flow chart for scenario 1

The digested sludge is dewatered to between 20% and 30% dry matter (d.m) content. It is transported to a sludge drying facility and dried between 90 and 95% d.m using biogas and natural gas as heat source. Part of the heat is recovered and used for district heating. The dried sludge is transported to a cement factory (Aalborg Portland) where it is used as a fuel and as an additive in the cement production. During incineration in cement kilns, the sludge is burned in an oven at 1400^{o}C with other fuels, to produce clinker. The cement produced with the sludge ash is deposited into an inert waste storage centre. When sludge is incinerated in this way, organic matter is destroyed and the mineral matter is recovered as building material. The sludge however has to be dried to 95% dried solid content and must be transported from the waste water treatment plant (WWTP) to the cement factory. Also some micro pollutants are transferred into the air during combustion of sludge (Houillon and Jolliet, 2004).

5.2 Scenario 2: Anaerobic Digestion + Agricultural Land Spreading

The digested sludge instead of being sent for incineration is transported to fields for direct land application. Agricultural land spreading requires a substitution which is related to the fertilisation provided by the sludge on agricultural land. Substitution is considered for nutrients (NPK) available in sewage sludge. The amount of nutrients available in the sludge is determined based on sludge. Spreading sludge on agricultural land has the disadvantage linked with spreading micro-pollutants on land and this effect is taken into consideration considering the composition of sludge and of fertilisers (Lassaux et al 2005)

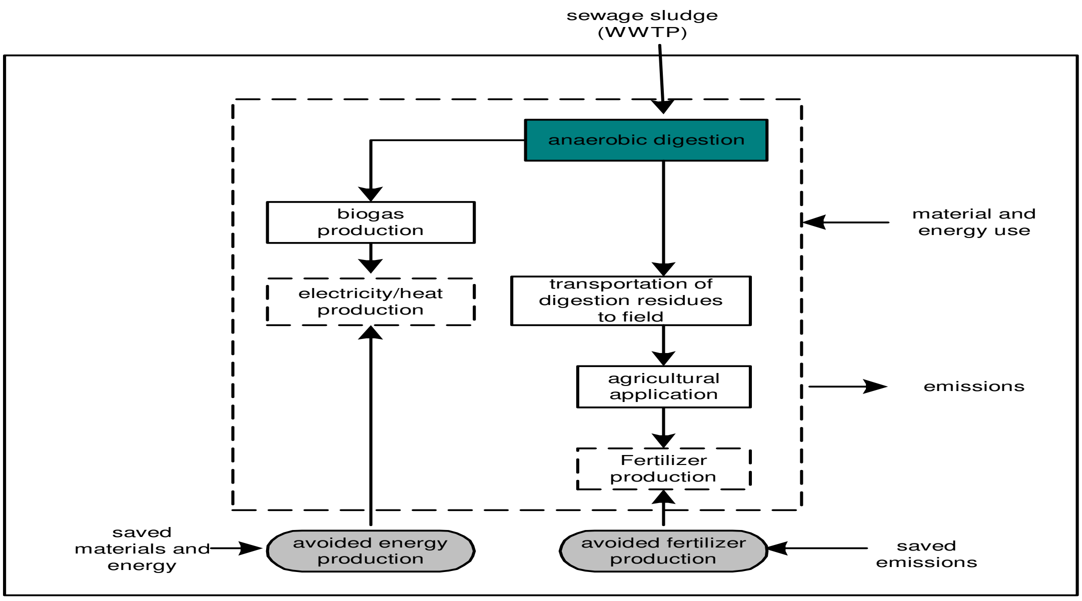

Fig. 5.2 Process flow chart for scenario 2

5.3 Scenario 3: Composting + Agricultural Land Spreading

The sludge is composted before being applied to soil in which case, the mass of the sludge is further reduced following degradation of organic matter and evaporation of water, pathogens present in the sludge are inactivated and organic pollutants are degraded. The method of composting used in this study is windrow composting. This process produces heat enough to destroy pathogens and produce a stabilised product for use as soil conditioner. Organic material is left to decompose outdoors with the aid of just watering and mechanical turning for aeration. Though this process is slow, it has a low capital cost. The incoming sewage sludge is mixed with bulking agent such as finished compost and also supplemented with an external amendment like yard waste, straw or sawdust then the material is formed into piles to decompose. The compost is formed into long piles called windrows and the windrows are aerated mechanically by turning. The composted material is then transported to farmlands where it is spread on fields in which case it acts as soil supplement.

Composting is the biological breakdown of biodegradable waste by micro-organisms in the presence of oxygen and water to produce compost. It occurs in two stages: in the first stage, microorganisms decompose the feedstock into slumber compounds, producing heat as a result of their metabolic activities. At this stage, the size of the composting pile is reduced. In the second, the compost produced is finished, where micro organisms deplete the supply of readily available nutrients in the compost, which, in turn slows their activity. Hence, heat generation reduces and the compost becomes dry and crumbly in texture (US EPA 1994).

Assumptions made when modelling the composting system include:

- **Land Requirement:** The required area per ton compost is 0.13 ha, which gives energy use per ha of 115 MJ/ha (Finnveden et al. 2000).
- **Compost:** It is assumed that the amount of compost generated is 50 % of the weight of the incoming waste.
- **Leaching of Nutrients:** This study assumes that nutrients leaching from the digested sludge and compost are equal to those from artificial fertilizers which they replace. Therefore this aspect (leaching of nutrients) will not be considered any further in the analysis (Björklund and Finnveden 2007).

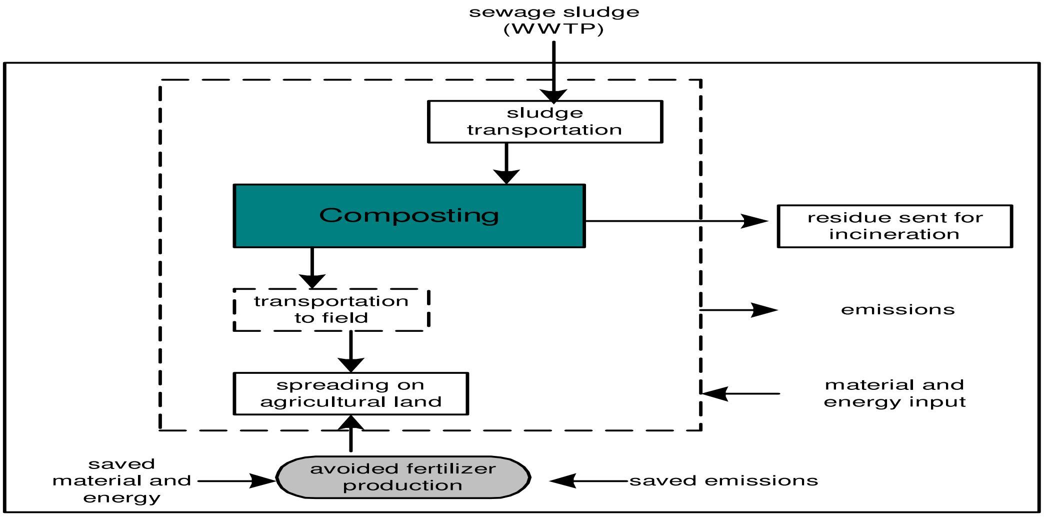

Fig. 5.3 Process flow chart for scenario 3

5.4 Scenario 4: Anaerobic Digestion + Fluidised Bed Incineration

The raw sludge first undergoes anaerobic digestion as described in scenario 1 after which the resulting digestate is again dewatered and dried at the drying facility before being transported to the incineration plant. At the incineration plant, it is fed into the lower part of the furnace and air is injected at pressures from 20 to 35 kilopascals which simultaneously fluidises the bed of hot sand and the incoming sludge. Temperatures of 750 to 925°C are maintained in the bed. Residence time is between 2 to 5 seconds and as the sludge burns, fine ash particles are carried out of the top of the furnace. Some amount of sand is removed in the air steam. The combustion of sludge occurs in two zones; within the bed itself (zone 1), where evaporation of water and pyrolysis of the organic materials occur almost simultaneously as the temperature of the sludge is rapidly raised. In the second zone, the remaining free carbon and combustible gases are burned. With fluidisation, there is an ideal mixing between the sludge and combustion air and turbulence facilitates the transfer of heat from hot sand to the sludge.

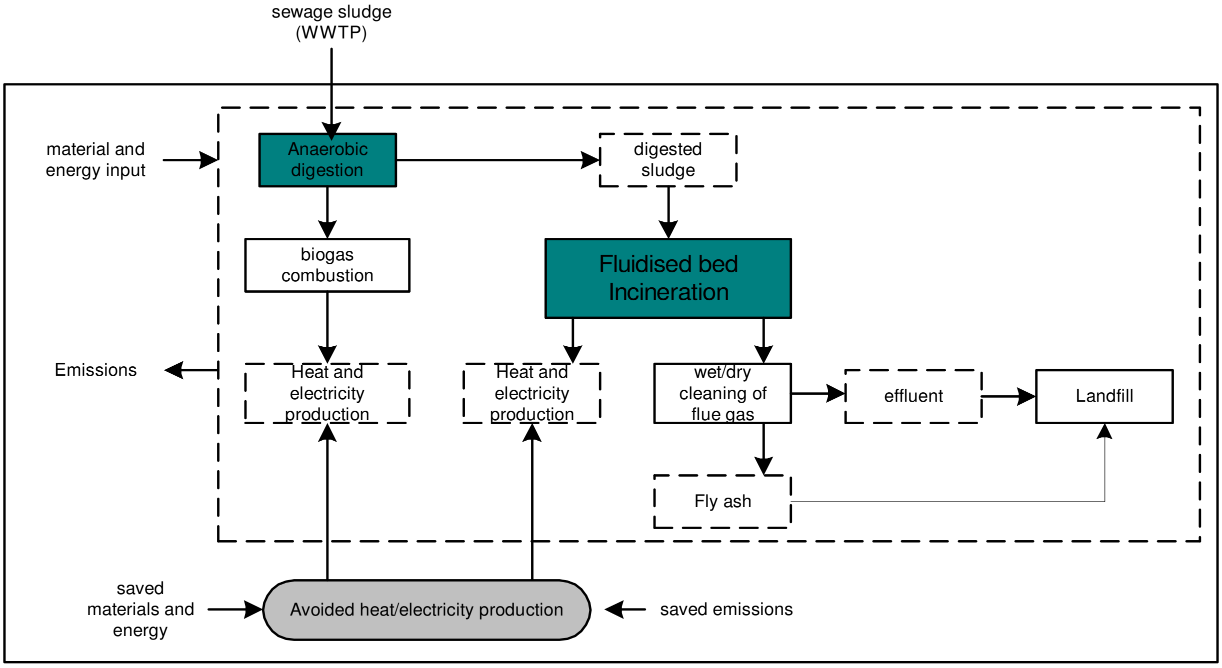

Fig. 5.4 Flow chart for scenario 4

CHAPTER SIX

LIFE CYCLE INVENTORY

This chapter deals with the life cycle inventory phase of the LCA which entails a calculation of the emissions to air, water and soil as well as the material and energy used. These are all expressed per functional unit.

The total LCI for the sludge treatment system would be calculated as

- Direct burdens from the waste management system
- Plus indirect burdens associated with providing material and energy to the sludge management activities
- Minus avoided burdens associated with processes which are avoided because of production of material and energy.

The next step of this study describes the different systems studied and related inventory

6.1 ANAEROBIC DIGESTION + INCINERATION IN CEMENT KILNS

6.1.1 General System Description

In this system one ton of raw sludge resulting from wastewater treatment, is subjected to anaerobic digestion. The sludge is assumed to be mixed sludge coming from both primary and secondary wastewater treatment processes. Anaerobic digestion is a stabilisation process aimed at reducing, stabilising and partially reducing the treated volume of the sludge. The biogas produced is incinerated and the energy released is reused by the plant. The digestate produced is then further dewatered, dried in a drying plant then transported to the cement production factory to be incinerated in cement kilns.

6.1.2 Transportation

Transportation distance is obtained from literature on the wastewater treatment plant in Aalborg. Transportation distance from wastewater treatment plant (WWTP) to sludge drying plant is given as 10km and distance from drying plant to cement factory is 5km, giving an average distance of 15km. Transportation is carried out by diesel trucks with a carrying capacity 40 tons (Poulsen & Hansen 2003). The transportation process is modelled in SimaPro as *'Transport, lorry 40t/CH U'* (Ecoinvent 2004).

6.1.3 Anaerobic digestion Process

6.1.3.1 General description

Data for the digestion process is obtained from existing literature on wastewater treatment in Aalborg and literature review of related LCA studies.

6.1.3.2 Energy Model

Electricity is needed for the sludge digestion process and heat is needed for heating the digester and general space heating. Part of the energy demands can be fulfilled with energy produced from biogas incineration while the rest is obtained from natural gas. Biogas production at WWTP (digestion process) is given as 176.2 Nm^3/ton COD which is equivalent to 734.16 Nm^3/ton d.m. The energy content of the biogas is given as 16.88GJ/ton d.m (Tjalfe and Jens 2002).

1. Energy Recovered

Biogas produced from anaerobic digestion process is incinerated to produce energy which is reused by the plant. Hence part of the heat and electricity used for this processes comes from biogas source while the rest is from fossil fuel origin. Electricity consumed is given as 318.8 MJ/ton d.m and this obtained from studies by Hospido et al (2005), heat consumed is obtained from DEA et al (2005) and is given as 170 MJ/ton d.m.

Energy production during biogas combustion is given as 6836.4MJ and 6076.8MJ respectively per ton dry matter content of sludge (Poulsen & Hansen 2003). This is considered as avoided marginal heat and electricity.

Table 6.1a: An inventory on the energy production for the digestion process

Digestion Process	Value/Unit
Biogas yield	734.16 Nm^3/ton d.m
Energy content of biogas	16.88 GJ/ton d.m
Rate of electricity production	36
Rate of heat production	40.5

Source: Poulsen & Hansen 2003

Table 6.1b: energy use for the digestion process

Parameter	Value and unit
Electricity consumption	318 MJ/ton d.m
Heat consumption	170 MJ/ton d.m

Source: Hospido et al 2005 & DEA et al 2005

2. Energy Substituted

The substituted product during digestion and biogas combustion is energy. Electricity is assumed to be obtained from coal while heat is obtained from natural gas. The inventory data used for modelling the avoided marginal electricity in scenario 1 is *'electricity, hard coal, burned in power plant/NORDEL U'* taken from Ecoinvent (2004). Data used for heat generation is obtained from *'Natural gas, burned in industrial furnace low-NOx>100kW/ RER U'* (Ecoinvent 2004).

Table 6.1c: Energy Production (per ton d.m content of sludge)

Parameter	Amount (MJ)
Heat	6836.4 MJ
Electricity	6076.8 MJ

Source: Poulsen & Hansen 2003

3. Emissions from digestion process

Emissions associated with the digestion process include emissions of biogenic CO2, some methane escapes from this process into the atmosphere, also breakdown of organic matter releases nitrogen which forms oxides of nitrogen (NO_2, N_2O, NOx). Values for emissions were obtained from Hospido et al (2005) and Hansen & Poulsen (2003). The emissions are presented in the general LCI table for scenario 1.

6.1.4 Drying

The sludge drying facility is present in the wastewater treatment plant which is the situation with the wastewater treatment plant at Randers and Aalborg. Drying is a thermal treatment and occurs at different temperatures. Level of dry mass reached is between 35-90%. Energy requirements are much higher and highly dependent on the water content of the sludge, hence the sludge is first dewatered before drying. Energy for drying is obtained from natural gas burned in a natural gas combustion engine at the plant. Energy needs for the drying process is shown on table 4.1

Table 6.1d: Energy needs for drying process (per ton input d.m content of sludge)

Energy	Value in kWh
Heat consumption	1638
Electricity consumption	118

Source: Hospido et al 2005

Sludge drying also produces a high amount of heat and electricity. Part of the energy is recovered and used for district heating (Poulsen & Hansen 2003).

Table 6.1e Energy production for drying process (per ton d.m content of sludge)

Energy Production	Amount
Heat	1228.5 kWh
Electricity	-

Source: Hospido et al 2005

6.1.5 Incineration in Cement kilns

6.1.5.1 General description

At the incineration plant, the sludge is burnt with other fuels for clinker production and the cement produced is deposited in an inert waste storage center. The incineration plant has an efficiency of 99% and the amount of residual waste produced at the plant is given as 2.1kg/ton. Cement clinker production is done in a rotary kiln using high temperatures around 1450^{o}C. Using dried sludge from WWTP part of the fuel and raw material used for clinker production, is substituted.

6.1.5.2 Energy Model

Heat recovery rate at cement plant is 8.5% (Poulsen & Hansen 2003). Energy consumptions include electricity, fuel and natural gas. Heat produced during cement kiln incineration is assumed to substitute marginal heat from natural gas. Energy consumption is given as 91.3 kWh for heat and 170.8 kWh for electricity, per ton d.m content of sludge (Houillon & Jolliet 2005).

1. Energy Recovered

Energy in the form of heat and electricity is produced during this process. In cement kilns incineration, sludge eliminates fuel oil and coal usage since sludge combustion produces heat for the cement production process. Heat is recovered on the direct sludge drying process more precisely from the condenser.

Table 6.1f: Energy recovered from cement kiln incineration

Energy Production	Amount per ton d.m
Heat	816
Electricity	-

Source:Svanstrom et al (2005)

2. Energy Substituted

The inventory data used for modelling the avoided marginal electricity in scenario 1 is *'electricity, hard coal, burned in power plant/NORDEL U'* taken from Ecoinvent (2004). Data used for heat generation is obtained from *'Natural gas, burned in industrial furnace low-NOx>100kW/ RER U'* (Ecoinvent 2004).

3. Emissions

When comparing the composition of raw material used for cement production and heavy metal content in sludge, the following conclusion can be drawn;

- The content of mercury and cadmium in sludge is higher than in both raw material and fuel used for cement kiln. Clinker is able to fix a part of these compounds.
- The contents of nickel, chromium and arsenic are comparable hence their content in sludge does not greatly influence the balance of heavy metals in the process.

Heavy metals like zinc, copper and lead are also fixed in clinker. Heavy metals can be transferred to the cement clinker, to off-gases, to the material from de dusting and external recycle of raw materials or can be absorbed by raw materials in the colder part of the kiln and released in a warmer part of the kiln-internal recycling (Stasta et al 2005).

6.1.4.3 *Material Input*

One ton of dried sludge input can substitute up to 1/3 of raw material. In addition, ash from sludge as well as a major part of pollutants (S,Cl and alkali) and heavy metal are bound and closely fixed to the clinker. According to Stasta et al (2005), maximum sewage sludge feed rate should not be more than 5% of the clinker production capacity of the cement plant.

Table 6.1g LCI for Scenario 1

Sub process 1 - Digestion Process (1 ton d.m sludge)				
		Input – Energy		
Electricity consumption	MJ/ton d.m	318.8	Hospido et al (2005)	
Heat consumption	MJ/ton d.m	170	DEA et al (2005)	
		Input- Materials		
Sewage sludge	Ton d.m	1	Functional Unit	
		Output		
Biogas produced	Nm3/ton d.m	734.16 (16.88 GJ ENERGY)	(Poulsen and Hansen 2003)	
Energy content of biogas	MJ/ton d.m	16880	calculation from above	
Digestate	Ton d.m	0.78	See calculations	
		Emissions		
CH_4 biogas process	%	2		
CH_4 gas engine	%	3		
CH_4	kg/ton d.m	6.49	own calculations	
CH_4 gas engine	kg/ton d.m	9.73	Own calculations	
CO_2 (biogenic)	kg/ton d.m	1,291	Hospido et al (2005)	
CO	kg/ton d.m	0.84	Hospido et al (2005)	
NO_2	kg/ton d.m	0.85	Hospido et al (2005)	
N_2O	kg/ton d.m	0.02	Hospido et al (2005)	
Air emission of particles	kg/ton d.m	0.08	Hospido et al (2005)	
Sub process 2 - Biogas combustion (in stationary engine) – 16880 MJ Biogas				
		Input - Energy		
Biogas	Nm3/ton d.m	734.16	(Poulsen & Hansen 2003)	
Energy content	MJ/ton d.m	16880	(Poulsen & Hansen 2003)	
		Output		
Total Energy production	GJ/ton dm sludge	16.88	calculations	
Heat production rate	%	40.5	Poulsen and Hansen (2003)	
Electricity production rate	%	36	Poulsen and Hansen (2003)	
Total Electricity production	MJ/ton d.m sludge	6076.8	calculations	
Total Heat production	MJ/ton d.m sludge	6836.4	calculations	
		Emissions		
CO_2, gas engine	kg/ton d.m	83.6	Nielson et al	
CH_4,gas engine	kg/ton d.m	5.45	Nielson et al	
N_2O	kg/ton d.m	0.00844	Nielson et al	
NO_x	kg/ton d.m	9.11	Nielson et al	
SO_2	kg/ton d.m	0.32	Nielson et al	
CO	kg/ton d.m	4.6	Nielson et al	
Sub process 3 – Drying – 0.78ton d.m sludge				
		Input – Energy		
Sludge Drying 20-93% d.m heat consumption	kWh/ton d.m	1638	Poulsen &Hansen 2002	
Sludge Drying 20-93% d.m electricity consumption	kWh/ton d.m	118	Poulsen &Hansen 2002	
		Output		
Dried sludge	Tons d.m	0.78	*see calculations	
Heat recovery rate	%	75	Poulsen 2003	
Heat recovered	kWh/ton d.m	1228.5	Stasta et al (2005)	
		Emissions		
Air emission of VOC	kg/ton d.m	0.0443	Hospido et al	
Sub process 4 – Incineration in cement kilns 0.78 ton d.m sludge				
		Input – Energy		
Electricity consumption	MJ/ton d.m	592.85	Houillon & Jolliet (2005)	
Heat consumption (natural gas)	MJ/ton d.m	12938.9	Houillon & Jolliet (2005)	

Input – Materials				
Polymer	kg/ton d.m	7.1	Houillon & Jolliet (2005)	
Fuel –	kg/ton d.m	40.5	Houillon & Jolliet (2005)	
Acid –	kg/ton d.m	5.4	Houillon & Jolliet (2005)	
Output				
Heat recovered	MJ	816	Svanstrom and Poulsen	*see excel
Residual waste produced	kg/ton	2.1	Poulsen and Hansen (2002)	
Emissions – green house gases (SimaPro)				
Emissions – heavy metals (SimaPro)				

6.2 AGRICULTURAL APPLICATION OF DIGESTED SLUDGE

6.2.1 General System Description

One ton of raw sludge resulting from wastewater treatment is subjected to anaerobic digestion. The sludge is assumed to be mixed sludge coming from both primary and secondary wastewater treatment processes. Anaerobic digestion is a stabilisation process aimed at reducing, stabilising and partially reducing the treated volume of the sludge. The biogas produced is incinerated and the energy released is reused by the plant. The digestate produced is then further dewatered. The sludge is first dewatered then limed to obtain a limed pasty sludge with 30% dry solid content. The sludge is limed at the WWTP then stored in a deodorizing building for seven months after which they are transported to the fields. The sludge is first stored for about a month before spreading with a tractor. Pertinent processes include micro-pollutants spread on agricultural land, long storage in controlled conditions, transport and liming (Houillon and Jolliet 2005).

6.2.2 Transportation

Transportation from WWTP to farmland site is taken into consideration. It is assumed to be 10km and it is done with a 40t truck (Poulsen and Hansen 2003).

6.2.3 Anaerobic digestion Process

4.2.3.1 General description

Most of the data for the digestion process is obtained from existing wastewater treatment facilities of the municipalities of Aalborg and Randers. Other sources of data have been used to supplement this inventory such as: data for the content of NPK in the digestion residues obtain from studies by Poulsen and Hansen (2003).

4.1.3.2 Energy Model

Electricity is needed for the sludge digestion process and heat is needed for heating the digester and general space heating. Part of the energy demands can be fulfilled with energy produced from biogas incineration while the rest is obtained from natural gas. Biogas production at WWTP (digestion process) is given as 176.2 Nm^3/ton COD which is equivalent to 734.16 Nm^3/ton d.m. The energy content of the biogas is given as 16.88GJ/ton d.m (Poulsen & Hansen 2003).

1. Energy Recovered

Biogas produced from anaerobic digestion process is incinerated to produce energy which is reused by the plant. Hence part of the heat and electricity used for this processes comes from biogas source while the rest is from fossil fuel origin. Electricity consumed is during digestion is given as 318.8 MJ/ton d.m and this is obtained from studies by Hospido et al (2005), heat consumed is obtained from DEA et al (2005) and is given as 170 MJ/ton d.m. Energy production during biogas combustion is given as 6836.4MJ for heat and 6076.8MJ for electricity per ton dry matter in sludge.

Table 6.2a: Energy Production Scenario 2 (per ton d.m content of sludge)

Parameter	Amount (MJ)
Heat	6836.4 MJ
Electricity	6076.8 MJ

2. Energy Substituted

The substituted product during digestion and biogas combustion is energy. Electricity is assumed to be obtained from coal while heat is obtained from natural gas. The inventory data used for modelling the avoided marginal electricity in scenario 1 is *'electricity, hard coal, burned in power plant/NORDEL U'* taken from Ecoinvent (2004). Data used for heat generation is obtained from *'Natural gas, burned in industrial furnace low-NOx>100kW/ RER U'* (Ecoinvent 2004).

Table 6.2b an inventory on the energy production and use for the digestion process in Scenario 2

Digestion Process	Value/Unit
Biogas yield	734.16 Nm^3/ton d.m
Energy content of biogas	16.88 GJ/ton d.m
Rate of electricity production	36%
Rate of heat production	40.5%
Electricity consumption	318 MJ/ton d.m
Heat consumption	170 MJ/ton d.m

Source: Poulsen & Hansen 2003 and Hospido et al 2005

3. Emissions from digestion process

Emissions associated with the digestion process include emissions of biogenic CO2, some methane escapes from this process into the atmosphere, also breakdown of organic matter releases nitrogen which forms oxides of nitrogen (NO_2, N_2O, and NOx). Values for emissions were obtained from Hospido et al (2005) and Hansen & Poulsen (2003). The emissions are presented in the general LCI table for scenario 2.

4.2.3.3 Mechanical dewatering

Energy is consumed during this process as well as polymer. The polymer allows for binding of the dry matter in sludge thus increasing removal of water. Electricity consumed is given as 176.72 MJ per ton dry matter content of sludge.

4.2.3.4 Spreading of Digestion Residues

When sludge is spread on agricultural land, heavy metals present in the sludge are transferred to the soil. The amount of metals in this sludge usually depends on the source of wastewater. Agricultural land spreading also consumes electricity and other material inputs which include; lime, diesel for sludge application, Acid (sulphuric acid) and polymer. Some of the inventory data for spreading of digestion residues on the field is taken from Ecoinvent database in SimaPro. Inventory for spreading or sludge on agricultural fields takes into account the consumption of diesel fuel. Fuel used for sludge application to soil is modelled as '*solid manure loading and spreading, by hydraulic loader and spreader/CHU'* and electricity consumed is from '*electricity, medium voltage, production NORDEL, at grid/NORDEL U'* (Ecoinvent 2004). The values for these parameters are obtained from Houillon and Jolliet (2005) and are represented in the general LCI table for scenario 2. Emissions to air from combustion are considered and emissions not included are dust from combustion and noise. The technology for spreading of residues is based on emissions and fuel consumptions of the newest models of tractors.

4.2.3.5 Avoided Products

Substitution is considered for nutrients (NPK) available in sewage sludge. The concentration of NPK in the digested sludge is used to calculate the avoided quantity of chemical NPK-fertiliser. The replaced fertilizers include; ammonium nitrate (for N), triple super phosphate (TSP for P) and potassium sulphate (for K).

Table 6.2c: Content of NPK in digested sludge (Poulsen & Hansen 2003)

Parameters	Value (kg/ton d.m)
Content of N	48
Content of P	33
Content of K	4
Total NPK	85

The inventory data for the production of these artificial fertilizers is obtained from Ecoinvent database in SimaPro 7 (Pré Consultant 2007). The unit process for each of the avoided fertilizers production takes into account the production from raw materials, transportation of the intermediate products to the fertilizer plant as well as the transportation of the fertilizer product to the regional storehouse. Production and waste treatment of catalysts, coating and packaging of the final fertiliser products are not included. The avoided process of spreading the chemical fertilizers is considered in this study. The total avoided NPK which is suppose to be spread is 150kg/ha (White et al. 2001) and it is presented in table 6.10

Table 6.2d: The Applied NPK fertilizers per hectare

Total NPK	Nutrient content (kg)	Area applied (ha)	Area applied (m^2)
NPK	**150**	**1**	**10000**
NPK	**85**	**0.56**	**5666.6**

Table 6.2e: LCI for scenario 2

Sub process 1 - Digestion Process (1 ton d.m sludge)				
		Input – Energy		
Electricity consumption	MJ/ton d.m	318.8	Hospido et al (2005)	
Heat consumption	MJ/ton d.m	170	DEA et al (2005)	
		Output		
Biogas produced	Nm3/ton d.m	734.16	Poulsen and Hansen 2003	
Energy content of biogas	MJ/ton d.m	16880	calculation from above	
Digestate	Ton d.m	0.78		
		Emissions		
CO2 (biogenic)	kg/ton d.m	1,291	Hospido et al (2005)	
CH4 biogas process	Kg/ton d.m	6.49	Own calculation	
CO	kg/ton d.m	0.84	Hospido et al (2005)	
NO2	kg/ton d.m	0.85	Hospido et al (2005)	
N2O	kg/ton d.m	0.02	Hospido et al (2005)	
Air emission of particles	kg/ton d.m	0.08	Hospido et al (2005)	
Sub process 2 - Biogas combustion (in stationary engine) – 16880 MJ Biogas				
		Input - Energy		
Biogas	Nm3/ton d.m	734.16	(Poulsen & Hansen 2003)	
Energy content	MJ/ton d.m	16880	(Poulsen & Hansen 2003)	
		Output		
Total Energy production	GJ/ton dm sludge	16.88	Own calculations	
Heat production rate	%	40.5	Hospido et al (2005)	
Electricity production rate	%	36	Hospido et al (2005)	
Total Electricity production	MJ/ton d.m sludge	6076.8	calculations	
Total Heat production	MJ/ton d.m sludge	6836.4	calculations	
		Emissions		
CO2, gas engine	kg/ton d.m	83.6	Nielson et al	
CH4,gas engine	kg/ton d.m	5.45	Nielson et al	
N2O	kg/ton d.m	0.00844	Nielson et al	
NOx	kg/ton d.m	9.11	Nielson et al	
SO2	kg/ton d.m	0.32	Nielson et al	
CO	kg/ton d.m	4.6	Nielson et al	
Sub process 3 – Mechanical dewatering and Storage (0.78ton d.m sludge)				
		Input - Energy		
Electricity consumption	MJ/ton d.m	176.72	Hospido et al	
Electricity dehydration facilities	MJ/ton d.m	249.4	Houillon & Jolliet (2005)	
Electricity storage facilities	MJ/ton d.m	223.2	Houillon & Jolliet (2005)	
Sub process 4 – Agricultural Landspreading (0.78ton d.m)*				
		Input - Energy		
Electricity consumption	MJ/ton d.m	210.6	Hospido et al (2005)	
		Input- Material		
Lime	kg/ton d.m	400	Houillon & Jolliet (2005)	
Diesel for sludge application	kg/ton d.m	0.73	Hospido et al (2005)	
Acid	kg/ton d.m	1.8	Houillon & Jolliet (2005)	
Polymer	kg/ton d.m	7.1	Houillon & Jolliet (2005)	
		Output		
N-Content in Digest	Kg/ton d.m. Sludge	48	Poulsen & Hansen (2003)	
P-Content in Digest	Kg/ton d.m. Sludge	33	Poulsen & Hansen (2003)	
K-Content in digest	Kg/ton d.m. Sludge	4	Poulsen & Hansen (2003)	
		Emissions – green house gases		
CH4 from land application	kg/ton d.m	3.18	Hospido et al (2005)	
NH3 from land application	kg/ton d.m	1.9	Svanstrom et al (2005)	

NOx from land application	kg/ton d.m	0.82	Svanstrom et al (2005)	
CH4 from land application	kg/ton d.m	3.18	Hospido et al (2005)	
NH3 from land application	kg/ton d.m	1.9	Svanstrom et al (2005)	
		Emissions- heavy metals		
Soil emission of Cr	kg/ton d.m	0.08	Hospido et al (2005)	
Soil emission of Cu	kg/ton d.m	0.19	Hospido et al (2005)	
Soil emission of Pb	kg/ton d.m	0.33	Hospido et al (2005)	
Soil emission of Zn	kg/ton d.m	1.51	Hospido et al (2005)	

6.3 COMPOSTING

6.3.1 General System Description

Mixed sludge from waste water treatment is dewatered and then transported to a composting plant. After composting, it is applied on agricultural land. During composting some percentage of sludge degrades into CO_2, H_2O and NH_3. The dry percentage of the solid waste reaches about 60%. Most of the ammonia is oxidized and converted to nitrate during odour removal process. Sources of consumption are in two folds; electricity for ventilation (which is 3.8 MJ/ton of sludge) and oil consumption for the mobile equipment (about 1.7kg/ton of sludge) (Poulsen & Hansen 2003).

Open windrow composting is the method used in this scenario and it consists of laying the wastes into long, relatively narrow strips of waste called windrows (Daiz and Warith 2006). Windrows are kept moist and at an optimal nutrient concentration. The composting facility consumes a total of 5,000tons of organic waste. The applied inventory for composting is "*compost, at plant/kg/CH*" Ecoinvent (2004). It involves energy demand for operating a compost plant, process emissions, and the infrastructure of the compost plant. Also, other inventory data such as spreading of compost is taken from Ecoinvent (2004), and the content of NPK in compost is obtained from Poulsen & Hansen (2003).

6.3.2 Composting Process

6.3.1 Energy Consumption

Energy is consumed during dewatering as well as polymer. The polymer allows for binding of the dry matter in sludge thus increasing removal of water. Electricity consumed is given as 176.72 MJ per ton dry matter content of sludge. Electricity consumed during composting process is given as 3.8 MJ per ton sludge (Poulsen and Hansen, 2003).

6.3.2 Material Input and Output

Incoming sludge from the waste water treatment plant must first be mixed with a bulking agent such as woodchips, straw or yard waste, so as to provide structural support and maintain airspace in the windrows.

Table 6.3a Material Input (Poulsen & Hansen 2003)

Material Input	Value and unit
Dewatered sludge	1 ton D.M
Mass reduction	57%
Bulking agent (wood chips, sawdust)	380kg/ton d.m sludge
Oil consumption	1.7kg/ton sludge

6.3.3 Transportation and Spreading of Compost

When sludge is spread on agricultural land heavy metals present in the sludge are transferred to the soil. The amount of metals in this sludge usually depends on the source of wastewater. Agricultural land spreading also consumes electricity and other material inputs which include; diesel for sludge application, Acid (sulphuric acid) and polymer. Some of the inventory data for spreading of digestion residues on the field is taken from Ecoinvent database in SimaPro. Inventory for spreading or sludge on agricultural fields takes into account the consumption of diesel fuel. Fuel used for sludge application to soil is modelled as '*solid manure loading and spreading, by hydraulic loader and spreader/CHU'* and electricity consumed is from '*electricity, medium voltage, production NORDEL, at grid/NORDEL U'* (Ecoinvent 2004). The values for these parameters are obtained from Houillon and Jolliet (2005) and are represented in the general LCI table for scenario 3. Emissions to air from combustion are considered and emissions not included are dust from combustion and noise. The technology for spreading of residues is based on emissions and fuel consumptions of the newest models of tractors.

6.3.4 Avoided Products

Substitution is considered for nutrients (NPK) available in sewage sludge. The replaced fertilizers include; ammonium nitrate (for N), triple super phosphate (TSP for P) and potassium sulphate (for K). The amount of compost recovered from the sludge composted is 0.43 ton d.m which means 57% weight loss (Poulsen & Hansen 2003). The amount of nutrients available in the compost is determined based on compost analysis which is given on table 6.3b

Table 6.3b: Content of NPK in compost kg per ton D.M sludge input (Poulsen & Hansen)

Prameters	Value and Unit
Content of N	32.16
Content of P	31.02
Content of K	4
Total NPK	67.18

Data on the avoided spreading of the NPK fertilizer per hectares is taken from White et al. (2001) i.e. about 150kg of NPK fertilizer is spread per hectares of land in Europe table 6.3c

Table 6.3c: The applied NPK fertiliser (nutrient per hectare)

Total NPK	Nutrient content (kg)	Area applied (ha)	Area applied (m^2)
NPK	**150**	**1**	**10000**
NPK	**67.18**	**0.447**	**4478.6**

Table 6.3d LCI for scenario 3

Sub process 1 – Mechanical Dewatering (1ton d.m sludge)				
		Input		
sewage sludge	Ton d.m	1		
NPK in sludge				
N	kg/ton d.m	48		
P	kg/ton d.m	33		
K	kg/ton d.m	4		
		Input- Energy		
Electricity consumption	MJ/ton d.m	176.72	Hospido et al	
Electricity dehydration facilities	MJ/ton d.m	249.4	Houillon & Jolliet (2005)	
Sub process 2 – Composting (1ton d.m sludge)*				
		Input - Energy		
Electricity consumption	MJ/ton sludge	3.8	Poulsen & Hansen (2002)	
Oil consumption (diesel)	kg/ton sludge	1.7	Poulsen & Hansen (2002)	
		Input - Material		
Bulking agent (wood chips, yard waste, straw)	kg/ton d.m sludge	380		
Water	Litre/ton d.m	Very little		
		Output		
Mass reduction, composting	%	57	Poulsen & Hansen	
N reduction, composting	%	33	Poulsen & Hansen	
P reduction, composting	%	6	Poulsen & Hansen	
Compost	ton d.m sludge	0.43	Poulsen & Hansen	
N content	kg/ton d.m	32.16	Poulsen & Hansen	
P content	kg/ton d.m	31.02	Poulsen & Hansen	
		Emissions from composting process		
CO2 (biogenic)	From SimaPro			
CH4	”			
NO2	”			
Heavy metal in compost				*amount in sludge
Hg	kg/ton d.m	0.0011	Jepsen & Jensen (2004)	
Cd	kg/ton d.m	0.0013	Jepsen & Jensen (2004)	
Pb	kg/ton d.m	0.05	Jepsen & Jensen (2004)	
Cr	kg/ton d.m	0.021	Jepsen & Jensen (2004)	
Ni	kg/ton d.m	0.02	Jepsen & Jensen (2004)	
Zn	kg/ton d.m	0.7	Jepsen & Jensen (2004)	
Cu	kg/ton d.m	0.243	Jepsen & Jensen (2004)	
Sub process 3 – Agricultural Land spreading (0.43 ton d.m sludge)				
		Input - Energy		
Fuel	kg/ton d.m	7.1	own calculations	
Electricity consumption	MJ/ton d.m	210.6	Hospido et al (2005)	
		Output		
N-Content in compost	kg/ton d.m. Sludge	32.16	Hansen & Poulsen(2003)	
P-Content in compost	kg/ton d.m. Sludge	31.02		
K-Content in compost	kg/ton d.m. Sludge	4		
		Emissions – green house gases from fuel use by tractors (choose process in SimaPro)		
		Emissions –Heavy Metals (same as amount in compost		
Hg	kg/ton d.m	0.0011	Jepsen & Jensen (2004)	
Cd	kg/ton d.m	0.0013	Jepsen & Jensen (2004)	
Pb	kg/ton d.m	0.05	Jepsen & Jensen (2004)	
Cr	kg/ton d.m	0.021	Jepsen & Jensen (2004)	

Ni	kg/ton d.m	0.02	Jepsen & Jensen (2004)	
Zn	kg/ton d.m	0.7	Jepsen & Jensen (2004)	
Cu	kg/ton d.m	0.243	Jepsen & Jensen (2004)	

6.4 INCINERATION OF DIGESTED SLUDGE IN A FLUIDISED BED

6.4.1 General description

In this system one ton of raw sludge resulting from wastewater treatment, is subjected to anaerobic digestion. The sludge is assumed to be mixed sludge coming from both primary and secondary wastewater treatment processes. Anaerobic digestion is a stabilisation process aimed at reducing, stabilising and partially reducing the treated volume of the sludge. The biogas produced is incinerated and the energy released is reused by the plant. The digestate produced is then further dewatered, dried in a drying plant then transported to an incineration plant to be incinerated in a fluidised bed.

6.4.2 Anaerobic digestion Process

6.4.2.1 General description

Data for the digestion process is obtained from existing literature on wastewater treatment in Aalborg and Randers municipality.

6.4.2.2 Energy Model

Electricity is needed for the sludge digestion process and heat is needed for heating the digester and general space heating. Part of the energy demands can be fulfilled with energy produced from biogas incineration while the rest is obtained from natural gas. Biogas production at WWTP (digestion process) is given as 176.2 Nm^3/ton COD which is equivalent to 734.16 Nm^3/ton d.m. The energy content of the biogas is given as 16.88GJ/ton d.m (Poulsen & Hansen 2003).

1. Energy Recovered

Biogas produced from anaerobic digestion process is incinerated to produce energy which is reused by the plant. Hence part of the heat and electricity used for this processes comes from biogas source while the rest is from fossil fuel origin. Electricity consumed is given as 318.8 MJ/ton d.m and this obtained from studies by Hospido et al (2005), heat consumed is obtained from DEA et al (2005) and is given as 170 MJ/ton d.m. Energy production during biogas combustion is given on Table 6.4a

Table 6.4a: Energy Production

Parameter	Amount (MJ)
Heat	6836.4 MJ
Electricity	6076.8 MJ

2. Energy Substituted

The substituted product during digestion and biogas combustion is energy. Electricity is assumed to be obtained from coal while heat is obtained from natural gas. The inventory data used for modelling the avoided marginal electricity in scenario 1 is *'electricity, hard coal, burned in power plant/NORDEL U'* taken from Ecoinvent (2004). Data used for heat generation is obtained from *'Natural gas, burned in industrial furnace low-NOx>100kW/ RER U'* (Ecoinvent 2004).

Table 6.4b an inventory on the energy production for the digestion process

Digestion Process	Value/Unit
Biogas yield	734.16 Nm^3/ton d.m
Energy content of biogas	16.88 GJ/ton d.m
Rate of electricity production	36 %
Rate of heat production	40.5%

Source: Poulsen & Hansen 2003

Table 6.4c: energy use for the digestion process

Parameter	Value and unit
Electricity consumption	318 MJ/ton d.m
Heat consumption	170 MJ/ton d.m

Source: Hospido et al 2005 & DEA et al 2005

3. Emissions from digestion process

Emissions associated with the digestion process include emissions of biogenic CO2, some methane escapes from this process into the atmosphere, also breakdown of organic matter releases nitrogen which forms oxides of nitrogen (NO_2, N_2O, NOx). Values for emissions were obtained from Hospido et al (2005) and Hansen & Poulsen (2003). The emissions are presented in the general LCI table for scenario 4.

6.4.3 Drying

The sludge drying facility is present in the wastewater treatment plant which is the situation with the wastewater treatment plant at Randers. Drying is a thermal treatment and occurs at different temperatures. Level of dry mass reached is between 35-90%. Energy requirements are much higher and highly dependent on the water content of the sludge, hence the sludge is first dewatered before drying. Energy for drying is obtained from natural gas burned in a natural gas combustion engine at the plant. Energy needs for the drying process is shown on table 6.4

Table 6.4c: Energy needs for drying process (per ton input d.m content of sludge)

Energy	Value kWh
Heat consumption	1638
Electricity consumption	118

Source: Hospido et al 2003

Sludge drying also produces a high amount of heat and electricity. Part of this energy is used for processes in the plant and the rest is used for district heating.

Table 6.4d Energy production for drying process (per ton d.m content of sludge)

Energy Production	Amount
Heat	1228.5 kWh
Electricity	-

Source: Stasta et al 2005

6.4.4 Incineration in fluidised Bed

6.4.4.1 General description

The technology applied for mono-combustion of sewage sludge is fluidised bed incineration due to its lower extra fuel consumption and emissions. Exhaust gases from the furnaces are used for the production of energy; a large amount is used by the incineration plant and the rest is used for heating and production of warm water via the city district heating. The plant is equipped with a furnace, boiler, electrostatic precipitator and wet scrubbers, advanced flue gas cleaning system and a wastewater treatment facility.

6.4.4.2 Energy Model

1. Energy Recovery

Energy produced during incineration is given as 9954 MJ/ton d.m for heat and 3476MJ/ton d.m for electricity. Energy consumed is assumed to be the marginal electricity and is given as 250MJ/ton waste for electricity and 15.4 MJ/ton waste for heat (Kangala 2007).

2. Energy Substituted

During incineration of sludge, electricity and heat are substituted. The inventory data used for modelling the avoided marginal electricity in scenario 4 is *'electricity, hard coal, burned in power plant/NORDEL U'* taken from Ecoinvent (2004). Data used for heat generation is obtained from *'Natural gas, burned in industrial furnace low-NOx>100kW/ RER U'* (Ecoinvent 2004).

6.4.4.3 Material input and Output

The incineration process includes combustion of sludge, energy recovery, flue gas treatment and fly ash disposal. This process requires a lot of energy and also materials are released into the atmosphere while some are collected and further treated. Energy recovered is used heat and electricity production and fly ash is landfilled. In addition to energy consumption, other inputs include NaOH, lime ammonia and heavy fuel oil consumption.

6.4.5 Landfilling of Incineration Residues

During incineration, 200kg of fly ash is produced per ton d.m sludge (Poulsen and Hansen, 2003). This is sent for landfilling. Sewage sludge ash contains high amounts of trace elements such as Pb, Cd, Zn and Cu, which are assumed to be leached all out, during landfilling.

Table 6.4 f LCI for scenario 4

Sub process 1 - Digestion Process (1 ton sludge d.m)				
		Input – Energy		
Electricity consumption	MJ/ton d.m	318.8	Hospido et al (2005)	
Heat consumption	MJ/ton d.m	170	DEA et al (2005)	
		Output		
Biogas produced	Nm3/ton d.m	734.16 (16.88 GJ ENERGY)	Poulsen and Hansen 2003	
Energy content of biogas	MJ/ton d.m	16880	calculation from above	
Digestate	Ton d.m	0.78	See notes for calc	
		Emissions		
CO2 (biogenic)	kg/ton d.m	1,291	Hospido et al (2005)	
CH4 biogas process	Kg/ton d.m	6.49	Own calculation	
CO	kg/ton d.m	0.84	Hospido et al (2005)	
NO2	kg/ton d.m	0.85	Hospido et al (2005)	
N2O	kg/ton d.m	0.02	Hospido et al (2005)	
Air emission of particles	kg/ton d.m	0.08	Hospido et al (2005)	
Sub process 2 - Biogas combustion (in stationary engine) – 16880 MJ Biogas				
		Input - Energy		
Biogas	Nm3/ton d.m	734.16	Poulsen and Hansen 2003	
Energy content of biogas	MJ/ton d.m	16880	calculation from above	
		Output		
Total Energy production	GJ/ton dm sludge	16.88	Own calculations	
Heat production rate	%	36	Poulsen & Hansen (2003)	
Electricity production rate	%	40.5	Poulsen & Hansen (2003)	
Total Electricity production	MJ/ton d.m sludge	6076.8	calculations from above	
Total Heat production	MJ/ton d.m sludge	6836.4	calculations from above	
		Emissions		
CO2, gas engine	kg/ton d.m	83.6	Nielson et al	
CH4,gas engine	kg/ton d.m	5.45	Nielson et al	
N2O	kg/ton d.m	0.00844	Nielson et al	
NOx	kg/ton d.m	9.11	Nielson et al	
SO2	kg/ton d.m	0.32	Nielson et al	
CO	kg/ton d.m	4.6	Nielson et al	
Sub process 3 – Drying (0.78ton d.m sludge)				
		Input – Energy		
Heat consumption	MJ/ton d.m	1638	Poulsen &Hansen 2003	
Electricity consumption	MJ/ton d.m	118	Poulsen &Hansen 2003	
		Input – Materials		
Water consumption	m^3/ton d.m	15.2		
Digested sludge	Ton d.m	0.78		
		Output		
Heat recovered	kWh/ton d.m	1228.5		
Heat recovery rate	%	75		
		Emissions		
Air emissions of VOC	kg/ton d.m	0.0443	Hospido et al (2005)	
Sub process 4 – Fluidised Bed Incineration (0.78 ton d.m sludge)				
		Input - Energy		
Electricity Consumption	MJ/ton d.m	250	Kangala 2007	
Heat	MJ/ton d.m	15.4	"	
		Input - Material		
NaOH consumption	kg/ton d.m	12.2	Hospido et al (2005)	
Lime consumption	kg/ton d.m	4.96	Hospido et al (2005)	
Ammonia consumption	kg/ton d.m	3.72	Hospido et al (2005)	
Heavy fuel oil	kg/ton d.m	31	Hospido et al (2005)	
		Output		
Incineration efficiency	%	90.3	DEA (2005)	
Electricity production rate	%	22	Poulsen & Hansen (2002)	
Heat production rate	%	63	Poulsen & Hansen (2002)	
Heating value of sludge	MJ/kg d.m	15.8	Svanstrom et al (2005)	
Heating value of sludge	MJ/ton d.m	15800	Calculations	
Heat Produced	MJ/ton d.m	9954	Calculations	

Electricity produced	MJ/ton d.m	3476	Calculations	
Residual waste	kg/ton d.m	40	Poulsen & Haansen (2002)	
Residual waste density	tons/m3	1.6	Poulsen & Hansen (2002)	
Emissions - to Air				
From Flue gas				
CO2, biogenic	kg/ton d.m	1500	Hospido et al (2005)	
CO2	kg/ton d.m	800	Hospido et al (2005)	
CO	kg/ton d.m	0.151E-6	Hospido et al (2005)	
NO2	kg/ton d.m	1.0E-6	Hospido et al (2005)	
Air emission of particles	ug/ton d.m	2.00	Hospido et al (2005)	
Dioxin & Furan	ug/ton d.m	3.0E-5	Hospido et al (2005)	
Emissions – Incineration residues				
Fly Ash	kg/ton d.m	200		
Bottom Ash	kg/ton d.m	0		
Slag	kg/ton d.m	0		
Landfilling of incineration residues (1 kg incineration residues- fly ash)				
Input (See SimaPro)				
Emissions per kg of fly ash deposited at landfill				
Air Emissions	SimaPro			
Heavy metals in Fly ash	*200kg/ton d.m			

CHAPTER SEVEN
LIFE CYCLE IMPACT ASSESSMENT

This chapter presents the impact assessment phase of the life cycle study which is carried out in accordance with well established procedures in the ISO 14044 guidelines. The impact assessment includes a classification step using the EDIP/UMIP 97 V2.03 method and Cumulative Energy Demand (CED) method..

7.1 GLOBAL WARMING POTENTIAL (GWP 100)

This is the phenomenon where the earth's atmosphere absorbs part of the energy emitted as infrared radiation from earth towards space and thus becomes heated. The consequences of global warming include increased global average temperatures and sudden regional climatic changes. The compounds contributing most to this green house gas effect CO_2, CH_4 and N_2O. As far as these gases are concerned their global warming potential for 100 years is given as 1 for CO_2, 21 for CH_4 and 310 for N_2O. Avoided emissions linked to substitutions are subtracted (such as production and spreading of fertilisers). The same amount of biogenic carbon is subtracted in all scenarios. The global warming potential is analysed for each scenario for a period of 100 years (GWP100). The net contribution to global warming of each scenario is presented in table 7.1

Table 7.1: Global Warming Potential (GWP100) in kgCO_2eq

Sc.1- AD+DR+CK	Sc.2 – AD+AP	Sc.3 – CP + AP	Sc. 4 AD+DR+FBI
-1100	-638	-362	-957

The global warming balance shows that all scenarios show emission saves. Scenario 1 however shows the best balance followed by scenario 4 then scenario 2 and then 3. Thus Sc. 1 is the most promising method for sludge disposal as regards global warming potential. For scenario 1, even though the impact of drying is significant, heat (from natural gas) and electricity (coal based) substitutions are also significant during biogas combustion and incineration for both scenario 1 and 4. These substitutions provide emission saves and thus account for reduced emissions in scenario 1 compared to the other scenarios. Summarily, emission saves in scenarios 1, 2 and 4 arise from energy substitutions during biogas combustion and the incineration process for scenarios 1 and 4. Whereas in scenario 3, there are no energy substitutions; only fertilizer substitutions are offered. Transportation shows insignificant contributions for all scenarios. Table 7.1 gives an overview on the contribution to GWP of the different processes and from this table, it can be observed that both scenario 1, 2 and 4 offer significant emission saves during both biogas combustion and incineration (in cement kiln and fluidised bed respectively).

Table 7.2: Processes contributing to GWP100 ($kgCO_2eq$)

Scenarios ► / Processes ▼	Scenario .1 AD + DR + CK	Scenario 2 AD + AP	Scenario 3 CP + AP	Scenario 4 AD + DR + FBI
Digestion	164	164	X	164
Slurry store	193	193	X	193
Compost plant	1430	1430	0.164	1430
Biogas combustion	- 2340	- 2340	X	- 2340
Drying	200	X	X	200
Incineration	-911	X	X	-769
Transportation	1.95	1.3	2.376	1.3
Mech. Dewatering	55.9	43.6	55.9	55.9
Electricity	101	101	-	101
Heat	14	14	-	14
K fertiliser	X	-6.84	-6.84	X
N fertiliser	X	-429	-288	X
P fertiliser	X	-153	-143	X
Fert. by broadcaster	X	-14.4	-11.2	X
Agric. Application	X	365	28.7	X
Loading/spreading	X	X	0.00132	X
Total	**-1091.15**	**-631.34**	**-362**	**-949.8**

From these results it can be concluded that, biogas combustion is a very important process vis-à-vis energy production hence, combining the processes of anaerobic digestion/biogas combustion and incineration is efficient since biogas produced during biogas combustion can be burned to produce energy which substitutes energy from fossil origin. Also during incineration both in cement kilns and fluidised bed, heat is produced which substitutes fossil fuel (natural gas) used. Though the processes of mechanical dewatering and thermal drying contribute highly to global warming, this is balanced by energy recovered during biogas combustion, drying and incineration. This is unlike scenario 2 where heat gain is only during biogas combustion but this also balances the impacts associated with agricultural application of sewage sludge. Scenario 4 contributes about 10% of energy produced during biogas combustion; thermal drying of sludge reduces it to a dry state which does not require a lot of energy for its incineration; it is assumed that the same amount of energy used for incinerating solid waste is used for incinerating dried sewage sludge. Sludge has a heating value and when burned, energy is produced which can be used for both heat and electricity production.

Thus scenario 1, 2 and 4 are energy efficient scenarios thanks to the biogas combustion process coupled with energy production during the incineration process (cement kiln and fluidised bed incineration) which is coupled with energy recovery – offering a beneficial effect.

7.2 OTHER IMPACT CATEGORIES

The other environmental impact categories taken into consideration include acidification and eutrophication. The contributions to other impact categories not discussed here are presented in the appendix section.

7.2.1 Acidification

Acidification describes a process whereby, acids forming compounds when emitted to the atmosphere and deposited in water and soil, with the addition of hydrogen ions, eventually cause a decrease in pH, hence increase in acidity (Wenzel, Hauschild & Alting 1997). As concerns contribution to acidification of the different scenarios, scenario 3 is considered the best scenario as it is the only scenario contributing to emission saves in this impact category as shown on table 7.3

Table 7.3: Contribution to Acidification in kgSO_2eq

Sc.1- AD+DR+CK	Sc.2 – AD+AP	Sc.3 – CP + AP	Sc. 4 AD+DR+FBI
11.2	11.8	-3.27	10.5

The contributions to acidification of scenario 1, 2 and 4 are almost equal in extent with the highest contribution coming from scenario 2. In scenario 1, processes contributing to acidification include biogas combustion followed by drying. Only the cement kiln incineration process offers emission saves for this impact category. The highest contribution to acidification in scenarios 1, 2 and 4, come from the construction of capital equipment for the anaerobic digestion. The technologies and processes in these scenarios produce emissions in the form of SO_2 which results to acidification. In scenario 2, contribution to acidification also results from biogas combustion and agricultural land application with the latter giving the highest contribution (3.7E3gSO_2eq). The only process contributing to emission saves in this scenario is from NPK substitution with highest emission saves exhibited by phosphorus. In scenario 4, the fluidised bed incineration also process offers emission saves of -2.02kgSO_2eq).

The technologies used in scenarios 1, 2 and to some extent 4, are not quite efficient when it comes to SO2 emissions. For scenario 3, most of the emissions contributing to acidification result from mechanical dewatering and agricultural application and these are quite insignificant considering the other scenarios. This technology is thus the most efficient since only the mechanical dewatering and agricultural process use fossil fuel which release SO_2. Green house gases associated with the composting process include CO_2, N_2O and NH_3 and these gases are related to the global warming impact category. Conclusively, the composting process is the best scenario in terms of contribution to acidification with emission savings observed for fertiliser substitution processes and low contribution of its other processes compared to other scenarios.

7.2.2 Eutrophication

Eutrophication is a syndrome of ecosystem responses to human activities that fertilize water bodies with nitrogen (N) and phosphorus (P), often leading to changes in animal and plant populations and degradation of water and habitat quality. Human activities that artificially enrich water bodies with N and P result in unnaturally high rates of plant production and accumulation of organic matter that can degrade water and habitat quality. These inputs may come from sewage treatment plants or run-off of fertilizer from farm fields (Cloern & Krantz 2007).

Table 7.4: Contribution to Eutrophication in kgNO_3eq

Sc.1- AD+DR+CK	Sc.2 – AD+AP	Sc.3 – CP + AP	Sc. 4 AD+DR+FBI
24.2	-4.9	-33.1	23.5

Both scenario 1 and 4 represent the worse scenarios vis-à-vis eutrophication with the former contributing slightly higher. Scenario 2 and 3 offer emission saves for this impact category with scenario 3 offering the highest save. For scenario 3, the main processes' contribution to eutrophication is insignificant. Emission saves are observed for NPK fertiliser substitution and transportation providing an insignificant contribution. The effectiveness of this technology is due to the absence of processes contributing to high amounts of SO_2 emissions when compared to the other scenarios. In scenario 1 and 4, processes contributing highly towards this impact category include the biogas combustion and digestion process. In scenario 1, only the cement kiln incineration process offers emission saves in the said impact category; the characterisation results are given as -0.544kgNO_3eq, while in scenario 4, emission saves are observed during the fluidised bed incineration process as -2.02kgNO_3eq. The digestion and biogas combustion process as well as construction of capital equipment, make these technologies quite inefficient as far as eutrophication is concerned. The absence of these processes in scenario 3 gives it an upper hand making it the best scenario so far.

7.2.3 Other Impacts

Regarding the contribution of the different scenarios to selected impact categories, it can be observed that the composting option (scenario 3) is the best option since it offers saves in all the chosen impact categories unlike the other categories where saves are only observed for the global warming impact category (except for scenario 2 which offers saves vis-à-vis eutrophication). Scenario 3 has fewer processes contributing to these impact categories, when compared to the other scenarios. The absence of the anaerobic digestion/biogas combustion phase (for scenario 3) and drying phase (both scenario 2 &3)

allow these scenarios to contribute less to eutrophication. These processes are responsible for the highest emissions contributing to eutrophication in scenario 1 and 4.

In addition, scenario 3 is best so far when other impact categories apart from the ones selected, are taken into consideration. This is because; the technologies and the processes associated with this scenario tend to offer emission saves of varying degrees in the given impact categories. This situation is opposite when considering scenario 1, 2 and 4 whose emission saves are limited to the global warming impact category. For scenario 1 and 4, emissions mostly come from the digestion process coupled with mechanical dewatering meanwhile the incineration processes are seen to offer emission saves (negative values). Figure 7.1 depicts graphical representations of scenario contributions to different impact categories other than the ones adopted for the study;

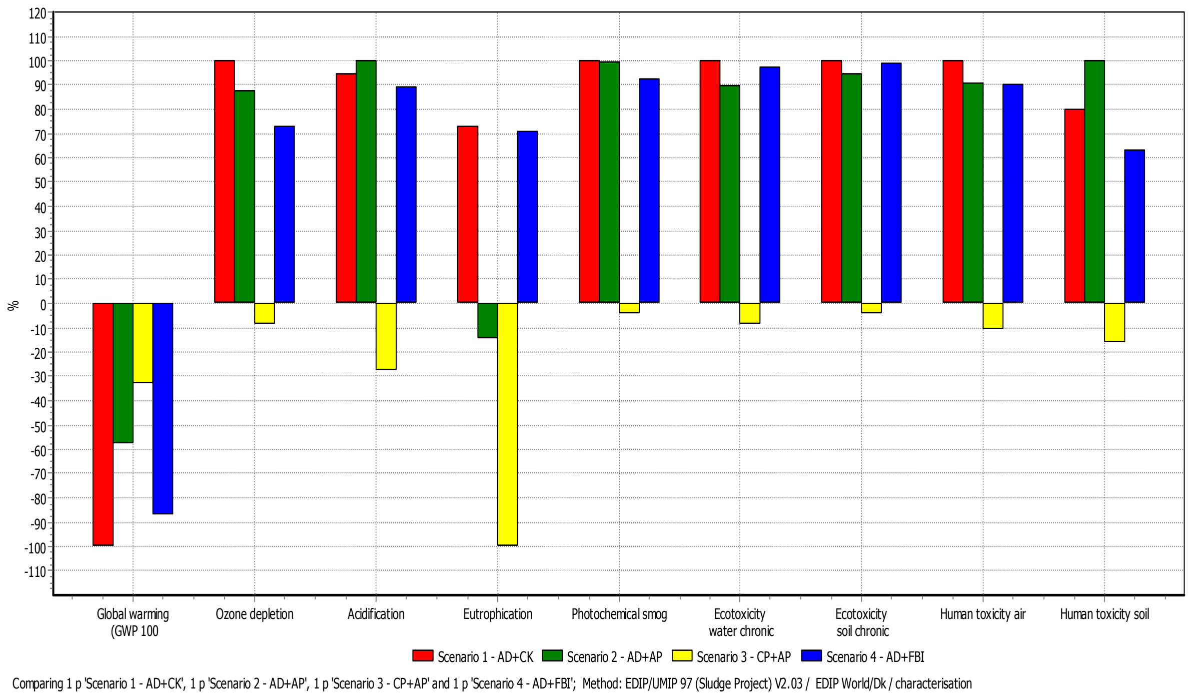

Fig. 7.1: Graphical representation of scenario contributions to different impact categories (see appendix for larger picture).

7.3 Discussion on Results

From the results obtained for global warming balance of all scenarios, it can be observed that scenario 1 and four are the most promising scenarios with scenario 1 being the best with respect to global warming. This is an indication of how important substitution is in these scenarios: however it is important to take into account the risk linked to an ineffective substitution, which is high for scenario 4 but less important for fluidised bed incineration. That is to say, if sludge replaces another waste in cement kilns, this scenario would be the worst vis-à-vis energy and green house gas effect. In identifying the importance of these substitutions, we realise that using sludge as a resource is an efficient way to compensate for emissions related to treatment.

The key parameters and issues which contribute to maximise the beneficial effects of substitution are identified below:

- Fertilisation value alone is not sufficient to obtain a positive energy balance (reason why scenario 1, 2 and 4 have more emission saves than scenario 3 in relation to the global warming impact category). Hence it is necessary to take into consideration both the nutrition value and energy content of sludge in waste water.
- Since sludge drying has a high energy requirement, it is thus necessary to use an efficient dehydration system.
- Combined heat and electricity production increases energy substitutions. (Houillon & Jolliet 2005).

Contrary to prejudiced ideas, thermal processes have got the best global warming balance especially for incineration in cement kilns and fluidised bed incineration, compared to agricultural spreading and composting. The choice of sludge treatment can be oriented towards one or another sludge disposal process based on the weight given to each criterion (energy and global warming). Hence thermic processes can compete with or even be more efficient if adequate technology is used (Houillon & Jolliet 2005). However, based on only energy balance and global warming balance, it is not sufficient to conclude that these scenarios are the best when taking into consideration the impact categories of Acidification and Eutrophication. Scenario 3 proves to be the best scenario in all, because as well as offering saves in the global warming impact category, it also offers more saves in other impact categories unlike the other scenarios.

7.4 SENSITIVITY ANALYSIS

A sensitivity analysis is performed to validate or check the reliability of the LCA results as well as to test how sensitive these results are to the various assumptions made in the study. Table 7.6 represents, the sensitivity analysis considered in this study and also, explains the aim of each of the analysis performed. Each sensitivity analysis is carried out using the same functional unit as the main scenarios and same scenario for the purpose of consistency and also to maintain the comparability of the study (with regards to the three scenarios).

Table 7.6: Sensitivity Analysis studied

No.	Aim	description
1	Uncertainty	**Heat production only:** this sensitivity compares results obtained when the fluidised bed incineration plant produces only heat.
2	Uncertainty	**Electrical efficiency increased:** it compares the results obtained when the efficiency of electricity and heat production of the fluidised bed incineration plant changes.
3	Uncertainty	**N reduction:** the sensitivity compares the results when the percentage reduction of N fertilisers increases during composting.
4	Uncertainty	**Scenario 4 without anaerobic digestion:** this tries to compare the change in results when undigested sludge is incinerated.
5	Uncertainty	**The LCIA method**: EDIP 97 is applied as the default LCIA method. This sensitivity analysis compares the results when using the CML 2000 baseline methods

7.4.1 Sensitivity Analysis 1

This analysis is used to find out what the situation will look like if only heat is produced during fluidised bed incineration instead of the normal heat and electricity production. This assumes a heat production rate of 85% which implies 13,430MJ of heat produced per ton d.m sludge incinerated.

Table 7.7: Results of Comparison

Impact Category	Unit	SA 1- Heat Production Only	Scenario 4- AD + FBI
Global Warming Potential	$kgCO_2eq$	-398	-949.8
Acidification	$kgSO_2eq$	12	10.5
Eutrophication	$kgNO_3eq$	24.3	23.5

The above results show that producing only heat provides less emission saves as concerns global warming potential (GWP100) and a little bit higher impact with regards to the other two impact categories. That is to say less emissions are avoided when only heat is produced as energy because in the original scenario -949.8 $kgCO_2eq$ of emissions contributing to GWP is avoided whereas only -398$kgCO_2eq$ is avoided when only heat is produced. It can be attributed to the fact that producing heat only is less efficient since with the use of combined heat and power generation it is possible to capture the heat that would otherwise be rejected when using traditional separate generation of electricity and heat. Thus the total efficiency of this integrated system is much greater than from separate systems (Elliot & Spurr 1999).

7.4.2 Sensitivity Analysis 2

This analysis tries to compare the situation where the efficiency of electricity production at the fluidised bed incineration plant is increased from 22% to 40% and the heat production rate is reduced from 63 to 50%. This is to verify if it is more environmentally efficient to produce more electricity than heat during sludge incineration.

Table 7.8: Results of Comparison

Impact Category	Unit	SA 2- Electricity efficiency increased to 40%	Scenario 4- AD + FBI
Global Warming Potential	kgCO2eq	-1570	-949.8
Acidification	kgSO2eq	9.07	10.5
Eutrophication	kgNO3eq	22.6	23.5

From table 7.8 it can be noticed that, increasing the electricity production efficiency results to increase in emission saves for scenario 4 vis-à-vis global warming potential (GWP 100) and the contribution to acidification and eutrophication is less than that for the original scenario. This implies increasing the efficiency of electricity production of the incineration plant produces less emissions and this has a significant impact on the LCIA results. This is the effect of substituting more coal (marginal electricity) than natural gas (marginal heat) which is positive (reduced emissions) as far as global warming is concerned.

7.4.3 Sensitivity Analysis 3

This sensitivity analysis aims to compare the results obtained for scenario 3 when the reduction of N during composting is increased to 40%.

Table 7.9: Results of Comparison

Impact Category	Unit	SA 3 - N reduction	Scenario 3 – CP + AP
Global Warming Potential	kgCO2eq	-322	-362
Acidification	kgSO2eq	-3.17	-3.27
Eutrophication	kgNO3eq	-32.9	-33.1

Increased loss of N during composting results in reduction in the emission saves observed for scenario 3 though the extent of reduction is quite small, for all impact categories. This however implies the more N lost during composting, the less saves are produced by this scenario since the reduced N is lost as N_2O a green house gas also contributing to global warming. Usually not much phosphorus is lost that is all the phosphorus remains in the compost. The percentage loss indicated in scenario is to some extent related to calculation errors when measuring amount of P in compost.

7.4.4 Sensitivity Analysis 4

This scenario analyses a situation where scenario four occurs without the anaerobic digestion process

Table 7.9: Results of Comparison

Impact Category	Unit	SA 4 – FBI without AD	Scenario 4 – AD + FBI
Global Warming Potential	kgCO2eq	-673	-949.8
Acidification	kgSO2eq	-2.05	10.5
Eutrophication	kgNO3eq	-1.2	23.5

In terms of global warming potential, the absence of the anaerobic digestion/biogas combustion process results in a decrease in emission saves for this scenario. This is because these are the processes that actually contribute to emission saves as seen for scenario 4. However, this change results in emission saves for the other two impact categories; in addition to offering emission saves, the digestion/biogas combustion processes provide higher green house gas emissions and this is seen in how the results for the acidification and eutrophication impact categories are affected. Thus, though this scenario less favourable vis-à-vis global warming, it is a favourable option with respect to contribution to its contribution to acidification and eutrophication.

7.4.5 Sensitivity Analysis 5

When using the EDIP 97 method, some uncertainty usually arise hence to assess the impact of the four sewage sludge management scenarios, the IMPACT 2000+ is used to validate the results obtained by EDIP 97. The study will use two impact categories to make this sensitivity analysis: global warming potential and acidification. This analysis tries to observe how similar the results are for the chosen impact categories using the two different impact assessment methods. Eutrophication is avoided due to dissimilar units.

Table 7.10: Using a different Impact Category

Impact category	**Unit**	**Impact 2002+**				**EDIP 97**			
Scenarios		**Sc. 1**	**Sc. 2**	**Sc.3**	**Sc. 4**	**Sc. 1**	**Sc. 2**	**Sc.3**	**Sc. 4**
Global Warming Potential	kgCO2eq	-1280	-786	-261	-1120	-1091.15	-631.34	-362	-949.8
Acidification	kgSO2eq	11.6	12.2	-3.27	10.9	11.2	11.8	-3.27	10.5

This analysis tries to determine how close the similarities between the results are for two different impact categories. As indicated on table 7.10, using both impact categories, the technologies used are seen to provide almost similar emission saves for the global warming impact category. Also for the acidification impact category, the contributions of all scenarios (when using both impact categories) fall in the same range. It can thus be concluded that using both impact categories, almost similar results are obtained.

7.4.6 Summary of Sensitivity Analysis

Conclusively, significant changes were observed when using sensitivity analysis except for the last sensitivity which provided near to similar results.

7.5 EVALUATION OF RESULTS

The elements of evaluation that are considered in this chapter includes: completeness check, sensitivity check, and consistency check.

7.5.1 Completeness Check

The goal of the completeness check is to make sure all relevant information and data needed for the interpretation are available and complete (ISO 14044 2006, 34). Chapter 4 and 6 presents a comprehensive description of the goal and scope definition and the inventory process for each of the scenarios under study. Also, the study assessed all that is relevant to the study.

7.5.2 Sensitivity Check

The objective of the sensitivity check is to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data, methods or calculation of category indicator results, etc. The sensitivity check relies on the results of the sensitivity conducted in the LCIA chapter. A sensitivity analysis performed in the section 7.5 deals with issues such as LCIA-methods, Energy efficiency at incineration plants and NPK reduction during composting.

7.5.3 Consistency Check

A consistency check determines whether the assumptions, methods and data are consistent with the goal and scope of the study. According to the ISO (14044 2006, 35), the consistency check answers questions such as; have regional and/or temporal differences, if any, been consistently applied? Have allocation rules and system boundary been consistently applied to all product systems? Have the elements of the impact assessment been consistently applied?

In chapters four, five and six, all the sources of the inventory have been stated in each scenario. Also, the capital goods, i.e. the plant construction and machinery have been included in all processes. Most of the results of the study are similar to the results obtained in previous studies as presented in chapter 8. Hence, this aspect increases the confidence in the conclusions drawn in this study. The data source was mainly based on some existing databases, literature reviews and as well as some primary data from wastewater treatment plants of Randers and Aalborg. About ninety percent (90%) of the data used in the study were not more than five years old. LCIA results were obtained using the LCA software SimaPro7. This software is in line with the relevant scenarios laid down in the study, and link modules and partial inventories with inventory networks and makes calculations taking into account the relevant functional unit of the study.

Furthermore, since the scenarios identified are based on the recent country groupings by the EEA (2007), the marginal energy sources have been identified in this study. The consequential approach is the method of LCA applied especially with regards to the marginal energy and organic fertilizers, while the system boundary was expanded to include all the affected processes. Technology coverage is the state-ofart for all three scenarios and time coverage is fairly recent for all three scenarios. The geographical coverage is Europe.

CHAPTER EIGHT

CONCLUSION AND DISCUSSION

The creation of the EU water directive as a means to protect the aquatic environment has as consequence the production of more sludge and this conflict with waste prevention/minimisation with respect to the waste directive. Sludge can be considered a resource that can be utilised but the challenge is to be able to use efficient systems and technologies for its management so as to avoid/ reduce adverse effects on the environment.

8.1 CONCLUSION

8.1.1 General Overview

Life cycle assessment as defined by ISO 14040 is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a system throughout its life cycle. This is obtained through a systematic, four step procedure which includes the goal and scope definition, inventory analysis, impact assessment and interpretation. This tool has proven to be valuable in verifying and analysing environmental performances of waste treatment systems that need to be part of the decision-making process towards sustainability. It has been extensively used by researchers to analyse sewage sludge treatment technologies with major focus on energy and global warming balance; this has been the primary aim of this study but also included were the effect of these treatment options on other impact categories.

8.1.2 Conclusion on Results of Study

Sewage sludge is an avoidable waste product generated from the treatment of waste water and since its disposal to agriculture and landfill are more and more carefully controlled, alternative thermal routes are currently being used as disposal routes. The past years have been characterised by several opinions in favour of land application and incineration though many contradictions have also come up against the use of these processes. Several studies have been carried out to analyse and compare the effectiveness of these technologies and the conclusions attained assert that the most effective utilisation of sewage sludge implies both energy and material reuse, though this is not always possible. The agricultural application of sewage sludge was first a widely accepted sewage sludge disposal option but today, it is facing more pressure as stricter rules are applied for its use following increasing awareness of the presence of toxic compounds and pathogens. As far as composting and agricultural application of sewage sludge is concerned, much research needs to be carried out to establish the exact amount of heavy metals that is effectively take up by plants and crops as well as the amount transferred to another phase like leachate. (Hospido et al 2005)

Also, though thermal processes such as incineration in cement kilns and fluidised bed incineration prove to be promising technologies vis-à-vis global warming and energy recovery, more efforts are still needed to improve the valuable, viable products as nutrients are lost during the process. Moreover, these conclusions are base only on one impact category and since it is the subject of current debates and research, it is not surprising that most researchers use only this impact category to make their conclusions. It is worth noting that an evaluation of the environmental impacts of sewage sludge treatment should be based on an analysis of the effect of the treatment options on the different impact categories so as to be able to get a clear picture of the consequences of using these technologies. As indicated by the study, the thermal treatment scenarios show the best results only for the impact category of global warming. This is however not true for the other two impact categories Acidification and Eutrophication. An inclusion of other impact categories shows composting to be the bets scenario so far (see appendix); it thus necessary when analysing the effects of sludge treatment systems to analyse the effects on all impact categories.

8.1.3 Conclusion on Results from other Studies

As earlier mentioned several studies have been carried by different researchers to evaluate different treatment options for sludge with the use of LCA or other tools. Just recently, Houillon and Jolliet (2005) carried out LCA studies on six different scenarios for sewage sludge treatment with focus on only energy and emissions contributing to global warming. From their conclusions, thermal processes were seen as the best treatment options. Hospido et al (2005) also carried out LCA studies on slightly different scenarios and also emphasized the advantage of thermal processes and to some extent the land application of sewage sludge; as long as more research is carried out to evaluate the precise amount of heavy metals in sludge that is liable to be taken up by plants as well as the amount leaching out.

8.2 DISCUSSION

As earlier mention in chapter 3 of this study, the choice of technology for sewage sludge management should be based on the stipulations of the waste hierarchy. National policies have been set up in Denmark to serve as framework for sludge management; nevertheless it is the municipality concerned that determines which waste management system /technology to implement for sludge treatment. Several tools are available for use as methods of analysing the efficiency of sludge treatment options and the LCA tool is an extensively applicable tool and it has been used in several studies. The use of LCA as a decision support tool is thus necessary in order to ensure an effective sludge management system. However, the decision to go for a particular option should be based on fitness of purpose and on fair evaluation. Also the analysis of the impacts associated with a proposed sludge treatment option should be evaluated taking into consideration all the impact categories; it is worth noting that though global warming is currently a major issue, ignoring the effects of other impact categories is like ignoring the fact that these other impacts might become the next new object of debate in the near future.

Notwithstanding, the waste hierarchy should be used to aid in determining the optimal management option for sewage sludge. However, this hierarchy should be applied flexibly to avoid maximisation of certain options such as reuse and recycling. The choice of which option to apply should be based on strict environmental and economic considerations taken as a case-by-case basis (cepi 2007). In this study and most others, only the environmental perspective was taken into consideration; in order to be able to conclude that a chosen alternative for sewage sludge treatment is sustainable, all the three aspects that contribute to sustainability must be analysed that is in addition to an environmental assessment, there is the need for a social evaluation and an economic analysis as well.

Currently, the city of Aalborg has made a decision were sludge would be anaerobically digested and then followed by drying with heat recovery. In the next step, the dry fuel produced has to be used in several available alternatives as proposed in the study. As observed in the city of Randers, some of the dried sludge is sent for composting at a nearby composting plant while the rest is burned as fuel in Germany. The latter is practised due to a fee and tax systems in Denmark where incineration is charged. This option is a clearly unsustainable practice because a lot of distance has to be covered for transportation of this waste and also there is the problem of over haulage of sludge at the border. This is actually not an environmentally sustainable policy and is a resultant of institutional barriers and associated drivers (interview with Hansen 2007). This goes to highlight the point mentioned above which insists that the application of the waste hierarchy in the waste sector should be flexible enough so as to avoid the maximisation of certain options such as reuse and recycling. The Danish waste hierarchy which serves as framework for waste management in Denmark, ranks recycling higher than incineration with energy recovery, with landfilling ranking lowest. Incineration is not considered a method of recycling and together with landfilling, fall under the tax system while recycling is tax exempt; the major aim is to recycle as much waste as possible. In a situation were not all the sewage sludge can be recycled, other alternatives should be exploited but the institutional framework should be in favour of the use of such alternatives (this requires the use of LCA –as a decision support tool- to analyse and assert the efficiency of these treatment alternatives).

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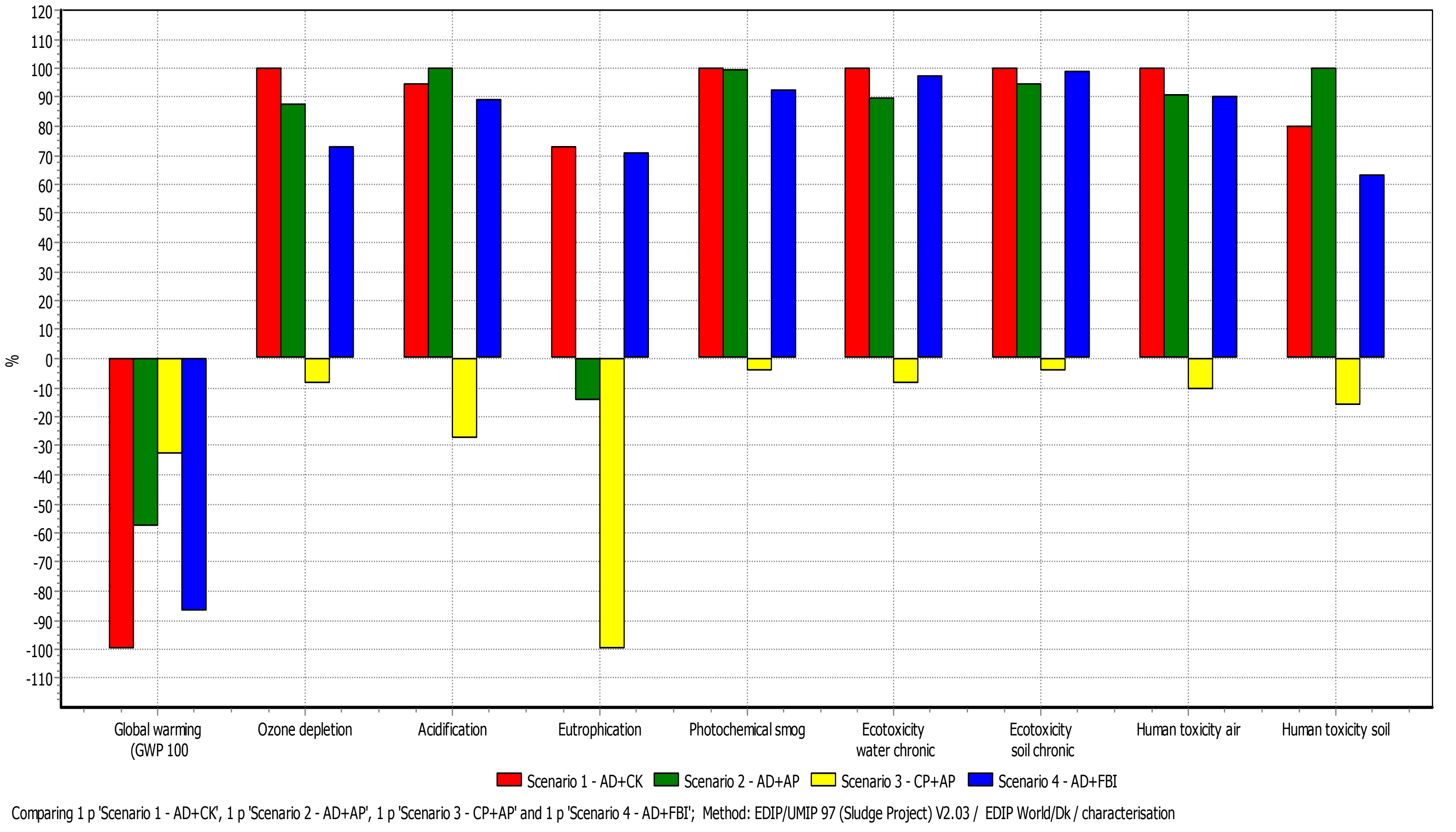
ABBREVIATIONS

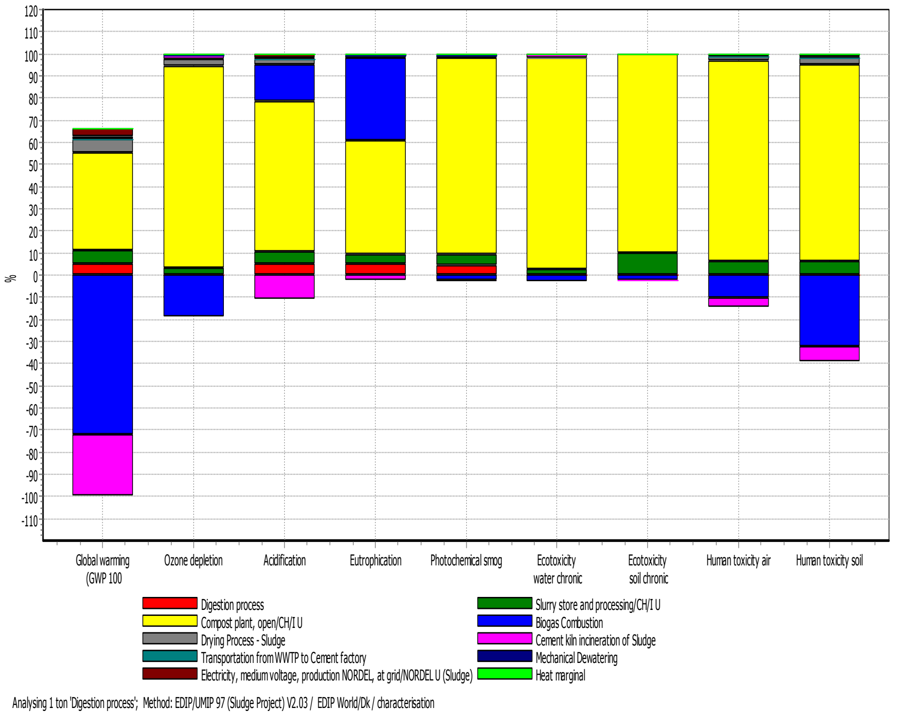
AD	Anaerobic Digestion
AP	Agricultural Application
CK	Cement Kiln Incineration
CP	Composting
CH4	Methane
CO2	Carbon dioxide
DR	Drying
EC	European Commission
EEA	European Environment Agency
EF	Effect Factor
EU	European Union
FBI	Fluidised Bed Incineration
GHG	Green house gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
MJ	Mega joule
kWh	Kilo watt hour
NH3	Ammonia
N_2O	Dinitrogen monoxide
SA	Sensitivity Analysis
Sc.	Scenario

APPENDIX A – SCENARIO CONTRIBUTIONS TO OTHER IMPACT CATEGORIES

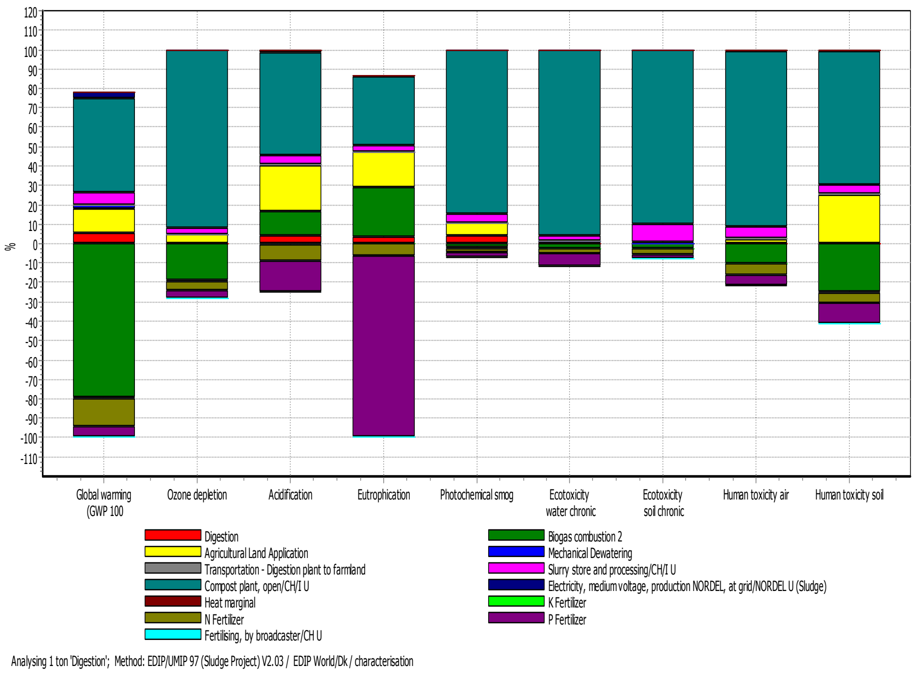


SCENARIO CONTRIBUTIONS TO OTHER IMPACT CATEGORIES
(Individual Processes in each Scenario)

Scenario 1

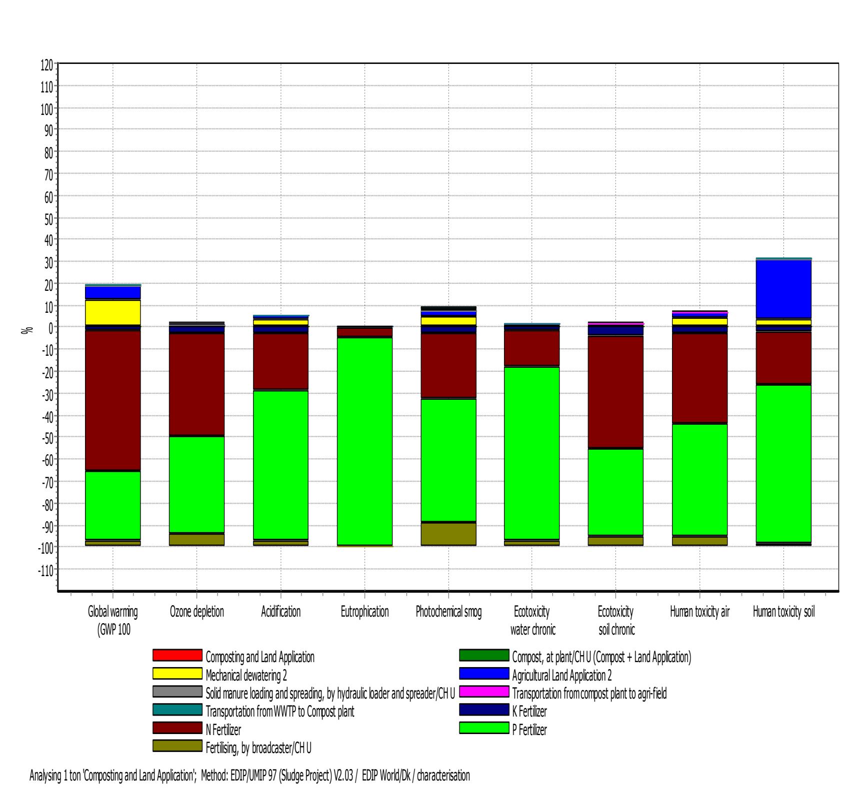


Scenario 2



Continuation:

Scenario 3



Scenario 4