Life Cycle Assessment of Municipal Waste Management: Improving on the Waste Hierarchy

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Department of Development and Planning

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Abstract

EU waste policy is currently encouraging all Member States to decrease the environmental impacts of waste management by restricting the amount of waste that can be landfilled, and instead encouraging technologies and management options that are placed higher on the waste hierarchy. This report investigates the use of life cycle assessment (LCA) as a planning tool to be used in conjunction with the waste hierarchy in order to identify the waste management option that provides the best environmental outcome for municipal waste management plans.

An LCA study is performed for household food waste management in the City of Aalborg, Denmark. In the LCA an incineration scenario is compared with an anaerobic digestion scenario. Both of these options are considered to be recovery operations and the technologies appear side-by-side in the waste hierarchy.

The results of the LCA show that when applied in conjunction with the waste hierarchy, LCA can be a useful tool for the planning of municipal waste management plans as it allows municipalities to directly compare the actual environmental impacts of different technologies and planning options. Furthermore, through system expansion a consequential approach to LCA may encourage municipalities to integrate waste management with processes in other sectors.

Key words: life cycle assessment, household food waste, waste hierarchy, manure, anaerobic digestion, biogas, incineration

Synopsis

EU's affaldspolitik opfordrer i øjeblikket alle medlemslande til at mindske miljøbelastningen fra affaldshåndtering ved at begrænse mængden af affald, der kan deponeres, og i stedet opfordre til udviklingen af teknologier og planlægningsmuligheder, der er placeret højere i affaldshierarkiet end deponering. Denne rapport undersøger brugen af livscyklusvurdering (LCA) som et planlægningsværktøj, der kan anvendes i forbindelse med affaldshierarkiet med henblik på at identificere den affaldshåndteringsløsning, der giver det bedste miljømæssige resultat for forvaltningsplaner af dagrenovation.
En LCA-undersøgelse til håndtering af husholdningernes madaffald i Aalborg Kommune er udført. I LCA'en sammenlignes et forbrændings scenario med et bioforgasnings scenario. Begge disse muligheder anses for at være nyttiggørelsesoperationer, og teknologierne optræder side om side i affaldshierarkiet.

Resultaterne af undersøgelsen viser, at LCA kan være et nyttigt redskab til udarbejdelse af kommunale planer for affaldshåndtering, når det anvendes i forbindelse med affaldshierarkiet, da det giver kommunerne mulighed for direkte at sammenligne de faktiske miljøpåvirkninger af forskellige teknologier og planlægningsmuligheder. Desuden kan udarbejdelsen af konsekvent LCA gennem systemudvidelse tilskynde kommunerne til at integrere affaldshåndtering med processer i andre sektorer.

Foreword

This project was completed as the thesis project for the degree Joint European Master in Environmental Studies (JEMES) at Aalborg University in the period of 1st February 2010 until 9th August 2010.

The referencing style used is the Chicago Referencing Style as described by the Murdoch University Library.

I would like to thank my supervisors, Prof. Per Christensen and Prof. Søren Løkke for their guidance and enthusiasm toward my thesis. Also a special thank you to Prof. Jannik Schmidt and Prof. Mikkel Thrane for their help in understanding and using the SimaPro computer programme.

Thanks are also extended to all the people at Reno-Nord, Aalborg Portland, Nordjyllandsværket and Aalborg Forsyningsvirksomhederne for their assistance in data collection.

Finally, I would like to thank my fellow classmates for their encouragement and for being wonderful sparing partners.

Picture on cover page:

Reno-Nord incineration plant, Aalborg, Denmark

Courtesy of Babcock & Wicox Vølund

http://www.volund.dk/news/more_news/news_archive/positive_feedback_at_waste_to_energy_seminar_at_aalborg_university

Indhold

1. Introduction

Waste is generally defined as something that is no longer wanted or useful: it is what is left over after the valuable and useful components have been removed (Cambridge English Dictionary, 2010). Today's environmentally conscious, global society has recognised that the production of waste is counterproductive to the attainment of a sustainable society. Ever increasingly, waste is being seen not as an end product, but as a resource that can be exploited to recover materials and energy.

The idea of using waste as a resource is not a new one: Many countries have had recycling programmes for decades, recovering materials that can be used to produce new products. However, with the current global emphasis on the reduction of environmental impacts, and in particular green house gas (GHG) emissions, principles such as sustainable resource use and life cycle thinking are being applied to waste management, clearly treating waste as a resource that is to be exploited to the greatest extent possible.

1.1 Waste in the European Union

The European Union is one example where the classification of waste as a resource is highly promoted. The Sixth Environmental Action Programme of the European Community identifies waste management as one of four areas of priority and has created a set of strategies and directives aimed at reducing the environmental impacts caused by the waste that is produced in the member states (European Commission, 2010). A hierarchy for the treatment of waste has been established and is set out in the so-called Waste Framework Directive (2006/12/EC). The directive gives a clear outline for national waste management strategies, and the waste hierarchy clearly states that the emphasis should be on reducing the amount of waste being produced, then recovering and recycling waste to the greatest extent possible. Remaining waste which cannot be recycled should then be used in energy recovery, such as through incineration or biogas production. The final, least desirable option is to incinerate or landfill without energy recovery (see figure 1). This hierarchy clearly echoes the life cycle thinking (LCT) approach to waste management, where waste is seen as a resource which is to be utilised, and only discarded in the case where it is not possible to be utilised as a resource.

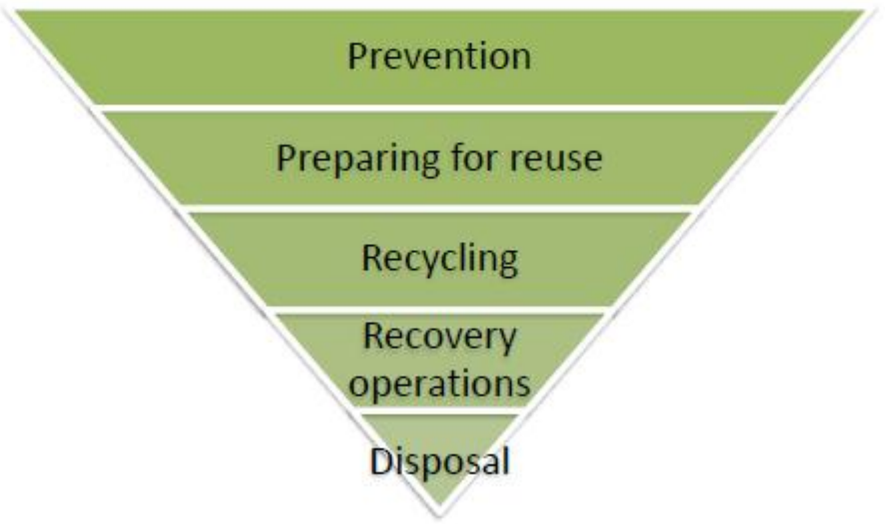


Figure 1. The waste hierarchy as it is described in the waste framework directive 2008/98/EC (European Parliament and Council, 2008)

Currently there is a focus in the EU legislation to restrict the use of disposal operations as an option for waste management, particularly landfill. The Council Directive 1999/31/EC on the landfill of waste concerns the minimisation of landfilling and its impacts and specifically states that the landfilling of biodegradable waste should be prevented and recycling or recovery operations should instead be pursued (European Council, 1999). The directive also sets out a qualitative target for the reduction of biodegradable municipal solid waste going to landfill. The result of these targets is a reduction of the biodegradable municipal solid waste being landfilled to 35% of the waste produced in 1995 no later than 2016. Many countries that have traditionally relied on landfill in their waste management strategies are currently shifting their focus to incineration as an alternative as this is considered as a recovery operation in the waste hierarchy (provided that the incineration facility meets a certain efficiency requirement).

However, incineration is just one of the available technologies included in the recovery operation tier of the waste hierarchy. In this respect, the waste hierarchy fails as a tool for guiding waste management strategies as it does not encourage thorough investigations and comparisons of alternative technologies. In some cases, these alternative technologies could give a greater environmental benefit than incineration. The waste framework directive, however, does indicate that some form of environmental assessment should be performed in conjunction with the waste hierarchy: "*When applying the waste hierarchy… Member States shall take measures to encourage the options that deliver the best overall environmental outcome*" (European Parliament and The Council, 2008, Article 4, paragraph 2). Furthermore, the directive suggests a life-cycle thinking approach to accomplish this.

"*When applying the waste hierarchy… Member States shall take measures to encourage the options that deliver the best overall environmental outcome*" (European Parliament and The Council, 2008, Article 4, paragraph 2).

1.2 Waste in Denmark

Denmark is a European country which has a strong, positive history with incineration of municipal waste, with waste first being incinerated with energy recovery for district heating as early as 1903 (Kleis &Dalager, 2004). The current Danish national waste strategy states that waste should be recycled to the greatest extent possible, that all combustible waste that is not recycled should be incinerated with energy recovery, and that disposal at landfill is only used in the case where waste is neither suitable for recycling or incineration. The quantitative target set in the strategy is 65% of waste recycled, and no more than 6% landfilled by the year 2012 (Government of Denmark, 2009).

While Denmark has already reached this ambitious target for landfilling, the strategy outlines an initiative to increase the incineration capacity to accommodate the increasing amounts of waste being produced in Denmark (Government of Denmark, 2009). This initiative does not seem to be in harmony with EU goals as the waste hierarchy, as outlined in the waste framework directive, states that Member States should focus first on reducing the amount of rubbish being produced (European Parliament and The Council, 2008). However the Danish national waste strategy does not include an initiative toward this goal.

1.3 Waste in Aalborg Kommune

In the case that this project focuses on, Aalborg Kommune, the Danish national waste strategy is upheld, with waste being incinerated to supply heat and electricity to the citizens. However, it was observed that the waste management system was not planned in a way which allowed recovered energy, to be utilised to the full extent. A potential problem lays in the fact that in Aalborg Kommune there are 3 different major heat producers all producing heat to full capacity without regard to the demand of heat in the district heating network. The result is that in the summer months when demand is low, there is a large excess of heat being produced that is not being utilised. In the winter months, however, the opposite problem occurs, where not enough heat is being produced to cover the demand and extra heat is produced by the burning of natural gas.

The 3 heat producers in Aalborg are; Reno-Nord (a waste incineration plant which accepts waste from 5 municipalities in the region of Northern Jutland), Aalborg Portland (a cement production factory), and Nordjyllandsværket (a coal fired combined-heat-power plant (CHP)). It is considered that the heat produced at Aalborg Portland and Nordjyllandsværket is a bi-product or waste product of other processes (cement production and electricity production, respectively). However, the incineration of waste is considered a process specifically undergone to recover the energy in the waste.

Central problem to be investigated: In Aalborg Kommune, an excess of heat is being produced, and wasted during the summer months, while in the winter months production must be supplemented from extra boilers.

There have been identified two causes which could have contributed to the situation of excess heat being produced in Aalborg Kommune:

1. Industrial Ecology has not been applied to investigate how the different actors interact with each other and with the overall system.
2. The EU directives and national waste strategy do not demand either an integrated approach to waste management, or provide a tool which allows municipalities to evaluate which recovery operation technology is best suited to the local situation.

This project takes its point of departure in the second identified cause of the problem and investigates the use of life cycle assessment (LCA) as the missing tool.

1.4 LCA

The term 'life cycle' means that all processes are included in the assessment, from the acquisition of the raw material, production, distribution, use and disposal. When LCA methodology is applied to waste management it focuses only on the disposal stage as can be seen in figure 2 below.

Despite the fact that an LCA of waste excludes the processes that come before disposal, it still follows a life cycle thinking (LCT) approach, which is in accordance with Article 2, Paragraph 4 of the EU Waste Framework Directive (European Parliament and The Council, 2008). The life cycle of waste is considered to start at the point where it becomes waste, which can be defined as the point where it no longer is of value to the owner and/or is placed into a waste receptacle (White, Franke & Hindle, 1995).

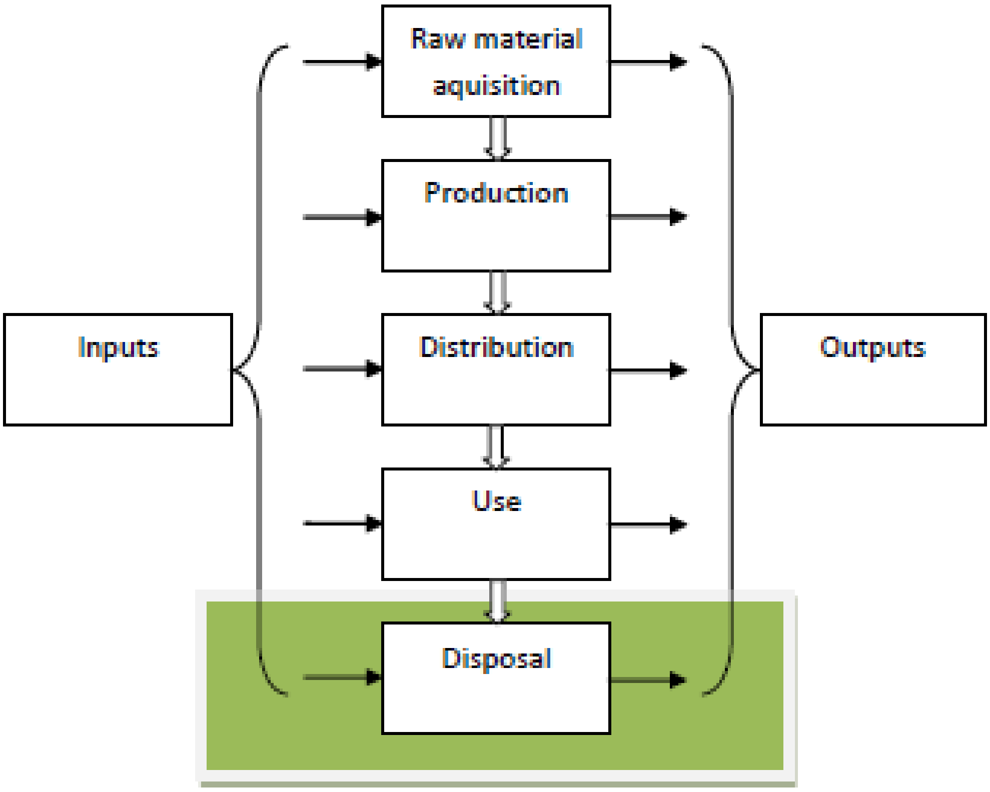


Figure 2. LCA as it applies to waste management (own figure).

In the mid 1980's LCA was applied to packaging waste, and made a major contribution toward the development of LCA as a methodology. Since then, LCA has been used in conjunction with more and more streams of waste and models have been produced to represent unit processes such as collection, landfilling, incineration, composting and anaerobic digestion (Baumann and Tillman, 2004). One of the benefits of applying a consequential LCA method to waste management is that through system expansion the investigation becomes an integrated waste management assessment. For example, in this investigation anaerobic digestion is investigated as an alternative technology: anaerobic digestion is a process which includes both municipal waste and agricultural waste, leading to an integration of the two sectors. It is also necessary to investigate the interplay between waste management and energy production. Therefore, the investigation assesses the ability of waste to be managed in a system that is integrated with other systems in the technosphere, namely the agricultural sector and the energy sector.

This report uses LCA to assess the environmental impact of different waste management scenarios for Aalborg Kommune in an effort towards solving the problem of wasted heat. The results of the LCA are then used to discuss the suitability of using LCA as a planning tool in conjunction with the waste hierarchy to encourage an integrated approach to waste management.

This leads to the research question:

How can the application of life cycle assessment methodology, in conjunction with the waste hierarchy, be applied at a municipal level to encourage an integrated waste management approach and ensure that the best overall environmental outcome is achieved?

In answering this question it was decided to undertake an LCA study concerning integrated waste management on a municipal level. Therefore there is a second research question:

How can a life cycle impact assessment lead to a decrease in the environmental impacts of household food waste management in the municipality of the City of Aalborg?

1.5 Focus on Household Food Waste

In order to limit this study to satisfy the time span given, it was decided to focus on one stream of waste. Waste can be classified in many different ways; by physical state (solid, liquid, gas), by its original use (e.g. packaging waste), by composition (plastic, organic, glass, etc), by physical property (combustible, compostable, recyclable), by origin (household, commercial, agricultural, etc), or simply as hazardous or non-hazardous (paraphrased from White, Franke and Hindle, 1995 pg 1).

This report will focus on Municipal *Solid* Waste (MSW), and in particular the waste generated by *households*. It was chosen to focus in this direction because household waste is considered to be one of the hardest waste streams to manage due to its varied and complex composition. Household waste is a mixture of many different materials including plastics, glass, organic waste (both food scraps and garden waste) metals and paper, with each material being present in small quantities. Separation of these components after collection is costly and difficult, while asking citizens to keep different materials separated creates logistical problems for collection as well being seen to be politically unpopular. Therefore, it should be thoroughly investigated whether or not real environmental benefits can be made through the separation of these components before pursuing waste management options that require separation.

Within the household waste stream the food waste stream was identified as being of particular interest for this investigation. The household food waste (HFW) stream is characterised as having both a high moisture content and a high organic carbon content. The high moisture content renders the stream less suitable to incineration than other waste streams while the high carbon content makes it better suited to composting and anaerobic digestion than other waste streams.

It was decided to design a scenario where the HFW stream was diverted away from incineration, and instead utilised for biogas production through anaerobic digestion. The environmental impacts of this scenario will then be compared with the current scenario in place, which is incineration of the HFW stream. The major potential benefits of anaerobic digestion that are predicted are:

1. Less impacts relating to global warming due to a more efficient energy conversion process; and
2. Recovery and utilisation of nutrients that would otherwise be lost in the incineration process.

This case is also an excellent example of the ability of consequential LCA to encourage an integrated waste management approach: The anaerobic digestion of HFW is always carried out in combination with a stream of agricultural waste. Therefore, the investigation of the environmental impacts of waste management will, in this case, also include an investigation of the management of pig manure.

1.6 Content of Chapters

Chapter 2 presents the methodology of this report, as well as giving an overview of the LCA methodology.

Chapter 3 gives an overview of the EU and Danish waste legislation with a discussion of the use of the waste hierarchy in this legislation. It also introduces some of the problems that have been identified with the waste hierarchy, and gives some insights into how these legislations may evolve in the future.

Chapter 4 introduces the case of Aalborg Kommune.

Chapter 5 is the LCA of household food waste in Aalborg Kommune, where the environmental impacts of each of the scenarios is assessed and the second research question is investigated.

Chapter 6 will then give a discussion of both the Aalborg LCA and of the use of LCA in municipal waste management planning as a tool to supplement the waste hierarchy.

Chapter 7 concludes the report by stating the most important findings.

2. Methodology

This chapter presents the methodology of this report, as well as giving an overview of the LCA methodology, which is the point of departure for this report.

2.1 Data Collection

In order to achieve the best basis for solving the research question, several different methods of data collection are employed in this report.

Both qualitative and quantitative data have been utilised. Quantitative research is generally, though not necessarily, concerned with numbers and quantification. It is generally a measurement and can take the form of statistical data, questionnaires, and structured interviews as a few examples. Qualitative data is typically not concerned with numbers and measurement, but is typically a larger overview of a collection of data. Qualitative data often takes the form of physical objects such as pieces of text or photos (Andersen, 2005). While many researchers in social science have traditionally considered these two approaches to research to be separate and opposing research approaches, there is now support for combining quantitative and qualitative research within one study. In Bryman (2008) it is argued that the differences between qualitative and quantitative research methods are often exaggerated and that elements of quantitative research exist within qualitative research and vice versa.

The data utilised in this report can also be further classified as being secondary data. Secondary data is not as desirable as primary data as secondary data is always interpreted previously by other researchers. However, the time and financial constraints of this report did not allow for the collection of primary data. Much of the data used is compiled from the green accounts of the involved parties, as well as LCA databases in the SimaPro programme.

As it was identified that the data should be as relevant to the case as possible, care was also taken to choose the most relevant sources for collecting secondary data. Where primary data could not be collected, secondary data was sought from a source local to the case area. In cases where there was no existing secondary data from the case area, Danish or European data and average data was sought.

2.2 Use of Theoretical and Empirical Research

In order to investigate and solve the problem described in the problem formulation both theoretical and empirical research methods were followed. Theory is generally described as a simplified picture of reality, and is utilised to achieve an understanding of the problem and to see how the investigation will contribute to the reality of the problem, before the identified solutions are tested in practice. Empiricism is the collection of experiences and observations which is then used to build upon the understanding that was created in the process of theory. (Andersen, 2005)

For the creation of a theoretical framework for the report two main approaches were taken:

- Literature studies; and
- Collection of expert knowledge.

The literature studies were used to build knowledge about the existing theories concerning the topics included in this report. Information was collected from articles, books, internet webpages and databases, and was used in a qualitative manner to get a broad overview of the knowledge and positions within the waste and district heating and agriculture fields, as well as within the field of LCA. Expert knowledge came from semi-structured interviews with stakeholders in the municipality and the involved companies in the Aalborg case, as well as discussion with experts in the field of LCA.

The empirical aspects of this report are based mainly on data collection through field studies together with semi-structured interviews with relevant stakeholders. Interviews were conducted with the following people:

- Thomas Lyngholm, Environmental Manager at Reno-Nord; and
- Dorte Ladefoged, Civil Engineer at Forsynings Virksomhederne (Aalborg Public Utilities Company).

Correspondences through email and telephone with the following people also contributed to the collection of empirical data:

- Bjarne Holm, Department Leader, District Heating, Forsynings Virksomhederne (Aalborg Public Utilities Company);
- Torben Ahlmann-Laursen, Environmental Engineer, Aalborg Portland;
- Preben Andreasen, Environmental Manager, Aalborg Portland; and
- Jørgen Jensen, Environmental Manager, Nordjyllandsværket.

2.3 Analysis and Interpretation

In order to establish a connection between the theoretical and empirical aspects of the project, both aspects must be analysed and interpreted. This allows for the production of results and conclusions and ultimately, an answer to the problem question. This process is especially evident in the process of conducting the LCA. In order to conduct the LCA, theoretic knowledge about the ISO standards, and about the computer programme SimaPro were necessary, and this knowledge was combined with the empirical knowledge that was collected about the case of Aalborg Kommune. This combination of theory and empiricism has allowed an LCA to be created which represents the specific circumstances in the case municipality.

The computer programme SimaPro that was utilised for the analysis includes a large database of essential information for the building and comparison of the scenarios. The programme has been created in accordance with the ISO standards, and is described further in chapter 2.4.6.

2.4 LCA

Life cycle assessment, or LCA, is an environmental assessment tool that can be applied to determine the entire environmental impact of a product or system over the entire life of the product. All aspects from raw material extraction, production, use and disposal are accounted for with the impacts being grouped into categories such as global warming potential, ecotoxicity, human health, etc. This is often referred to as a ‘cradle-to-grave’ approach. As well as being able to assess the entire life cycle, it is also possible to assess single stages within the life cycle to determine so-called ‘hotspots’ where efforts to reduce the impact should be focussed. This methodology is useful not only to industry and the producers of products, but also to decision makers in government and industry. Through the comparison of different future scenarios, LCA can contribute to strategic planning.

When applying LCA to waste management the initial life cycle phases, production and use, are disregarded and assessment begins at the point where the product is first considered to be waste. For this research project, the beginning of the life of the waste is the point where it is placed in the trash bin. This can be seen in the schematic representation in Figure 2 on pg. 14.

2.4.1 The Methodological Framework

The methodological framework for conducting an LCA has been standardised by the International Organization for Standardization (ISO). The ISO 14040 series describes four phases in conducting an LCA: Goal and Scope (ISO 14041), Life Cycle Inventory (ISO 14041), Life Cycle Impact Assessment (ISO 14042), and Life Cycle Interpretation (ISO 14043). In 2006 these Standards were revised and amalgamated to form a single standard, ISO 14044. Although there is a basic chronological order to be followed, the process is iterative and should be continually under review (see figure 3). Each of these phases will now be described.

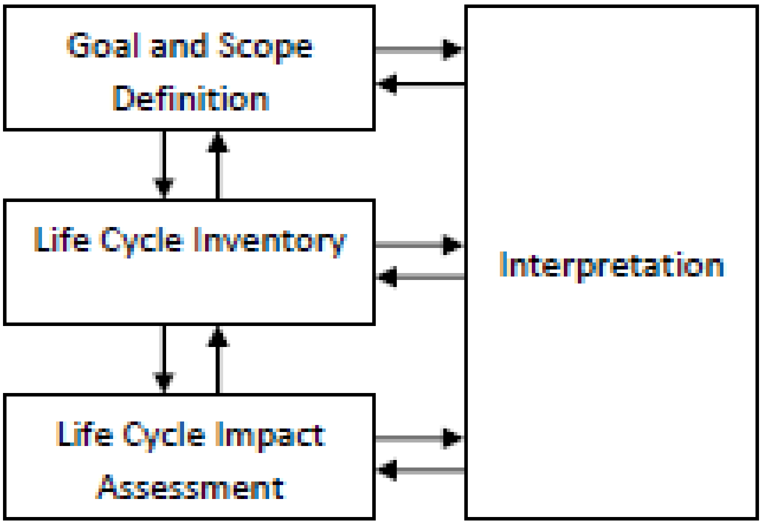


Figure 3. The 4 Phases of LCA, as they are described in ISO 14044

2.4.2 Phase One: Goal and Scope Definition

This can be considered as the frame of the LCA process; it is a guide created specifically for each individual LCA that is to be referred to throughout the process and helps to ensure that the LCA remains consistent throughout. The first step is to formulate a goal for the LCA and to state: why the LCA is being performed, the intended application and the intended audience. The purpose for the LCA, the reason why it is being performed, will define the system boundaries for the study and therefore will often greatly influence the results.

Another important step in the goal and scope phase is defining the functional unit. The functional unit is a unit which represents the product's function and should consist of three different elements: quality, quantity and duration period (Thrane and Schmidt, 2007). The functional unit is especially important in a comparative LCA as it ensures that each alternative is being equally assessed.

The goal and scope phase is also where the system boundaries are decided upon. There are 2 different methods for defining system boundaries, consequential modelling and attributional modelling, and it should be stated which model is being used for each study. Attributional modelling analyses only the bio-physical flows within the life cycle being assessed, while a consequential approach will take into account the processes which are affected when unit processes change. However, as this study is to take place in Denmark, where consequential modelling is accepted as the preferential method, it was not considered to use attributional modelling for this study.

A method for conducting the LCIA phase should also be decided upon and stated clearly. LCIA methods can generally be placed into 2 different categories: mid-point and end-point. A mid-point approach focuses on impacts closer to the beginning of the cause-effect chain such as chemical and physical changes, while an end-point approach focuses on the outcomes of these changes such as changes to human health or the ecosystem (Finnveden, Eldh & Johansson, 2006). It is generally accepted that the level of uncertainty is greater in end-point methods than in mid-point methods. Each methodology takes different impact categories into consideration, and therefore care should be taken to ensure that the impact categories contained within a method are relevant to the study at hand. The ISO standard distinctly states that the choice of impact categories should be chosen in relation to the product or system being studied. Therefore, the impact categories that are to be evaluated should be decided upon in this initial phase, and desired impact categories which are not included in the chosen method should not be disregarded.

A description of the type of data that is used in the study, what the sources of the data are and what quality the data is should also be included. And finally it should be stated whether or not a critical review of the study should be conducted.

2.4.3 Phase Two: Life Cycle Inventory (LCI)

This phase of the LCA is characterised by data collection and calculations of all the inputs and outputs in the system. It is also in this phase that the allocation procedure is handled if allocation is to be performed. The first step of the inventory phase is to create flow diagrams for each of the unit processes that are included in the LCA and to describe the unit process in detail. Once this has been done the relevant data should be collected and adjusted to represent the reference flow and entered into the chosen computer programme.

2.4.3.1 Data Collection and Calculation

Data collection should be both quantitative and qualitative (ISO 14044) and should be collected for all inputs and outputs in the system. In a screening LCA or an internal LCA for a specific product it is acceptable to use average data and databases. However for a generic LCA which predicts future scenarios, particularly those that have social and economic implications for government, data should be as specific as possible (Thrane and Schmidt, 2007). LCA's that are designed for this purpose have a greater demand for certainty than do LCA's conducted for a specific product.

Where possible, all data should be triangulated and validated. It is also of utmost importance that all data is measured in relation to the functional unit. This ensures that all impacts measured are equal, and allows the results of different scenarios to be directly compared to each other.

Finally, all sources, assumptions and decisions should be clearly recorded in order to preserve transparency and to allow others to reproduce the results.

2.4.3.2 Allocation Procedure

The ISO 14044 standard defines allocation as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems”. The procedure used for allocation shall be clearly stated in the LCA. It should also be documented and explained which outputs and inputs were allocated to which products (ISO 14044).

2.4.4 Phase Three: Life Cycle Impact Assessment (LCIA)

This LCIA phase identifies environmental impacts and effects of the processes that are outlined in the LCI phase. What makes this process different from other environmental assessment procedures is that all impacts are calculated relative to the functional unit.

According to the ISO 14044 standard, it is mandatory for the LCIA to include:

- Selection of impact categories, category indicators and characterisation models;
- Classification or the assignment of LCI results to the selected impact categories; and
- Characterisation or the calculation of category indicator results. (ISO 14044, pg 16)

Most LCA practitioners choose to utilise an LCIA method that has already been established. If this option is chosen, the method should be clearly stated and explained in the LCA and the chosen impact categories should be reviewed to ensure that they are relevant to the study at hand.

There are also 2 voluntary aspects to the LCIA; normalisation and weighting. Normalisation concerns normalising results of impact categories against a reference, thereby allowing the impacts in different categories to be compared. Weighting is a step which evaluates the importance of different impact categories, for example political importance, and applies this to the results.

> "Life cycle impact assessment is defined as the phase in the LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system."
> (SimaPro 7, 2008b, pg 19)

2.4.5 Phase Four: Interpretation

This final phase involves identifying the most significant results of the LCI and LCIA phases. This should also be accompanied by a discussion of the sensitivity and uncertainty of the study and a critical review of the methods that have been employed.

The interpretation also concludes the results of the study and gives recommendations based on the results and conclusions.

2.4.6 SimaPro

In order to conduct the LCA contained within this report, the computer program SimaPro 7.2 has been utilised. The SimaPro software has been developed in accordance with the ISO 14040 and ISO 14044 standards and allows for managing and storing the necessary data, as well as performing the calculations and required sensitivity tests.

3. The Waste Hierarchy and EU and Danish Legislation

This chapter discusses the waste hierarchy and how it is incorporated into and influences the relevant legislation regarding waste in the EU and in Denmark. When planning waste strategies for the future it is important to understand the current political context as EU and national legislations influence which technologies should be considered. Information that was collected in this chapter was therefore used in the planning of the alternative waste scenarios.

3.1 Introducing the Waste Hierarchy

The waste hierarchy is a guide that has been produced within the EU legislation which defines a priority for different waste management options. The priority is based on purely environmental preferences, with those options at the top of the hierarchy leading to the lowest environmental impact, and those at the bottom being the options with the most environmental impact and being intended only for use as a last resort. The waste hierarchy as it is defined in the 2008 revision of the waste framework directive is outlined in figure 1 on pg 10.

The waste hierarchy and the principles of life cycle thinking (LCT) are interlinking concepts as LCT and LCA both justify and compliment the waste hierarchy. In most cases and for most waste streams, LCA assessments support the order of the waste hierarchy, with those management options lower on the hierarchy leading to greater environmental impacts than those at the top of the hierarchy. However, the hierarchy is only intended to be a guide that should be complimented with LCT. This is due to several reasons: Firstly, the waste hierarchy does not take social or economical impacts into account. In some situations, one management option may have social costs that outweigh the benefits. For this reason the EU legislation recommends that LCA should be carried out in conjunction with an analysis of social and economic impacts. Secondly, the waste hierarchy is by its nature a general guide and does not take into account special circumstances in specific cases. By applying LCT to a specific case, it may become apparent that management options that appear lower on the waste hierarchy may in fact result in less environmental impacts than those higher in the hierarchy. This second issue with the waste hierarchy is the point of departure for this study as there was identified a special situation with district heat supply in the case municipality, Aalborg Kommune, which should be taken into account when planning and assessing waste management strategies.

3.2 History of the Waste Hierarchy

The waste hierarchy, or its principles, were first introduced into EU policy in 1975 in the first Directive on Waste 75/442/EEC (European Council, 1975). While the word 'hierarchy' does not appear in the text until the 2008 revision of the Waste Framework Directive, nor a legal commitment to apply the hierarchy, the different waste management approaches have always been listed in the same order within the EU waste legislation. Due to the ordering and the wording of the different waste management options in the directives it has often been interpreted in a hierarchical fashion.

Council Directive 75/442/EC states that Member States should:

- *"Firstly" prevent or reduce waste; and*
- *"Secondly" recycle and reclaim materials, or recover the energy.*

Since the first Directive on Waste, the principles of the waste hierarchy have been adopted into other legislations on waste, such as the EU Directives on packaging waste, batteries, and electrical and electronic waste (Rasmussen & Vigsø, 2005).

The purpose of including the waste hierarchy in the Directives on waste is explicitly to minimize the *environmental* effects of waste management. This emphasis on environmental effects is one of the first examples of an EU Directive being based on environmental considerations. This is itself a result of a series of well-publicised scandals in the 1970's and 1980's related to the mismanagement of waste in the EU and the increasingly visible effects on the environment and human health (European Commission, nd). To this day, the primary emphasis in the Directives relating to waste is still concerning the protection of the environment and human health.

3.3 EU Waste Policy

The most recent legislation from the EU is the 2008 revision of the Waste Framework Directive. In this newest edition of the Directive, the waste hierarchy is directly mentioned and in Article 4 the waste hierarchy is explicitly described. The order of priority for waste management options stated in Article 4 of the Waste Framework Directive 2008/76/EC is:

- Prevention;
- Preparing for re-use;
- Recycling;
- Other recovery, e.g. Energy recovery; and
- Disposal. (European Parliament and The Council, 2008)

Furthermore, the Directive encourages the Member States to pursue "options that deliver the best overall environmental outcome" where life cycle thinking can be applied to justify a departure from the waste hierarchy (European Parliament and The Council, 2008, pg 13, Article 4)

However LCT, as previously stated in this report, does not take into account social and economic impacts. When creating a waste management plan or strategy, social and economic factors are significant factors for the success of the plan or strategy. For this reason the Directive also instructs the Member States to "take into account" a broad range of factors such as economic and technical feasibility, social impacts and human health. Throughout the Directive there is not set any quantitative goals for these factors, and as there is no suggested methodology for assessing the economic and social impacts, it is largely to the discretion of the individual Member States how the waste hierarchy should be applied, and the degree of relevance of social and economic factors.

The Member States are bound by the Directive to each implement a national waste management plan and a waste prevention programme, both of which must comply with the waste hierarchy as outlined in Article 4. In addition to complying with the waste hierarchy, the plans and programmes must also comply with other directives concerning waste. Most relevant to this report is the Directive 1999/31/EC on the landfill of waste.

Article 5 of Directive 1999/31/EC sets clear quantitative goals for the treatment of biodegradable waste. The Member States are bound to progressively reduce the amount of biodegradable waste that is going to landfill, culminating in only 35% of the amount of biodegradable waste produced in 1995 being landfilled. It is suggested that Member States achieve this goal "by means of in particular, recycling, composting, biogas production or materials/energy recovery" (European Council, 1999, pg 5, Article 5). While it is not stated in the Directive that one of these alternative options is preferential to another, it can be interpreted that these alternative options are listed in an order of preference. This interpretation is based on two other observations of EU waste policy:

- Firstly, the ordering of the options is in coherence with the waste hierarchy (recycling and composting are prioritized over energy recovery);
- Secondly, the waste hierarchy itself was initially introduced without being explicitly described as a hierarchy but was simply written in a manner which lead to it being interpreted as a hierarchy.

It is therefore possible that the same approach has been taken here.

Further evidence to support the view-point of this report that bio-degradable waste should be used for biogas production as a preference to incineration can be drawn from the 2008 review of the Waste Framework Directive. Article 22 of 2008/76/EC concerns the management of bio-waste. According to the Directive, "bio-waste" is defined as "biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants" (European Parliament and The Council, 2008, pg 7). Article 22 explicitly states that the Member States should encourage bio-waste to be collected separately and composted or digested in accordance with the waste hierarchy. Furthermore, it is mentioned in Article 22 that the management of bio-waste will be assessed by The Commission and there is a very real possibility of further legislation relating to bio-waste in the coming years.

Another EU Directive that is relevant to this report is the 2000 Directive on the incineration of waste, 2000/76/EC. This Directive is concerned with preventing negative effects from the incineration of waste both to the natural environment and to human health. It gives clear definitions as to what is defined as an incineration or co-incineration facility, as well as setting strict standards for operational conditions and technical requirements. This is supported through setting emission limit values for emissions to air, soil, surface water and ground water from waste incineration and co-incineration (European Parliament and The Council, 2000).

These restrictions on incineration have been reinforced in the 2008 revision of the Waste Framework Directive. Here it has been defined which incineration activities can be considered as recovery operations and which should be considered as disposal operations. An incineration activity can only be considered as a recovery operation if it complies with a certain energy efficiency standard. In Annex 2 of the Directive an equation is given for determining the energy efficiency of a waste incineration facility. Any facility that does not satisfy the energy efficiency requirement can only be considered a disposal operation (European Parliament and The Council, 2008).

3.4 Danish Waste Policy

The Danish Government first published a national waste strategy in 1986 with the most recent strategy being the sixth strategy to be published. This newest strategy covers the years 2009 to 2012. The purpose of preparing a national strategy is to describe the political stance of the government and the national public administration's efforts in the waste sector. In addition to this, the national waste strategy also sets a framework for the municipal waste management plans (Government of Denmark, 2009).

In 2007 the Danish government began a reform of the waste management sector with a view to making the sector more effective and to further reduce the environmental impact of waste management. The Minister for the Environment was appointed to initiate the agreed changes in the waste sector. The central point of the waste reform is to make waste management simpler and more cost effective and to create a competitive market for recyclable materials. To achieve this, the 8000 previous regulations for the waste sector should be replaced with fewer regulations, capacity for management of waste at facilities should be increased, and a list of environmentally approved recycling facilities should be created.

One of the major changes that the reform is bringing about is that businesses will be free to choose a recycling facility to process their waste. Despite this new freedom for businesses, it will remain the responsibility of the municipalities to classify the waste as recyclable, suitable for incineration, or suitable for landfill. In cases where the municipality is in doubt of the correct classification it is the responsibility of the company to prove that one of the environmentally approved recycling facilities is able and willing to handle the waste. A lower fee for recycling will encourage companies to pursue this option.

The establishment of a competitive market for recycling and a taxing system that encourages businesses to recycle should help to bring about an increase in capacity for recycling of waste. This can be of benefit to municipalities in the concern of household waste to two reasons:

- Firstly, municipalities will also be able to make use of the greater and potentially more technologically varied capacity for recycling;
- Secondly, a competitive market should reduce costs and make alternatives to incineration more economically competitive.

The current national waste management strategy for 2009-2012 was prepared in accordance with the changes implemented in the waste sector reform. In accordance with the goals of the reform, the 2009-2012 strategy upholds the environmental standards that were achieved with the previous waste strategy with a high goal for recycling, at least 65%, and a low goal for landfilling, no more than 6%. To accomplish these targets, the strategy encourages municipalities to increase their capacity for incineration. Furthermore the strategy states that all "non-recyclable waste that is suitable for incineration" should be incinerated, and that only waste that is not recyclable should be incinerated. In this context "non-recyclable waste" appears to mean waste that cannot be recycled at an acceptable cost, both from an economical and social stance.

The reason that incineration is given such a high priority in the Danish strategy is that it is considered to be a source of renewable energy, which can be utilised as an alternative to coal and other fossil fuels. Only the plastic fraction of waste is not considered to be renewable as it originates from fossil fuels. In this context, the burning of waste with the recovery of energy is preventing the burning of fossil fuels that would take place in the absence of waste incineration. It is this saving of the burning of fossil fuels that makes incineration a preferred waste management option in Denmark.

While the recovery of energy through incineration is a recovery activity that is supported by the EU Directives, the classification of waste as a renewable energy source is somewhat controversial, and may be considered to contradict the principles of the waste hierarchy. The first priority for waste management according to the waste hierarchy is to reduce the amount of waste being produced. By classifying waste as a renewable energy source, a demand is created for the fuel (waste) which encourages production of waste to remain stable or even increase.

In relation to bio-degradable waste, the strategy advises that waste of this classification should be incinerated. This decision was made in 1997 to reduce the environmental impacts of landfilling. Specifically mentioned is the contribution to global warming that land-filled organic waste makes due to the production and release of methane. This is also in accordance with EU Directive 1999/31/EC on the landfill of waste, as discussed previously in this chapter. The LCA study presented in chapter 5 will test this decision by using LCA methodology to compare incineration of the food waste with the alternative technology of anaerobic digestion.

4. Aalborg Kommune

This chapter provides an overview of the municipality that is investigated in the LCA presented in chapter 5.

4.1 General Description

Aalborg Kommune is one of 98 municipalities in Denmark and is located in the northern region of the country. It covers an area of land of 1,144 km^2 and, as of January 2009, has a population of 196,292 inhabitants. Within the municipality of Aalborg is the city of Aalborg-Nørresundby which is the largest city in the northern region of Denmark with a population of 122,461 inhabitants as of January 2009. (City of Aalborg Department of Finance, 2009)

The municipality creates a new waste plan every 4 years in accordance with the national Order on Waste (Bekendtgørelse om Affald; Danish Ministry of the Environment, 2006). The current waste plan covers the period 2008 to 2016 and has two major goals:

- Firstly, to 'harmonise' waste management so that all inhabitants receive the same services; and
- Secondly to increase the amount of rubbish that is recycled and to decrease the amount of rubbish that is incinerated or sent to landfill (Forsyningsvirksomhederne, 2010).

However, as discussed in chapter 4, the national waste strategy encourages the municipalities to increase their capacity for incineration. This juxtaposition between the two plans is not of high importance for the waste management system in Aalborg Kommune as the amount of rubbish produced within the municipality is not projected to increase beyond the existing incineration capacity within the lifetime of the current waste plan (personal communication with Thomas Lyngholm, Environmental Manager at Reno-Nord).

Aalborg Kommune is a member of three collective agreements regarding handling and management of waste with other municipalities:

- Reno-Nord is primarily an incineration facility, and accepts waste from households and businesses. It also operates a controlled landfill site and a recycling facility for construction waste. It is collectively owned by 5 municipalities, Aalborg, Brønderslev, Jammerbugt, Mariagerfjord and Rebild, and accepts waste from each.
- Renovest carries out many different activities, including operating a recycling station where inhabitants of the municipality of Vesthimmerland can bring their recyclables, a storage facility for combustible waste and a sorting facility for slag from incineration. It is owned by the municipalities of Aalborg, Jammerbugt, Rebild and Vesthimmerland.
- Mokana is a receiving station for hazardous waste which is owned by several municipalities in Northern and Mid Jutland, and also accepts waste from the 4 municipalities in Greenland.

As this report is only concerned with household waste, and all waste of this nature is handled by Reno-Nord, only this facility will be investigated further (see chapter 4.3.1 for a description of the Reno-Nord incineration facility).

4.2 The Energy Situation in Aalborg Kommune

The City of Aalborg (herein referred to by the Danish title, Aalborg Kommune) is an interesting example to work with due to its complex system of heat and energy providers. Heat and electricity are supplied to homes and businesses in Aalborg Kommune from a waste incineration plant (Reno-Nord), a cement production firm (Aalborg Portland) and a combined heat-power plant (Nordjyllandsvaerket). There are also several other small suppliers of energy, mostly reserve, natural gas boilers operating only in times of peak demand.

In the municipality's environmental reporting, they consider the heat produced by Reno-Nord and Aalborg Portland to be "surplus" heat, and therefore calculate this heat to be CO2 neutral. For this reason, Reno-Nord has been chosen as the primary supplier of heat to the citizens of Aalborg with the right to sell all heat produced into the grid up to demand. When demand exceeds the capacity of production at Reno-Nord, Aalborg Portland and Nordjyllandsværket may then contribute to the grid. Finally, when the demand is higher than can be met by these heat providers, it is supplemented with heat produced by the reserve boilers which run on natural gas. This system is illustrated in figure 4.

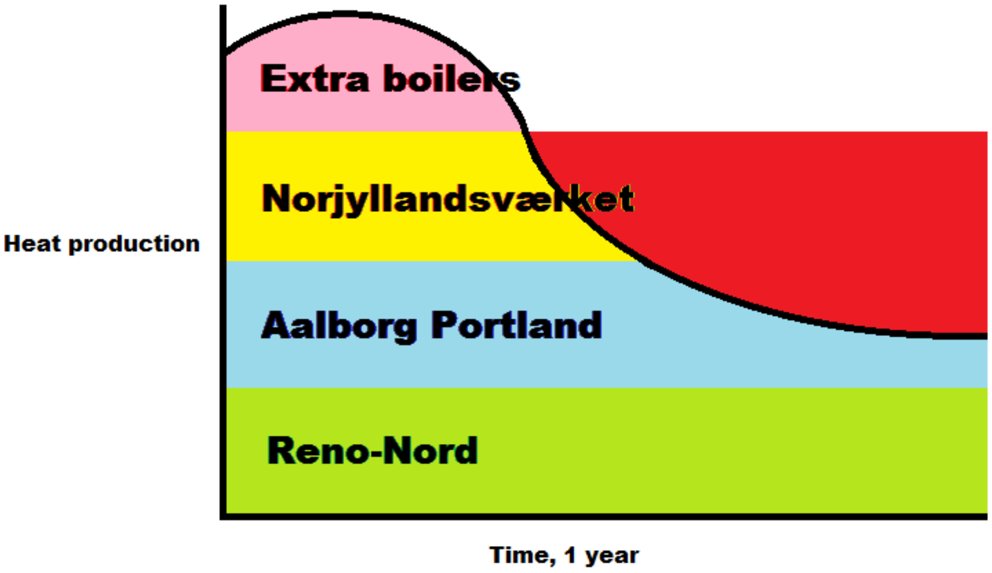
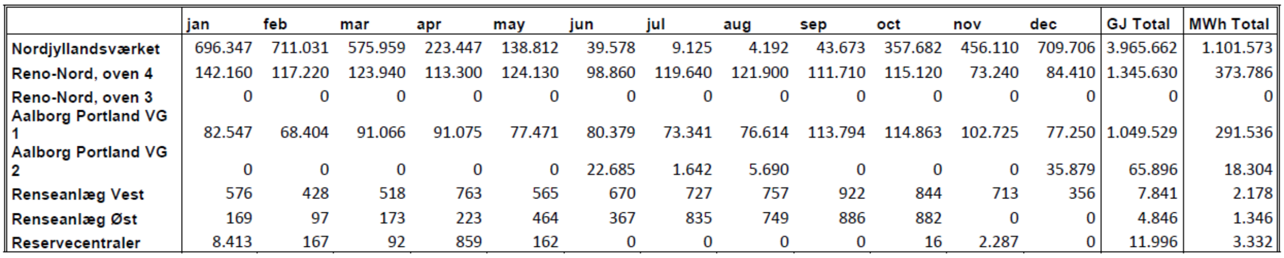


Figure 4. Heat Production vs. Demand. The area marked in red is unutilised heat (inspired by personal communication with Thomas Lyngholm, Reno-Nord)

However, in times of low demand, all energy producers continue to operate and produce heat. This is because the heat is a bi-product of other processes, such as cement and electricity production. The heat that is produced by Aalborg Portland and Nordjyllandsvaerket which cannot be sold into the grid is cooled through mixing with sea water before being released into the

Limfjord, the waterway that runs through the city of Aalborg-Nørresundby. This unutilised heat has implications for the environmental accounting for the municipality and for Reno-Nord which are currently not being considered. The heat produced by Reno-Nord is presently considered to be a saving from the burning of coal at Nordjyllandsvaerket. However, if Nordjyllandsvaerket continues to burn coal regardless of the production of heat by Reno-Nord, then the heat produced at Reno-Nord should not always be considered as a saving.

This report attempted to describe in detail, how much of the produced heat is being cooled and going unutilised. However, it became evident during the investigation that this information is not recorded by the heat producing companies, only how much cooling water is utilised. However, it was possible to find out from the public utilities company how much each heat each of the heat providers sold to the district heating network on a monthly basis (see table 1). Through combining this information with personal communication with the heat producing companies, the assumption was made that large amounts of excess heat produced by Aalborg Portland and Nordjyllandsværket are unutilised in the summer months of June to September (inclusive), while in the winter months of October to May all the heat that is produced is utilised in the district heating network (see chapter 5.2.1.2).



	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	GJ Total	MWh Total
Nordjyllandsværket	696.347	711.031	575.959	223.447	138.812	39.578	9.125	4.192	43.673	357.682	456.110	709.706	3.965.662	1.101.573
Reno-Nord, oven 4	142.160	117.220	123.940	113.300	124.130	98.860	119.640	121.900	111.710	115.120	73.240	84.410	1.345.630	373.786
Reno-Nord, oven 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aalborg Portland VG 1	82.547	68.404	91.066	91.075	77.471	80.379	73.341	76.614	113.794	114.863	102.725	77.250	1.049.529	291.536
Aalborg Portland VG 2	0	0	0	0	0	22.685	1.642	5.690	0	0	0	35.879	65.896	18.304
Renseanlæg Vest	576	428	518	763	565	670	727	757	922	844	713	356	7.841	2.178
Renseanlæg Øst	169	97	173	223	464	367	835	749	886	882	0	0	4.846	1.346
Reservecentraler	8.413	167	92	859	162	0	0	0	0	16	2.287	0	11.996	3.332

Table 1. Heat sold to the district heating network from each supplier (Data supplied by Bjarne Holm, Aalborg Public Utilities Company).

4.3 The Waste Situation in Aalborg Kommune

In 2002 72% of all waste in Aalborg Kommune was recycled, 19% was incinerated, and 9% was landfilled. This is an impressive level of recycling which exceeds the national target of at least 65% of waste being recycled. However, 84% of all waste originated from businesses, with around half of this waste being composed of earth and building materials which is part of an effective recycling system in Aalborg Kommune. When looking at the figures for household waste, the same trend of recycling is not evident with only 39% being recycled, 58% being incinerated, and 3% going to landfill (see figure 5; Jørgensen, 2003). The LCA presented in chapter 5 investigates a scenario where more of the household waste is diverted away from incineration to test whether or not this will result in environmental benefits.

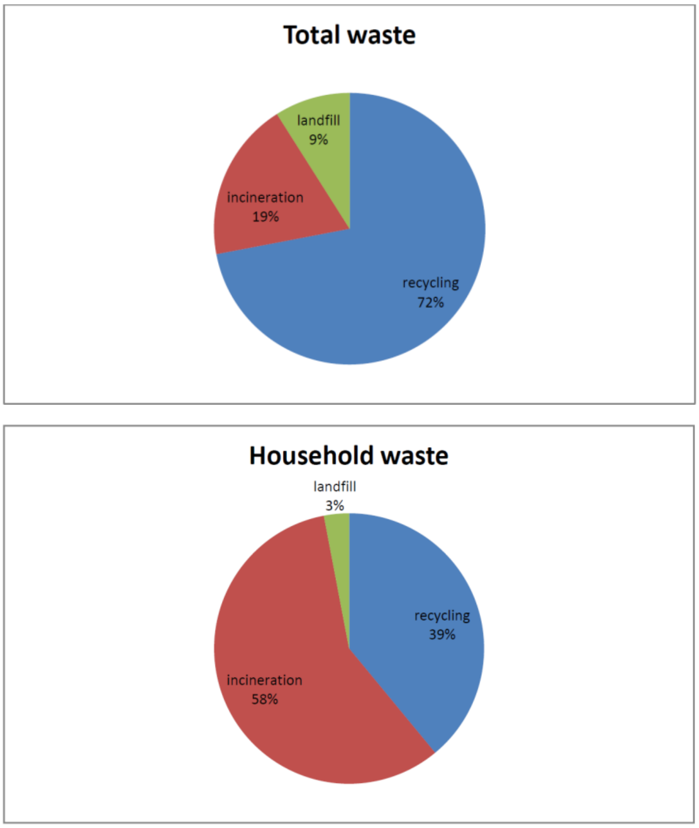


Figure 5. Management of waste in Aalborg Kommune (Jørgensen, 2003)

4.3.1 Reno-Nord

As the Reno-Nord facility is the focus of the LCA study that will be presented in the next chapter, a description of the company and facility will now be presented. Aalborg Portland and Nordjyllandsværket will not be further discussed as both of these facilities are outside of the system boundary of the LCA. The facts relating to the Reno-Nord facility that are presented in this chapter were collected during a visit to the facility.

The Reno-Nord incineration facility was established in 1978 as a cooperative between 7 Northern Jutland municipalities, which under the reorganisation of the municipalities in 2007 became the 5 municipalities of Aalborg, Brønderslev, Jammerbugt, Mariagerfjord and Rebild. There are currently 2 boiler lines in operation: The newest kiln (kiln 4), commissioned in 2005, is primarily used, with an older kiln (kiln 3) from 1991 being used as a reserve kiln. Kiln 4 is considered to be one of Europe's most modern incineration plants and is compliant with new, strict environmental standards set by the EU for the incineration of waste.

The facility possesses an advanced emission control system which incorporates an electrostatic filter to remove solid particles from the flue gas, along with a system of three wet scrubbers. The polluted water from the wet scrubbers is treated on site to a high quality, and is then released to the nearby Limfjord.

The plant is also very efficient with an efficiency of 97% of energy being harnessed from the waste. It is possible to process 22.5 tons of waste every hour to produce 10.7 GJ/ton of energy. Of the 66.67 MW capacity of the plant, 18 MW is harnessed for electricity which is the sufficient to supply 30,000 homes with their electricity needs, and 48 MW is harnessed for heat production which is sufficient to supply 16,000 homes with their heat supply.

Of the heat production, 45 MW is supplied from the main boiler while a further 3 MW is supplied from the flue gas condenser. During periods of low demand in the summer, the flue gas condenser can be taken offline to avoid an overproduction of heat. This is important as the Reno-Nord facility does not possess cooling towers to cool water before releasing it to the Limfjord.

Approximately 65% of the waste received at Reno-Nord is household waste, with the remainder of the waste coming from businesses as well as some hazardous waste from hospitals (wastes containing heavy metals are not received by Reno-Nord). A special observation bay situated at the plant allows representatives from the municipality to investigate the waste being produced by selected businesses. It is required by Danish law that information on the origin of the waste is recorded upon deliver to a waste management facility. The information gathered from these observations can then be used in consultation with the businesses to improve their waste management. For example: If it is observed that in the waste coming from an office building empty printing cartridges are present, then the opportunities for recycling printing cartridges can be discussed with the company. All consulting is conducted through Energicenter Aalborg, and is provided as a free service to all homes and businesses in Aalborg Kommune.

As a result of the incineration process, about 20% of the waste remains as bottom ash. Reno-Nord has entered into a contract with another company which is responsible for sorting valuables (particularly metals) out of the bottom ash and then sells these fractions on the market, usually to Germany or the Netherlands. After any valuable components have been sorted from the bottom ash, the remaining ash is then recycled as a component in the building of new roads, or solidified in cement and used to fill vacated salt mines in Germany. It could be argued that the sorting of metals from the bottom ash replaces the need to collect metals separately from the consumers, however it should be noted that the burning process does affect the quality of the metal: Purity is affected by the presence of pollutants, and a certain percentage of the metal is also oxidised in the burning process.

In addition to the incineration facilities, Reno-Nord also utilises landfill and composting. Contaminated soils are either cleaned or landfilled, treated wood is land filled, and bricks and concrete are crushed and recycled in road construction with around 150,000 tons of recycled construction waste per year.

5. LCA of Household Food Waste Management in Aalborg Kommune

The following chapter is a Life Cycle Assessment (LCA) of the current waste management system, and alternative scenarios, for household food waste in Aalborg Kommune, Denmark. The study has been conducted in accordance with the ISO 14040 (2006) and ISO 14044 (2006) standards. The results of the study will be drawn upon to draw conclusions about the use of the waste hierarchy in waste management planning.

5.1 Phase One: Goal and Scope Definition

5.1.1 Purpose of the Study

This study is a single product LCA for the management of household food waste in Aalborg Kommune, Denmark. The main purpose of this study is to evaluate and compare different scenarios for waste management in Aalborg Kommune in order to assess the usefulness of the waste hierarchy and LCA in the planning of waste management systems, and the benefits of integrating different sectors. As the results of this study are not intended to be used to influence waste management strategy, no critical review is to be performed.

5.1.2 Functional Unit

The functional unit, in this case, is equal to the reference flow. This is said to be the entire amount of household food waste produced in Aalborg Kommune in the year 2009 in the wet basis (19000 ton) plus the amount of pig manure that is needed for the co-digestion with said amount of household food waste in the wet basis (150000 ton). Household food waste is hereby defined to be any vegetable or animal matter as well as paper that is used in the kitchen.

While the choice to use the amount of waste produced in Aalborg Kommune in one year may restrict the ability to use this study to draw conclusions about waste management in other municipal areas, it was considered more relevant to the current study than to use a standard unit such as 1 ton of waste. This study attempts to define the situation as it is specifically in the municipal area of Aalborg Kommune.

5.1.3 Method for System Delimitation

This study utilises a consequential approach to system delimitation, meaning that the system represented in the study actually reflects the physical processes that are affected. Some of the benefits of taking a consequential approach are that it avoids co-product allocation through system expansion (in attributional method allocation factors are utilised), and marginal processes and suppliers are included in comparison to average processes and suppliers with an attributional approach. The ISO 14044 (2006) standard also supports a consequential approach over an attributional approach, stating that "Wherever possible, allocation should be avoided" (ISO 14044, 2006, pg 14).

5.1.3.1 System Delimitation in Waste Management

Many existing LCAs concerning waste and waste management take a consequential approach with system expansion (Weidema, 2003; Tillman, Svingy & Lundström, 1998). This is because waste management processes often lead to the production of useful products such as electricity, heat, nutrients and recovered materials (Baumann and Tillman, 2004). One example where system expansion is particularly beneficial is when assessing how energy-from-waste processes affect the energy supply system. With system expansion it is possible to identify the marginal energy supply, which is the energy supply that is actually affected by changes in the system. This approach of system expansion, through its ability to model the system as it actually presents, gives a more realistic assessment of the system. However, this more realistic view is gained at the cost of higher uncertainty; as the system is expanded, more and more processes are included leading to the collection of increasing amounts of data and often more uncertain data (Tillman, Svingy & Lundström, 1998).

5.1.4 Method for Life Cycle Impact Assessment

The impact assessment method that was chosen for this study is the EDIP 2003 method (Environmental Design of Industrial Products; Wenzel, Hauschild & Alting, 1997). This method was chosen as it is a Danish method and because it is relatively new compared to some other methods. All the impact categories included in the method were assessed; however the interpretation of the assessment focuses on the following four impact categories:

- Global warming 100a
- Human toxicity soil
- Aquatic eutrophication N; and
- Aquatic eutrophication P.

5.1.5 Data Collection

The data relating to waste is gathered from several sources including reports from the Danish EPA on the composition of household waste and home composting (Petersen and Domela, 2003) and a study on the collection of organic waste in Aalborg Kommune (Jørgensen, 2003), and from the green accounts from Aalborg Kommune (Forsyningsvirksomhederne, 2010), and Reno-Nord (Reno-Nord, 2009). The green accounts provide the data for the amount of waste that was collected in Aalborg Kommune, while the reports from the Danish EPA provided information on the composition of the waste and what percentage each waste fraction represents.

Data on the individual processes were collected through interviews, visits and email communication with the heat producing facilities and the public utilities company.

5.1.6 Limitations of the Study

This LCA is limited both geographically and in relation to time as it is a representation of a specific situation, namely Aalborg Kommune in the year 2009. The results of the LCA are not intended to be used to draw conclusions about waste management situations in other areas.

The study is also limited by the system boundaries of the LCA. The LCA only includes processes that occur after the waste and the pig manure have been delivered to their respective waste management facilities. Transport processes for the products of the waste management scenarios (ash and digestate) are also not included in this study. The following is a discussion of the transport processes that are not included in this LCA.

5.1.6.1 Collection of Household Food Waste

At the beginning of the life cycle of waste is the collection and transport to the waste management facility. The zero scenario in this study is the current practice which occurs in Aalborg Kommune. This is that household food waste is mixed in the home with other household waste streams. The waste is collected in trucks and driven to the Reno-Nord facility to be incinerated. In scenario one it is assumed that the household food waste is separated in the homes and collected independently from other household waste. The household food waste is then transported to a different facility to the waste that is destined for incineration.

In 2009, 46 collection trucks drove a total of 973,000 km to collect the total amount of waste produced in Aalborg Kommune. The majority of these trucks (24) are classified as EU-3, and the municipality is committed to replacing old vehicles with new vehicles of at least EU-3 classification (Personal communication with Dorte Ladefoged, 2010; Forsyningsvirksomhederne, 2009).

In 2000 a year-long trial of separate collection of organic household waste was conducted in Aalborg Kommune. In this trial a special truck named "Vaskebjørnen" was used to collect organic waste from households and attached dwellings. During this period ordinary collection of other household waste continued as usual. This indicates that the collection and transport of separated household food waste would significantly increase the environmental impacts related to collection and transport.

Despite this difference in collection and transport of waste, it was decided not to include transport as a process in the life cycle inventory. Firstly, in similar investigations to this report (for example Odgaard, et al, 2009) the collection and transport phase of waste management was only found to contribute a small fraction of the environmental impacts. Secondly, the collection of waste is itself a complicated process with many alternative options that each deserves consideration. For example, waste can be collected individually from each home, or from central collection points, it can be collected simultaneously with other waste with the use of special trucks or collected separately with the same trucks, collection can occur weekly or fortnightly, collection can occur in paper or plastic bags, or in washable plastic containers. This report considers this to be worthy of a separate investigation and is therefore beyond the boundaries of this report.

In addition to these reasons, the collection and transport stage is often one of the most costly aspects of waste management. Due to this, waste collection and transport methods are usually decided based on economical benefits instead of on environmental considerations (Jørgensen, 2003).

5.1.6.2 Collection of Pig Manure

The most common collection method for pig slurry in Denmark is through a stall system with a slatted floor. The manure is then pumped to an outdoor, cement storage tank. In order to reduce nuisance from smell, the slurry should be covered. It can occur that a natural layer or crust is formed at the top of the slurry. However, this natural crust does not form in all instances, and for this reason it is also common to cover the tank with an artificial floating cover (Wesnæs & Wenzel, 2009). While this collection process does lead to environmental impacts it was decided that this process was outside of the system boundary of the LCA. This is because the manure would be collected in the same fashion, regardless of whether the manure is used for anaerobic digestion or not.

The transport of the pig manure from the farm to the anaerobic digestion plant was also not included. This limitation is made as the process would be identical in all the scenarios of the LCA.

5.2 Phase Two: Life Cycle Inventory

The following section describes the different processes included in the LCA. Firstly, the general processes that are common to both scenarios will be described, followed by descriptions of the scenarios and the processes that are specific to each scenario.

5.2.1 Common Processes

In this section the processes that are common to both scenarios are described. These processes are:

- Marginal electricity production;
- Marginal heat production; and
- Avoided nutrient production.

5.2.1.1Marginal Electricity Production

The electricity supply in Denmark is a mixture of several different technologies. Centralised coal and natural gas power plants supply the majority of the electricity, with wind, waste incineration and decentralised coal and natural gas fired CHP's supplying the majority of the remaining electricity supply. However, not all of these suppliers are affected when the electricity supply changes; only technologies that are actually affected by a small change in demand are considered to be marginal electricity suppliers (Weidema, 1999). Wind power supply is determined by the available wind and the politically determined capacity. The electricity output from waste incineration plants is determined by the available waste supply. Electricity production in decentralised CHP's is primarily based on the local demand for heat. Therefore, only the centralised coal and natural gas power plants can be considered as marginal electricity suppliers.

Long term versus short term marginal supply

The *short term* marginal electricity supply is defined as the marginal production which is currently considered to be the most competitive supplier, as this is the most likely to be affected by changes when the consumption and demand for electricity is increasing (Schmidt, 2007). To determine the long term marginal supplier, future trends and resource supplies should be taken into account.

In Denmark, the short term marginal electricity supply is considered to be centralised coal CHP's. This is based on Weidema's (2003) assessment of the most competitive electricity technologies, which found that the most competitive was coal, followed by natural gas, heavy fuel oil and biomass in order of most competitive to least competitive. The Danish LCA Center (2006) also advises that consequential LCA practitioners consider coal to be the marginal electricity supply as opposed to natural gas.

When determining the *long term* marginal electricity production in Denmark, natural gas technologies are also worthy of consideration. This is because in the future all new fossil fuel based power plants in Denmark are planned to be natural gas fired instead of coal fired. Natural gas fired plants have many benefits over coal fired plants. Firstly, there is a political benefit as the fuel burns cleaner and more efficiently, and replacing coal produced energy with natural gas produced energy will help in reaching the political goals for reduction of SO_2, NO_x and CO_2 emissions. There is also an economic benefit to the facility itself as there are lower installation costs associated with natural gas fired power plants, as well as an ability to regulate the power output down to a minute-by-minute basis (Schmidt, 2007). This is not technologically possible with coal fired technologies. However, the prediction that natural gas will become the long term marginal electricity supply in Denmark should be made warily due to the rapidly decreasing domestic reserves of natural gas. It is predicted that the European reserves of natural gas will decrease their output, while reserves in non-OECD countries, particularly the Middle East, will increase their production considerably over the period up to 2035 (IEA, 2009). This will lead to a situation in the future where a majority of the natural gas supply in Denmark will be imported from outside of Europe. This has implications for the consideration of natural gas as the long term marginal electricity production as the supply of natural gas will be constricted: for natural gas to be considered a marginal electricity technology the supply of natural gas must be flexible (Schmidt, 2007).

Throwing Heat into the mix

The trend in Denmark for centralized power plants, both coal fired and natural gas fired, is to produce both electricity and heat. These power plants are able to adjust the output ratio of heat and electricity by switching from a condensation mode, which maximises heat production, and back-pressure mode, which maximises electricity production. The output from these CHP's is generally determined by the demand for heat in the local district heating network (Weidema, 2003). The electricity output from CHP plants should therefore not be considered as part of the marginal electricity supply as the change in relation to demand for heat, and not in relation to demand for electricity. Only electricity that is produced without co-generation of heat should be considered to be marginal electricity supply.

Coal or natural gas?

After careful consideration of all the available information and argumentations it was decided to consider the marginal electricity supply as 100% coal. The uncertainty of this assumption is accounted for through applying 50% coal and 50% natural gas as the marginal electricity supply in the sensitivity analysis (see chapter 5.4.1.3).

Unit Process: Marginal electricity supply, hard coal, nordic

The SimaPro unit process that was chosen to represent the marginal electricity that is avoided when electricity is produced via incineration and biogas combustion is called "Marginal electricity supply, hard coal, nordic". This process remains unchanged from the original Ecoinvent unit process, "electricity, hard coal, at power plant/kWh/NORDEL".

This unit process "describes the electricity production of an average plant for the country" (Ecoinvent documentation comment in SimaPro). This process was considered to be the most appropriate process to represent the situation as it was occurring in Aalborg Kommune, as electricity produced in coal-fired power stations was found to be the electricity supply technology that is affected when electricity is produced by alternate means such as biogas combustion and incineration (see discussion above).

5.2.1.2 Marginal Heat Production

When heat is recovered from waste, it can lead to an offset of environmental impacts through the prevention of alternative heat production activities. In order to quantify the environmental impacts of the different waste management scenarios, it is therefore necessary to identify and describe the heat production that is actually effected by the heat recovery from waste activity. This heat is referred to as the marginal heat supply.

While the electricity supply is connected to a grid and is therefore considered in a national sense, district heating supply in Denmark is largely restricted to individual networks for each metropolitan area. For this reason, when determining the marginal heat supply in Aalborg Kommune, only the heat supplies that currently exist in Aalborg were considered.

Currently, district heating is fed from 4 main sources; Reno-Nord (waste incineration facility), Aalborg Portland (cement production company), Nordjyllandsværket (coal-fired CHP plant) and several natural gas fired boilers that are fired in the winter months to supplement the baseline supply and satisfy demand.

Summer

During the summer months, sufficient heat is supplied in Aalborg Kommune from Reno-Nord, Aalborg Portland and Nordjyllandsværket. In some months it is actually the case that for some of the months there is more heat produced than there is demand for (June to September, inclusive). In this situation, heat that is produced by Nordjyllandsværket and Aalborg Portland is cooled through mixing with sea water before being released directly into the marine river that runs through the city of Aalborg-Nørresundby, the Limfjord.

In traditional LCA's concerning the impacts of incineration of waste, benefits from waste incineration are greatly attributed to an avoided heat production from an alternative marginal technology which is usually the burning of a fossil fuel such as coal, natural gas or oil. However, in the situation of Aalborg Kommune, where there is excess heat produced, the heat produced from the incineration of waste should not be considered to affect the other technologies. In other words, during the summer months there is no marginal heat supply in Aalborg Kommune that is affected by the production of heat through incineration.

Winter

During the winter months, demand for heat in the metropolitan area of Aalborg-Nørresundby exceeds the production from the three regular heat suppliers as described above. In this situation the increased demand is met through producing heat at a series of boilers placed throughout the metropolitan area. These boilers run on natural gas, and are considered to be the marginal source of heat in Aalborg Kommune. This is because it is the supply of heat that changes according to demand, while other sources of heat remain stable throughout the year, regardless of demand.

Unit Process: Marginal heat

The SimaPro unit process that was chosen to represent the marginal heat supply that is avoided when heat is produced via incineration and biogas combustion is called "Marginal heat". This process remains unchanged from the original Ecoinvent unit process, "heat, natural gas, at boiler modulating >100kW/MJ/RER".

This unit process describes the production of heat from natural gas, including the input of the fuel, infrastructure, emissions and the electricity that is consumed in the operation of the boiler. The process does not include the distribution of heat, however this is not considered to be a limitation as the distribution of the heat would occur regardless of the technology that is utilised to produce it. This process was considered to be the most appropriate process to represent the situation as it is occurring in Aalborg Kommune, as heat produced in natural gas-fired boilers was found to be the heat supply technology that is affected when heat is produced by alternate means such as biogas combustion and incineration (see discussion above).

5.2.1.3 Avoided Nutrient Production

One of the products of the anaerobic digestion process is the digested matter that is left after the biogas has been extracted. This organic matter is referred to in this study as digestate and can be used as a fertiliser replacement by spreading it onto farmland. When digestate from anaerobic digestion is used to fertilise fields, it can be assumed that the nutrients that are being applied to the fields are applied instead of mineral fertilisers. Therefore, an avoided production of these mineral fertilisers should also be considered.

Nitrogen

Nitrogen (N) is the most abundant nutrient present in pig manure. Danish studies carried out by the Danish Agricultural Research Institute (Danmarks Jordbrugs Forskning) have determined that the total N content in pig manure ex-storage is 5 kg per ton of manure (DJF, 2008). As this figure is a Danish average, it was assumed that the pig manure that would be used for anaerobic digestion in the Aalborg scenarios would also contain the same level of N. However, while it is assumed that this level of N remains stable throughout the anaerobic digestion process and that all N that is present in the raw pig manure reaches the fields in the form of the digestate from anaerobic digestion, it is not assumed that 100% of the N in the pig manure is available for uptake by plants. It is important to account for this unavailability of the N as in this process it is necessary to determine the amount of mineral fertiliser that is avoided.

In order to determine to what extent N in digestate replaces mineral fertilisers, direction was taken from the Danish law regarding the documentation of farmers' use of nutrients. In Denmark, it is a requirement that all farmers record the amount of nutrients that are distributed on the fields, and the amount of nutrients that exit the farm in the form of produce. The law that governs this practice, Gødskningsloven (fertilisation law), also gives guidelines as to how much mineral fertiliser the use of animal slurry replaces. Here it states that the use of animal slurry substitutes N from fertilisers at 75%. For example, where 75kg of N as mineral fertiliser is used, 100kg of N as manure would instead be used. When this information is combined with the average N content of Danish pig manure, we find that 3.75kg of N is avoided per ton of slurry (pre digestion) that is applied to the field.

Calcium ammonium nitrate was chosen as the mineral fertiliser that is avoided as it is the most commonly used N fertiliser in Denmark, although globally urea is the most commonly applied N fertiliser (Wesnæs & Wenzel, 2009). To represent the production of this fertiliser in the LCA, the Ecoinvent unit process "calcium ammonium nitrate, as N, at regional storehouse/kg/RER" was utilised.

Phosphorus

Another important nutrient that can be found in the digestate is phosphorus (P). Danish studies carried out by the Danish Agricultural Research Institute (Danmarks Jordbrugs Forskning) have determined that the total P content in pig manure ex-storage is 1.04 kg per ton of manure (DJF, 2008). As this figure is a Danish average, it was assumed that the pig manure that would be used for anaerobic digestion in the Aalborg scenarios would also contain the same level of P. P tends to not suffer the same problem as N in regards to bio-unavailability, with P found in fertiliser being considered to have the same value as P found in mineral fertilisers.

In reality, it is not likely that the amount of P found in the digestate would replace the same amount of P as mineral fertilisers. This is because the ratio of P:N in pig manure is greater than what is desired. This leads to P being applied in excess when applied as digestate. It was decided to assume that the P present in the digestate replaces P in mineral fertilisers 100% as the amount of P that is usually added to a field is an ever-changing figure that is dependent on a wide range of variables. It is normal practice to test the P levels in the soil and to add P fertiliser to adjust the soil P content to a desired level, as fitting for the needs of the crop (Poulsen & Rubæk, 2005). This assumption therefore must be recognised as a regrettable limitation to the study and should be bore in mind when interpreting the results of the LCA (see section 5.4.1.4).

Unit Process: Avoided nutrients from digestate application to fields

In order to characterise the avoided impact of mineral fertiliser production a new material process was created within SimaPro. This process was entitled "Avoided nutrients from digestate application to fields" and utilises the Ecoinvent unit process "triple superphosphate, as P2O5, at regional storehouse/kg/RER" and "calcium ammonium nitrate, as N, at regional storehouse/kg/RER" (see above for argumentation as to why these particular fertilisers were considered to be the marginal mineral fertilisers).

In order to determine the amount of mineral fertilisers that is avoided it was necessary to make a series of assumptions. Firstly, despite nutrient losses in the fertiliser collection and storage process, it was considered that all of the nutrients that were present in the pig manure ex-storage are also present in the digested matter and is not lost at any other point in the process. This assumption is made as pre storage nutrient loss is considered to be the point in the process with the highest nutrient losses, and because nutrient losses attributed to the application of the digested matter on the fields varies depending on many factors such as the method used to spread the digestate, the weather conditions such as temperature and precipitation and even the height of the crops at the time that the digestate is spread. Secondly, assumptions of the bio-availability of the nutrients were also made. (See the discussions of each individual nutrient for further discussion of these assumptions; pg. 56.)

5.2.2 Scenario 0 – Incineration of Household Food Waste

The following section describes the zero scenario, or reference scenario, for the management of household food waste in Aalborg Kommune. This scenario assumes that the household food waste is collected together with other household food waste and is incinerated at the local facility, Reno-Nord. While the rubbish is incinerated together with other waste fractions, this scenario only represents the burning of the food waste fraction. Other waste streams are beyond the system boundaries of this investigation. Also included in this scenario is the biogas production from pig manure, without household food waste. The process categories described are therefore:

- Incineration of household food waste;
- Biogas production from pig manure; and
- Biogas combustion.

Figure 6 shows the illustration of the scenario and the included processes.

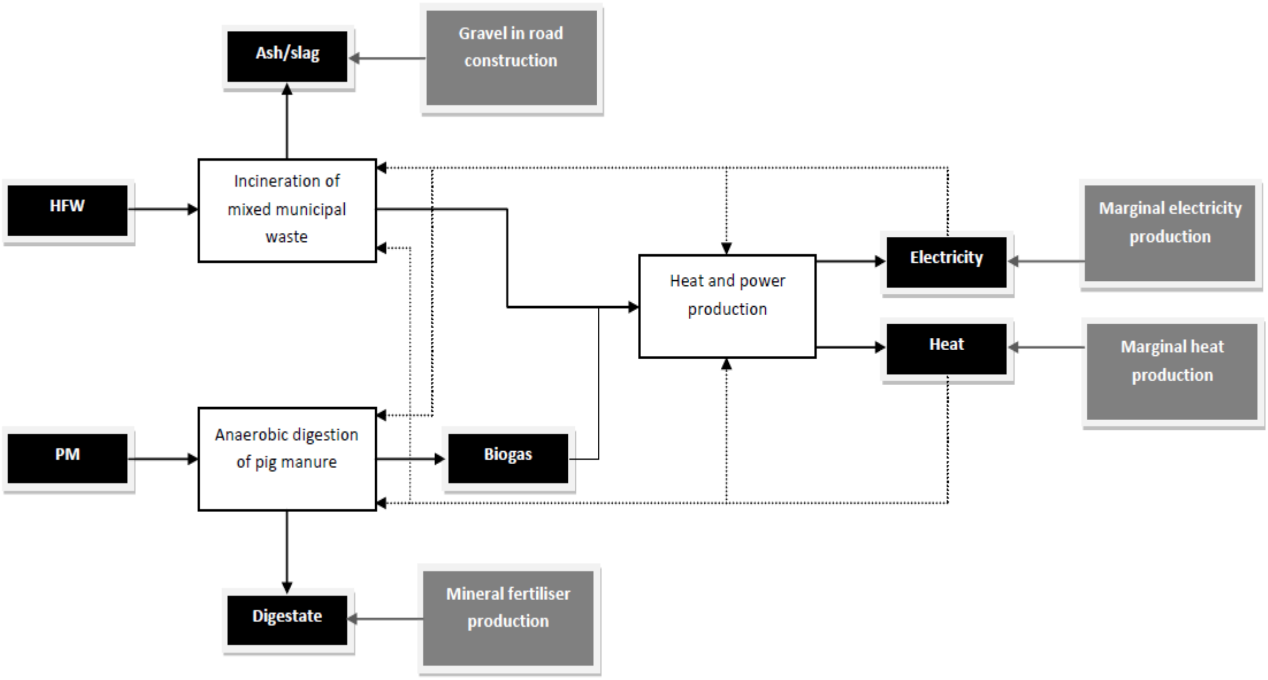


Figure 6. Scenario 0, schematic representation

5.2.2.1 Process Category: Incineration of Household Food Waste

The reference flow in this case is the total amount of household food waste collected in Aalborg Kommune in 2009, which equates to 19000 ton in the wet state. In Denmark, the energy content of mixed municipal solid waste is between 10 and 12 GJ/ton (Danish EPA, 2003). At the Reno-Nord facility in Aalborg, the energy content of the mixed waste is assumed to be 10 GJ/ton when calculating the green accounts (Reno-Nord, 2009). Therefore, for this investigation the same assumption has been made. When the food waste is separated from the mixture, the Danish EPA has found that the food waste fraction has a much lower energy content; between 4 and 4.5 GJ/ton (Danish EPA, 2003). Again, this investigation assumes the lower value of 4 GJ/ton to be the energy content of the food waste fraction. For a description of the incineration process as it occurs at Reno-Nord, see chapter 4.3.1.

To represent this system, a series of unit processes were defined as described below.

Unit Process: Disposal, food waste, Aalborg Kommune, 80% H2O, to municipal incineration

Ecoinvent process *Disposal, biowaste, 60% H2O, to municipal incineration, allocation price/CH U* was utilized to evaluate the impacts associated with the incineration of the household food waste. It was chosen because it best described the process as it occurs in Aalborg Kommune. The process includes the transport of waste within the incineration plant, the incineration process itself, the cleaning of water from the wet scrubbers, and the eventuating processing of the slag (the unburnable remains after incineration). However, this process was created to represent the incineration of mixed municipal bio-waste in a Swiss incineration plant, and therefore it was necessary to manipulate the data within the database so as to better represent the incineration of household food waste at the Reno-Nord facility in Aalborg.

Firstly, a parameter, CF (correction factor), was established to correct for the differing moisture content of the household food waste in Aalborg Kommune and the mixed municipal biowaste that was represented in the database. Food waste usually has a high moisture content, while a mixture of bio-waste will also include some paper and yard waste, which will lower the moisture content of the waste mixture. The Ecoinvent process that was used assumes a dry material content of 40%, while food waste in Aalborg Kommune generally has a dry material content of only 20% (Jørgensen, 2003). This means that for each ton of wet waste, there is only half as much solid matter being incinerated. Therefore, the CF parameter was set at 0.5 and all inputs and outputs that are dependent on the mass of dry matter were multiplied by this parameter.

Another difference between the Ecoinvent process and the actual process at Reno-Nord is the recycling of the ashes and slag. The Ecoinvent unit process assumes that the slag and ashes are solidified in cement and then landfilled. At Reno-Nord, most of the ash is utilised in the construction of roads while the remainder of the slag is solidified in cement and used to fill old salt mines in Germany where they perform the task of stabilising the mines and preventing land disturbances. Therefore the materials and processes associated with the disposal of ash and slag must also be adjusted to represent the actual situation at hand. The inputs of cement were adjusted to represent the amount of ashes that are in fact solidified, and process-specific burdens related to landfilling were removed.

In addition to these changes, it was also considered that the use of ash in the construction of roads avoids the use of another product, in this case gravel. The Ecoinvent unit process "Gravel, round, at mine CH/U" was used to represent the avoided use of gravel. This process was chosen to best represent the process as it occurs in Denmark as it documents the effects of digging gravel in a quarry, which is the practice in Denmark, while other processes documented the effects of removing rock from mountainous areas with the use of dynamite. Transport from the mine was not considered, as the transport of ash to road construction site is also not considered. This is because the transport distance is highly variable. Also, the input of electricity was adjusted to represent marginal electricity supply.

As described in earlier, the production of heat and electricity through the incineration of waste equates to an avoided production of heat and electricity from the marginal energy supply. To calculate the amount of electricity should be counted for avoided production, the amount of electricity that is utilised within the incineration facility is subtracted from the total amount of electricity that is produced. The electricity utilised by the incineration plant is calculated based on information from the 2009 Green Account of Reno-Nord (see section 5.2.1 for description of the processes for marginal electricity and marginal heat).

5.2.2.2 Process Category: Biogas Production from Pig Manure

In order to retain the same reference flow across both scenarios, it was necessary to also include the anaerobic digestion of pig manure alone in the reference scenario. It was also considered here to instead represent the direct application of raw pig manure direct to fields; however, this is a process with a great degree of uncertainties and would have led to results that would be difficult to interpret. In addition to this, anaerobic digestion is already a process which occurs in Aalborg Kommune and across Denmark. Finally, the main goal of this study was to identify the differences in environmental impacts between the incineration and the anaerobic digestion of *household food waste*. By representing the anaerobic digestion of the pig manure in the reference scenario, the results will clearly show the environmental differences between the different treatments of household food waste and will not be complicated by differences in the treatment of the pig manure.

Unit Process: Anaerobic digestion of pig manure

This process was adapted from the original Ecoinvent unit process "biogas, from slurry, at agricultural co-fermentation, covered/m3/CH". Described in this process is the infrastructure and energy used in the digestion process and the recovering of the methane gas, as well as emissions to the air during the process.

In order to represent the Aalborg situation as correctly as possible, the electricity and heat supplies were changed. The electricity and heat inputs were changed to represent the marginal energy supplies as they are defined in chapter 5.2.1.

This unit process is represented within the unit process "Electricity, at cogen with biogas engine" which is described in chapter 5.2.2.3.

Unit Process: Avoided nutrients from digestate application to fields

This process is concerning the digestate which is the organic matter which remains after the digestion process. As is described in section 5.2.1.3, this process describes the avoided production of mineral fertilizers when digestate is spread on fields as a fertilizer replacement.

5.2.2.3 Process Category: Biogas Combustion

After the biogas has been extracted from the pig manure through the anaerobic digestion process, the biogas is then utilized for the creation of heat and electricity. This is done by combusting the gas in an engine.

Unit Process: Electricity, at cogen with biogas engine

This process is adapted from the original Ecoinvent unit process "electricity, at cogen with biogas engine, allocation exergy/kWh/CH" and describes the impacts related to the combustion process, associated air emissions and the infrastructure required for the process.

The input of biogas was changed to represent the biogas that was produced in the previous process category (see chapter 5.2.2.2). In addition to this, the production of heat and electricity that results from the process was considered to lead to an avoided production from the marginal supplies as they are previously described in chapter 5.2.1. The efficiency of the biogas combustion was assumed to be 38% electricity and 45% heat based on findings in literature (Poulsen & Kuligowski, 2007; Poulsen & Hansen, 2009).

5.2.3 Scenario 1 – Biogas Production from a Mixture of Household Food Waste and Pig Manure

The following section describes scenario 1, or the alternative scenario, for the management of household food waste in Aalborg Kommune. This scenario assumes that the household food waste is separated in the homes and collected independently from other household waste and undergoes anaerobic digestion in a co-fermentation process with pig manure at a fictitious biogas production facility. The biogas is then combusted in an engine to produce heat and electricity. The process categories described are therefore:

- Biogas production from a mixture of food waste and pig manure; and
- Biogas combustion.

Figure 7 shows an illustration of the processes included in this scenario.

The digestion of food waste is never undergone without mixing it with another waste stream: In Denmark this is most commonly manure. In this scenario, the food waste represents 25% (dry matter) of the material for anaerobic digestion, while the remaining 75% of the waste stream is composed of pig manure. In Denmark, it is considered beneficial to mix manure with another waste stream for anaerobic digestion because the manure by itself has a low yield for biogas production, 25m3/ton (Christensen, 2007), while food waste has a much higher yield, between 110-180m3/ton (Jansen & Christensen, 2003). By mixing the two wastes the total yield of biogas is improved and this can have a significant positive impact on the economic efficiency of an anaerobic digestion facility (Nielsen et al, 2002). It is, however, important for the manure to be the most plentiful waste stream in the mixture as it has a high buffer capacity which allows the digestion conditions to remain stable at optimal conditions (Weiland, 2006). Other benefits of mixing pig manure and food waste include a dilution of the food waste as solid waste does not biodegrade as efficiently as liquid waste, and improving the nutrient, C:N, ratio available for the microorganisms as the manure is high in N and the food waste is high in C (Murto, Björnsson & Mattiasson, 2004). The reason why 25% food waste was specifically chosen is because in Denmark a municipal or industrial waste contribution above this level has significant implications for the potential use of the digestate as a fertilizer in accordance with the Sludge Order (Slambekendtgørelsen; Danish Ministry of the Environment, 2006).

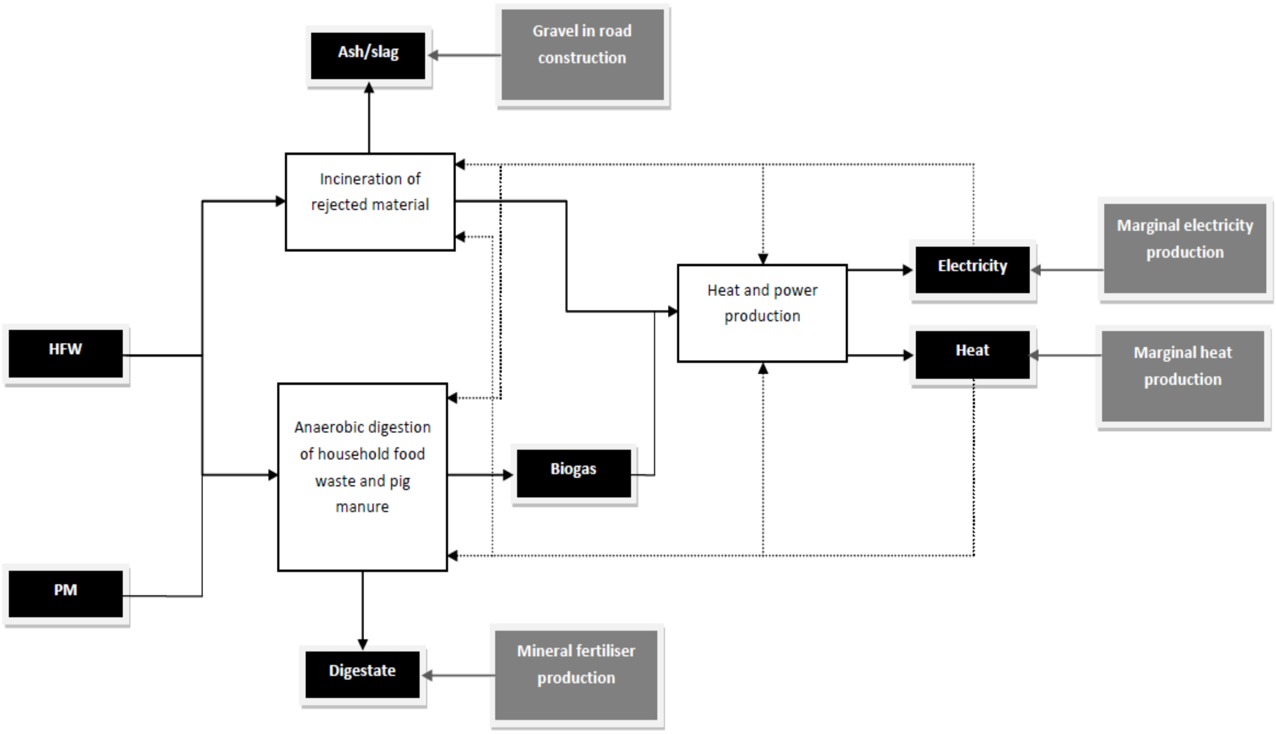


Figure 7. Scenario 1, schematic representation

5.2.3.1 Process Category: Biogas Production from a Mixture of Household Food Waste and Pig Manure

This process category combines the biogas production from household food waste, with the biogas production from pig manure. The two waste streams are mixed together in a pre-processing step, before going further to the anaerobic digestion stage. The anaerobic digestion process results in the creation of digested organic matter which is used as a fertilizer replacement, and biogas which in this scenario is used in the process category *biogas combustion*.

Pre-processing

When the food waste reaches the anaerobic digestion facility, it must undergo a process of mixing and separating foreign components, particularly plastics. Depending on the method of collection, the amount of plastics in the waste stream could be very high; for example if the waste is collected in plastic bags. When trials were undertaken at the Vaarst-Fjellerad biogas facility, which is situated within Aalborg Kommune, it was found that there was a rejection of between 0.1% and 1.2% of the food waste (Jørgensen, 2003). When collection of food waste occurs in plastic bags, the rejected material can be as high as 31-41% of the wet waste (Jansen & Christensen, 2006; Jørgensen, 2003). In this investigation the reject is assumed to be 1% of the wet waste that is brought to the biogas facility.

In Denmark, the most common technology utilized for the pre-digestion processing is called *DeWaster* and is a conical snail device that separates liquid and soft organic substances from substances which have a solid structure such as plastic and glass. This is the technology which is employed at the near-by Vaarst-Fjellerad facility (Jørgensen, 2003). After the waste has been through the DeWaster it is suitable for mixing with the pig manure and the digestion process.

Unit Process: Disposal, food waste, to anaerobic digestion

This unit process is based on the original Ecoinvent unit process “disposal, biowaste, to anaerobic digestion/kg/CH” and includes the pre-processing of the waste, the digestion process and the impacts of applying the digestate to fields. This process also originally included the incineration of the reject waste during the pre-processing step; however it was decided to not include these impacts here and instead represent this process in an individual unit process which is described below.

The Process was also adjusted in terms of the input of electricity and heat to represent the marginal energy supplies.

Unit Process: Anaerobic digestion of pig manure

This process is the same as was described in scenario 0 (see chapter 5.2.2.2).

This unit process is represented within the process "Electricity, at cogen with biogas engine".

Unit Process: Avoided nutrients from digestate application to fields

This process is concerning the digestate which is the organic matter which remains after the digestion process. As is described in section 5.2.1.3, this process describes the avoided production of mineral fertilizers when digestate is spread on fields as a fertilizer replacement.

Unit Process: Incineration of reject

During the pre-processing phase of the household food waste, 1% of the total is removed as reject material which is mostly comprised of plastics and other contaminants. This reject is disposed of at the incineration plant and is described in the process "Incineration of reject from anaerobic digestion". This process is an adaptation of the original Ecoinvent unit process "disposal, municipal solid waste, 22.9% water, to municipal incineration/kg/CH".

Similarly to the incineration scenario described in scenario 0, the process was adjusted to represent the process as it occurs at Reno-Nord. Namely, the amount of cement used to solidify ashes was adjusted, and the impacts of landfilling the resulting slag and ashes were removed.

Also, an avoided production of the marginal electricity and heat supplies is calculated.

5.2.3.2 Process Category: Biogas Combustion

After the biogas has been extracted from the mixture of the household food waste and the pig manure through the anaerobic digestion process, the biogas is then utilized for the creation of heat and electricity. This is done by combusting the gas in an engine.

Unit Process: Electricity, at cogen with biogas engine

This process is essentially the same as the process was described in scenario 0; however the input of biogas was changed to represent the biogas that was produced from the mixture of pig manure and household food waste.

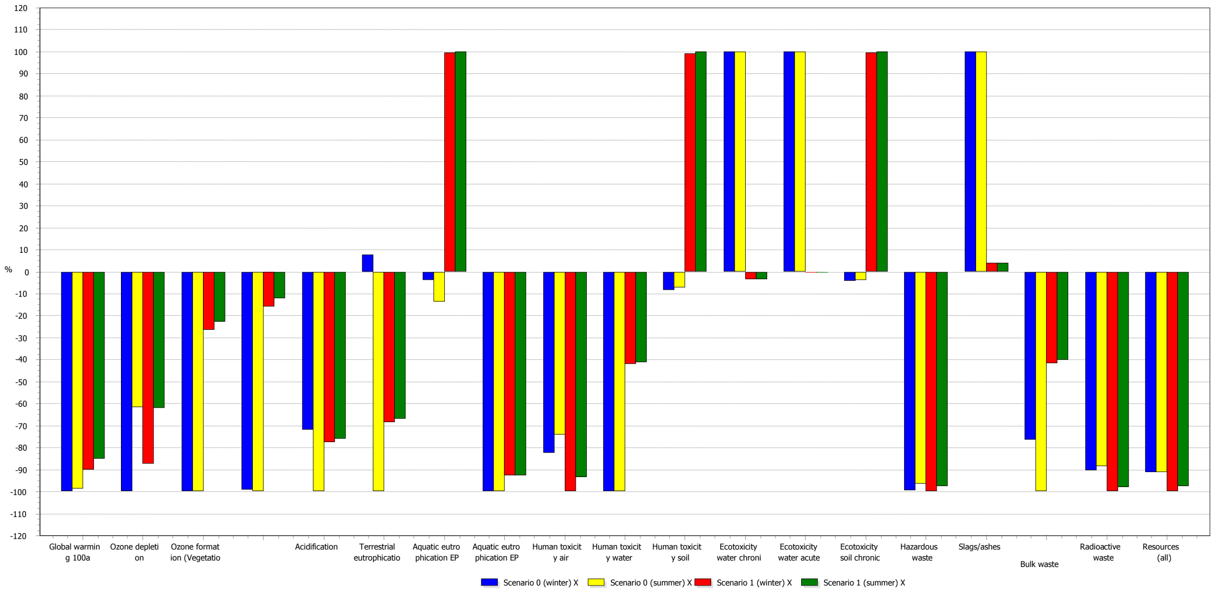
5.3 Phase Three: Life Cycle Impact Assessment

The results of the LCIA show that the combined environmental impact from the biogas scenario (scenario 1) is greater than the impact from the incineration scenario (scenario 0) (see figure 8 which is characterisation of the environmental impacts).

In the characterisation of the results, scenario 0 performs better than scenario 1 in 12 out of the 19 impact categories. However, when the weighting factor is applied to the results, only four of the categories show a significant impact and or differing impacts between the two scenarios. These categories are:

- Global warming 100a
- Human toxicity soil
- Aquatic eutrophication EP (N-eq)
- Aquatic eutrophication EP (P-eq).

The weighting factors in the EDIP 2003 method are set according to politically set target emissions per person in the year 2004 (SimaPro 7, 2008a).
The characterisation of impacts in each of these impact categories is now discussed.



Comparing 1,69E5 ton 'Scenario 0 (winter) X', 1,69E5 ton 'Scenario 0 (summer) X', 1,69E5 ton 'Scenario 1 (winter) X' and 1,69E5 ton 'Scenario 1 (summer) X';
Method: EDIP 2003 V1.02 / Default / Characterisation

Figure 8. Characterisation of the results

5.3.1 Global Warming

Global warming is one of today's most politically important environmental issues both in Denmark and globally. It has been shown by the IPCC that the release of certain compounds, known as green house gasses (GHGs) can lead to an increase in the global average temperature, as well as climate change at a regional level (IPCC, 2007). The EDIP 2003 method assesses global warming based on the IPCC 1994 Status Report with a time horizon of 100 years. The GHGs that are most significant in these scenarios and their corresponding global warming potential over 100 years are:

- Carbon dioxide, CO_2 = 1 GWP_{100};
- Methane, CH_4 = 21 GWP_{100}; and
- Nitrous oxide, N_2O = 310 GWP_{100}.

Both the incineration and the biogas scenarios show a positive environmental impact in respect to global warming (see figure 9). The positive impact is achieved as the use of waste to produce energy is considered to prevent the use of other technologies. In this study, the marginal energy technologies were considered to be coal for electricity production, and natural gas for heat production (see section 5.2.1 for description of marginal energy technologies). Therefore, the positive impact in the global warming category is directly attributable to the avoided burning of coal and natural gas for energy production. Table 2 shows the total global warming impact for each of the scenarios in $kgCO_2eq$.

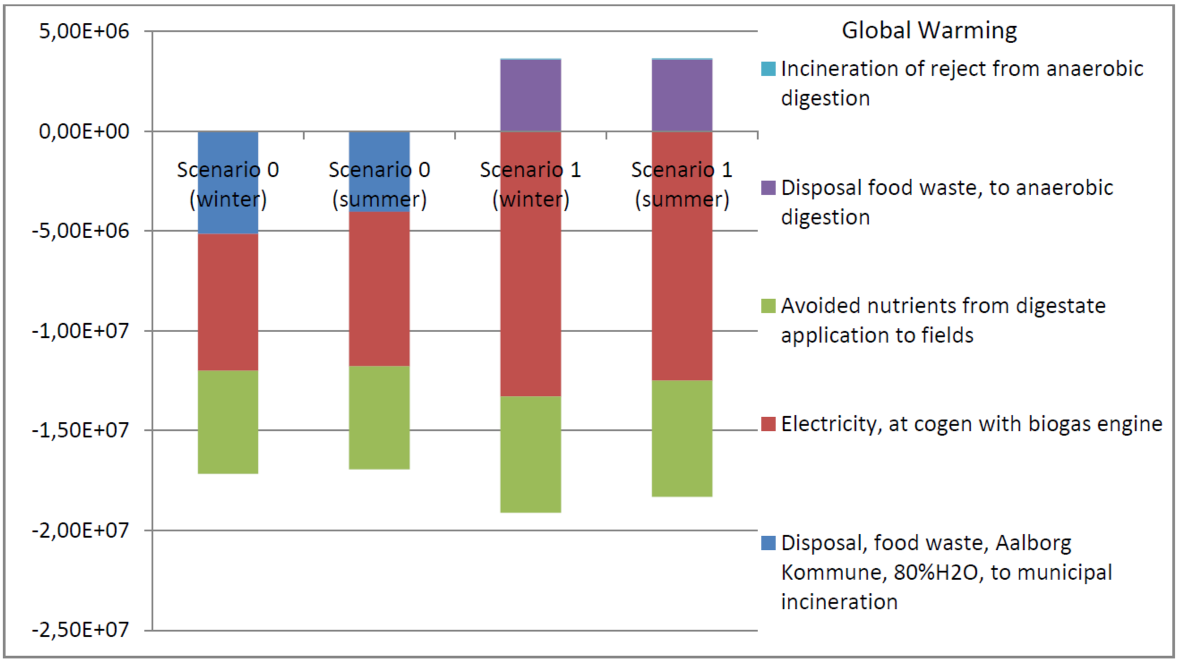
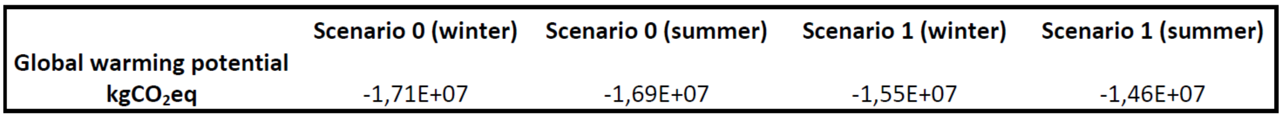


Figure 9. Global Warming 100a. Impact measured in $kgCO_2eq$.

The differences in global warming impact between the winter and summer scenarios are due to the assumption that during the summer months there is no marginal heat supply in Aalborg Kommune. The result of this assumption is that in the summer months there is a lower positive global warming impact than in the winter months.



	Scenario 0 (winter)	Scenario 0 (summer)	Scenario 1 (winter)	Scenario 1 (summer)
Global warming potential kgCO$_2$eq	-1,71E+07	-1,69E+07	-1,55E+07	-1,46E+07

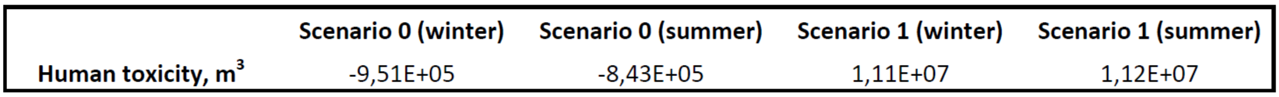
Table 2. Global Warming 100a. Total impact.

While scenario 1 does not perform as well as scenario 0 in this impact category, it should be noted that the combustion of biogas from food waste is preferable to the incineration of food waste. However, the production of the biogas through anaerobic digestion is itself a process which requires energy. This energy needed to produce the biogas is considered to come from the marginal energy supplies, coal and natural gas, which gives a negative impact of global warming. When this negative impact is excluded, the result is that scenario 1 has a lower positive impact than scenario 0.

5.3.2 Human Toxicity via Soil

This impact category measures the impact of human toxicity through exposure to soil. It is calculated via a chemical hazard screening method which accounts for toxicity, persistency and bio-concentration of different compounds. The EDIP 2003 method also takes the fate of these compounds into account, meaning that emissions to water and air can also result in human toxicity via soil.

An interesting result was achieved in this study for human toxicity via soil, with the incineration scenarios giving a positive impact, and the biogas scenarios giving a negative impact. The negative impact in scenario 1 is the most significant single impact attributable to that scenario when weighting is taken into account. Table 3) shows the total human toxicity impact via soil in m^3.



	Scenario 0 (winter)	Scenario 0 (summer)	Scenario 1 (winter)	Scenario 1 (summer)
Human toxicity, m^3	-9,51E+05	-8,43E+05	1,11E+07	1,12E+07

Table 3. Human Toxicity via Soil. Total impact.

These impacts are largely attributable to the infrastructure of the biogas facility and the transport associated with bringing the digested material out to the fields. It is therefore not clear why these impacts are so high in the biogas scenario and not in the incineration scenario, as the incineration scenario also includes the impacts of the anaerobic digestion of pig manure. Therefore, the infrastructure of the biogas plant and the transport of the digestate to the fields occur in all scenarios.

It is therefore assumed that this result does not reflect the reality of the situation. It is possible that the difference in the scenarios originates due to different inputs and outputs being included in the Ecoinvent databases for the anaerobic digestion of pig manure and of food waste. Figure 10 shows the contribution to human toxicity via soil for each of the processes.

As this result cannot be adequately explained, it will not be used to draw conclusions about the impacts of the different scenarios.

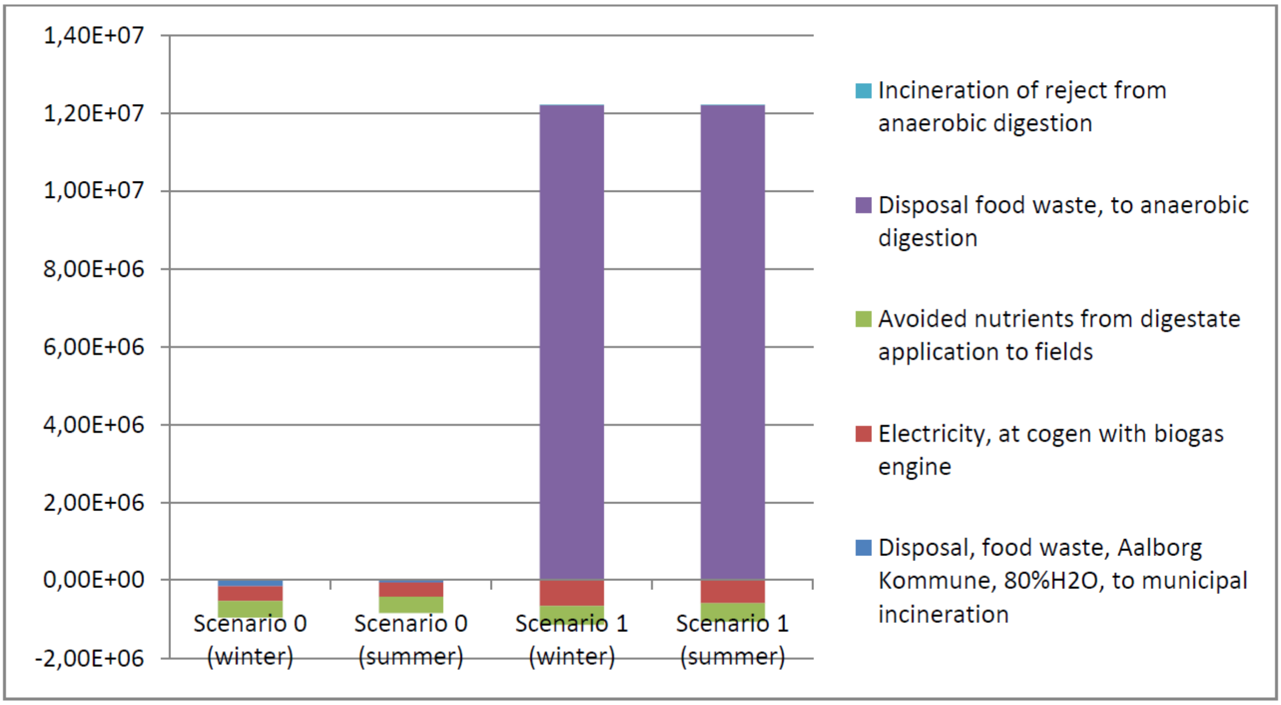
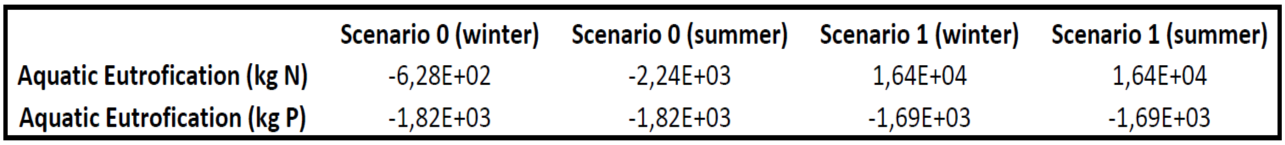


Figure 10. Human Toxicity via Soil. Impact measured in m^3.

5.3.3 Aquatic Eutrophication

Aquatic eutrophication is the pollution of water sources by the addition of nutrients. In the EDIP 2003 method aquatic eutrophication impacts are measured in two different impact categories, one measured in N equivalents, and one measured in P equivalents. While aquatic eutrophication occurs in both inland waters and marine waters, only the effects on inland waters are included in SimaPro 7. This is simply to avoid a double counting of the impacts. Eutrophication is also an important issue in Denmark, as the protection of underground waters as a safe and clean source of drinking water is of a high priority for municipal authorities.

All scenarios show a positive impact of aquatic eutrophication P which is attributable to the avoided fertiliser production. However, in relation to aquatic eutrophication N, scenario 0 shows a positive environmental impact, while scenario 1 shows a negative environmental impact (see table 4).



	Scenario 0 (winter)	Scenario 0 (summer)	Scenario 1 (winter)	Scenario 1 (summer)
Aquatic Eutrofication (kg N)	-6,28E+02	-2,24E+03	1,64E+04	1,64E+04
Aquatic Eutrofication (kg P)	-1,82E+03	-1,82E+03	-1,69E+03	-1,69E+03

Table 4. Aquatic Eutrophication. Total impact.

As was seen with human toxicity via soil, the negative impacts of aquatic eutrophication are attributable to the unit process "Anaerobic digestion of food waste".

Upon closer investigation of these impacts it is evident that those from the unit process "Disposal food waste, to anaerobic digestion" are attributable to the building of the anaerobic digestion facility and transport processes. A was seen in the human toxicity via soil impact category this result does not seem to reflect reality as these processes should be present in both scenarios as the biogas facility is already existing for the digestion of pig manure in scenario 0.

If the impacts attributable to the unit process "Disposal food waste, to anaerobic digestion" are discounted, then scenario 1 performs better than scenario 0 in both the aquatic eutrophication impact categories (see figures 11 and 12).

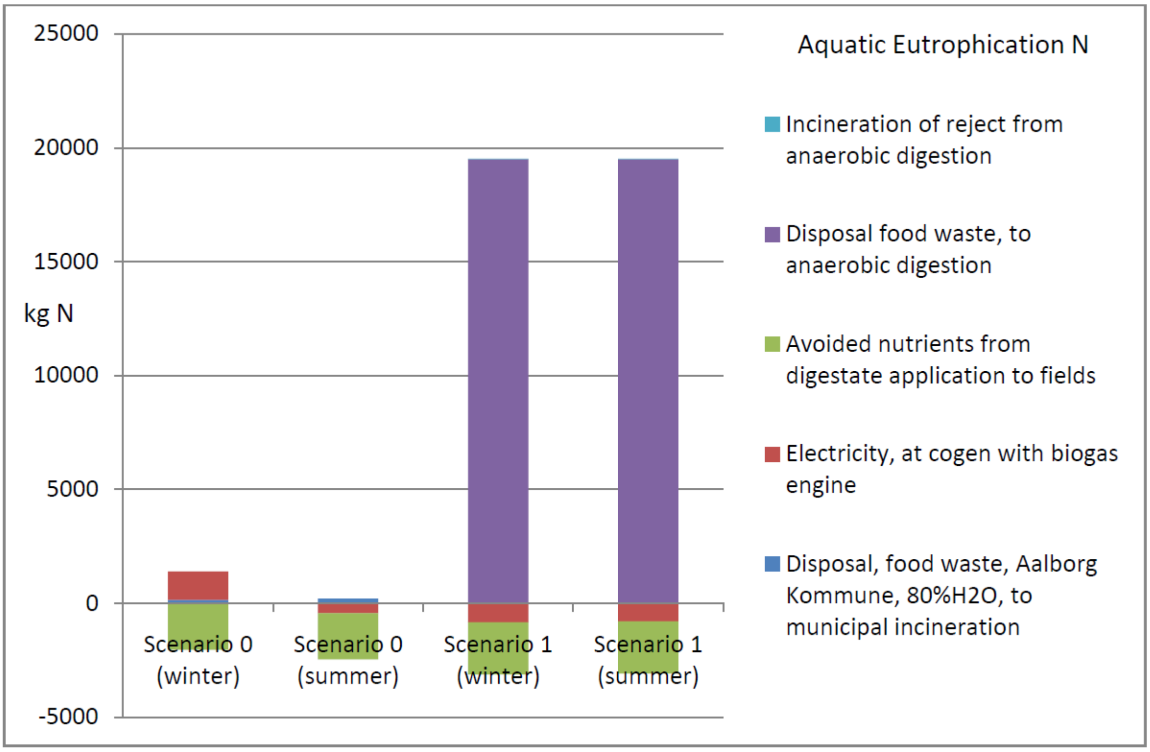


Figure 11. Aquatic Eutrophication measured in kg N.

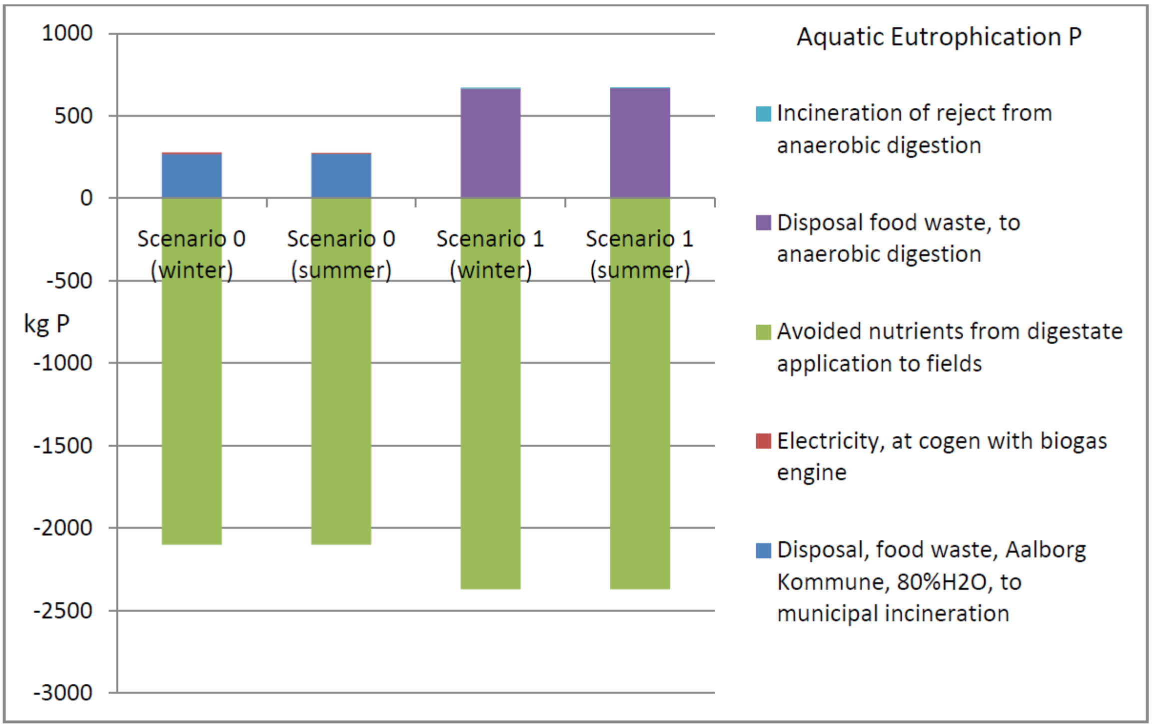


Figure 12. Aquatic Eutrophication measured in kg P.

5.4 Interpretation

The goal of this LCA was to investigate the management of household food waste in Aalborg Kommune through comparing the current strategy (incineration) with an alternative strategy (anaerobic digestion). The result of the LCIA was that the incineration scenarios showed a more desirable environmental impact than the biogas scenarios. This result is the opposite to what was expected based on results gained in other similar studies comparing incineration to biogas production, which generally show that biogas production is preferable to incineration, particularly in relation to global warming impacts. However, this report differs from other studies in that it assumes that the biogas plant already exists and is being fed with pig manure. Other LCA studies concerning the same comparison instead assume that the biogas plant does not already exist and that the pig manure is instead disposed of without digestion. In Denmark this means spreading raw pig manure directly onto fields where the methane would be released directly to the atmosphere.

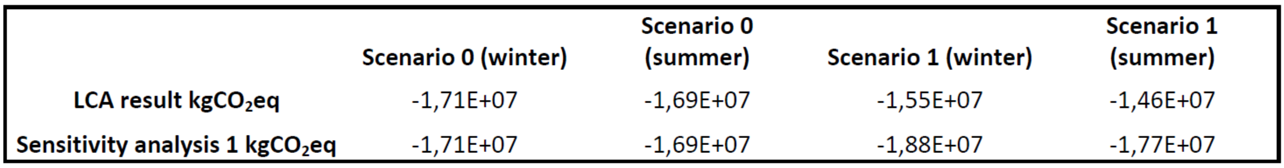
The impacts related to the unit process "Anaerobic digestion of household food waste" seemed to be disproportionate to those impacts related to other unit processes. Particularly, if this process is compared with the unit process "Anaerobic digestion of pig manure" one could expect the impacts to be similar, yet more negative for the pig manure process due to the much greater quantity being measured (150000 ton pig manure compared to 19000 ton household food waste). However, the results show the opposite to be true.

5.4.1 Sensitivity Analysis

5.4.1.1 Sensitivity Analysis 1 – Biogas yield

One of the assumptions made in the LCA was to use the lower value for biogas extraction from household food waste of 110m^3 per ton of waste. The impact of this assumption on the results of the study was tested by conducting a sensitivity analysis using the upper value for biogas extraction from household food waste of 180m^3 per ton of waste.

The result of this sensitivity analysis shows that the assumption had an important influence on the results for global warming impacts. When the lower biogas extraction value was used, it showed that the incineration scenario was preferable to the biogas scenario in relation to global warming impacts. When the upper value is utilised, the result is that the biogas scenario becomes the scenario which performs best in the global warming 100a impact category (see table 5 and figure 13).



	Scenario 0 (winter)	Scenario 0 (summer)	Scenario 1 (winter)	Scenario 1 (summer)
LCA result kgCO$_2$eq	-1,71E+07	-1,69E+07	-1,55E+07	-1,46E+07
Sensitivity analysis 1 kgCO$_2$eq	-1,71E+07	-1,69E+07	-1,88E+07	-1,77E+07

Table 5. Global Warming 100a, assuming 180m^3 biogas per ton HFW.

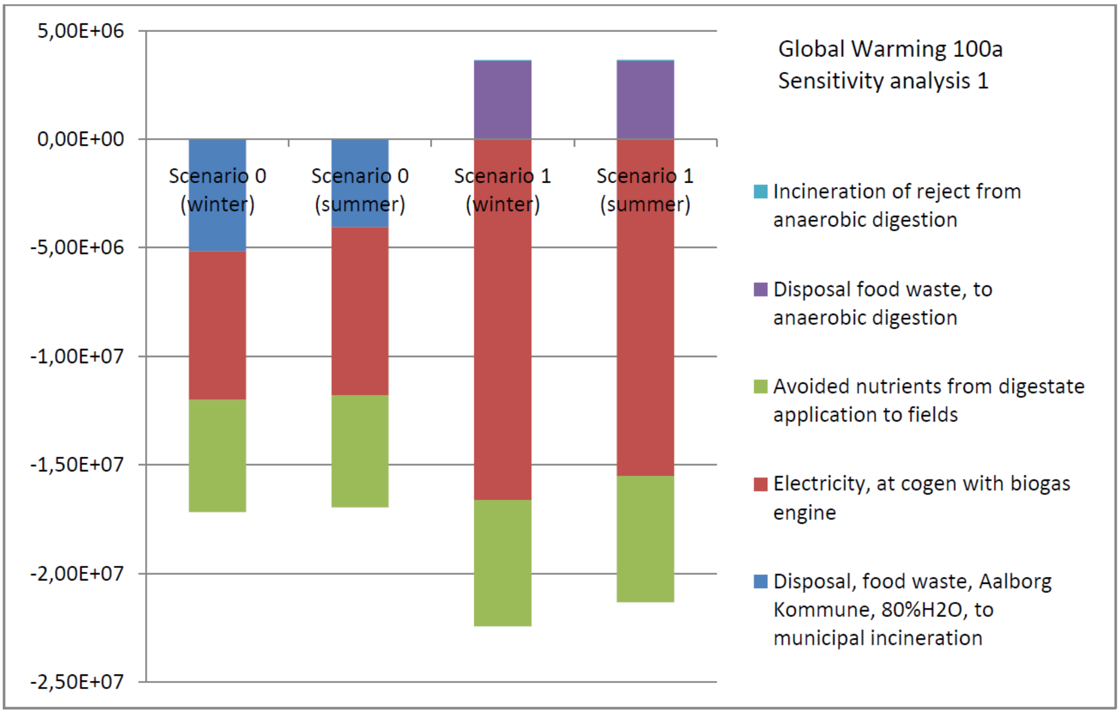


Figure 13. Global Warming 100a, assuming 180m^3 biogas per ton HFW. Scenario 1 is now preferable to scenario 0.

5.4.1.2 Sensitivity Analysis 2 – Efficiency of biogas combustion

The efficiency of the gas combustion turbine was assumed to be 38% electricity and 45% heat; an assumption that was based on literature and other LCA studies that have been conducted in Denmark. However, the Danish company *Xergi* is able to supply a biogas combustion turbine that has an efficiency of 42% electricity and 48% heat (Thyø &Wenzel, 2007). As the biogas plant that is assumed to be used in this LCA is fictitious, it was decided to perform a sensitivity analysis on the result if this best practice technology was to be used.

While the result of this sensitivity analysis showed an improved environmental impact for all scenarios, it did not change the essential result; the incineration scenarios still showed a greater environmental benefit than the biogas scenarios (see table 6).

	Scenario 0 (winter)	Scenario 0 (summer)	Scenario 1 (winter)	Scenario 1 (summer)
LCA result kgCO$_2$eq	-1,71E+07	-1,69E+07	-1,55E+07	-1,46E+07
Sensitivity analysis 2 kgCO$_2$eq	-1,79E+07	-1,77E+07	-1,70E+07	-1,59E+07

Table 6. Global Warming 100a, assuming a biogas combustion efficiency of 42% electricity and 48% heat.

5.4.1.3 Sensitivity Analysis 3 – Marginal electricity

In chapter 5.2.1 it was argued that the marginal electricity supply in Denmark was coal. However, the assumption of the marginal electricity supply is often a highly debated assumption. In the discussion in chapter 5.2.1 it is mentioned that due to political reasons, the long term electricity supply in Denmark may in fact be natural gas. Due to the uncertainty associated with this assumption, it was decided that it should be tested in the sensitivity analysis by creating a unit process for marginal electricity that was described as 50% coal and 50% natural gas.

The result of this sensitivity analysis shows that the positive impacts in the global warming 100a impact category are less than in the original scenarios where the marginal electricity supply is 100% coal. This is an expected result as these positive impacts are associated to the avoided production of marginal energy. As coal is a more polluting fuel than natural gas we see that the choice of marginal energy supply will influence the degree of impact that is seen in the global warming category, but will not affect the relationship between the different scenarios (see table 7).

	Scenario 0 (winter)	Scenario 0 (summer)	Scenario 1 (winter)	Scenario 1 (summer)
LCA result kgCO$_2$eq	-1,71E+07	-1,69E+07	-1,55E+07	-1,46E+07
Sensitivity analysis 3 kgCO$_2$eq	-1,48E+07	-1,46E+07	-1,31E+07	-1,23E+07

Table 7. Global Warming 100a, assuming a marginal electricity supply of 50% coal 50% natural gas.

5.4.1.4 Sensitivity Analysis 4 – Avoided nutrient production

When calculating the avoided production of mineral fertilisers it was assumed that the P that is contained in the pig manure replaces P in mineral fertiliser 100%. This assumption was made as the amount of mineral P fertiliser that is avoided due to the utilisation of digestate is a highly variable parameter. However the ratio of P to N in digestate is higher than the ideal ratio for crop production and therefore P is usually applied in excess. Therefore P in digestate will rarely, if ever, replace mineral P fertiliser 100%.

To test the importance of this assumption on the results of the LCA a sensitivity analysis was performed where only 50% of the P content in the digestate led to an avoidance of mineral P fertiliser. The result of this sensitivity analysis showed that this assumption did not significantly impact the results of the LCA in most impact categories. There was, however a decreased positive impact in the impact category of aquatic eutrophication P (see figure 14). This result is due to the reduced avoided production of P fertiliser.

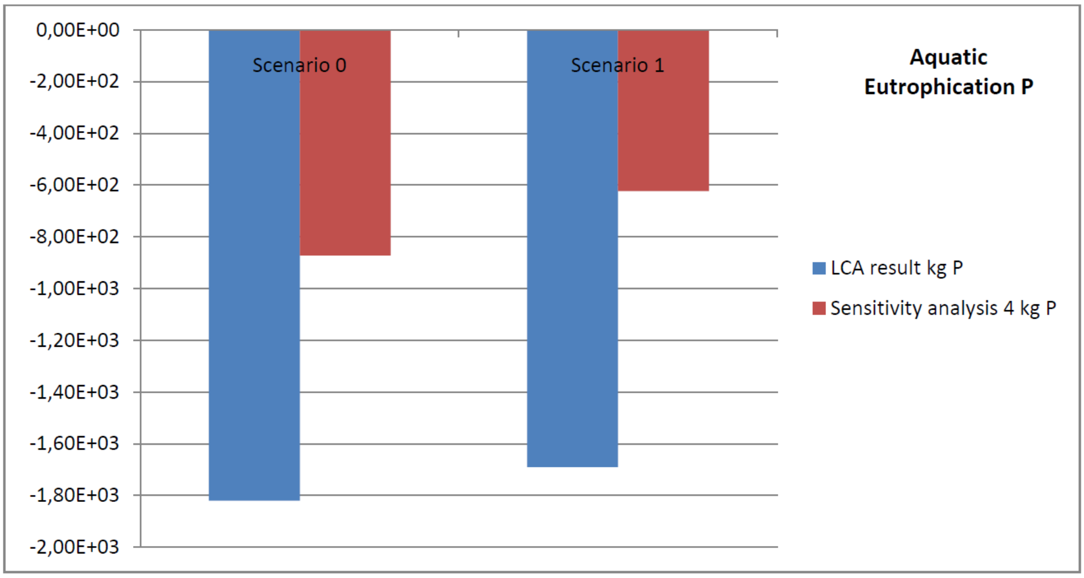


Figure 14. Aquatic Eutrophication P measured in kg P, assuming only 50% of P leads to avoided miner fertiliser production.

5.4.1.5 Summary

In general, the assumptions tested in the sensitivity analysis did not significantly impact the results of the LCA. However, the assumption of the lower value of biogas extraction from household food waste proved to be an assumption that greatly influenced the result. When the upper value for biogas production was chosen, the result of the LCA was that the biogas scenarios were preferable to the incineration scenarios.

One important observation that can be made in relation to the assumptions that were made in this LCA, is that more assumptions were made in relation to the biogas scenario than were made in relation to the incineration scenario. The main reason for this is that the biogas plant depicted in this LCA is fictitious, while the incineration plant is already in place and operating. This allowed specific data to be collected to describe the incineration process, while the biogas process could only be described through an investigation of the average Danish biogas technology and the best practice technology.

The question that this LCA sought to answer was:

How can a life cycle impact assessment lead to a decrease in the environmental impacts of household food waste management in the municipality of the City of Aalborg?

The results of the LCA show that the anaerobic digestion of household food waste, with the technologies and limitations assumed in this study, would not decrease the environmental impact that results from the incineration of the waste. However, the sensitivity analysis shows that if the best case technologies for the biogas scenario are assumed, then anaerobic digestion may in fact be preferable to incineration, particularly from a global warming point of view.

This finding is significant for this report, as it shows that LCA can in practice be used to assess the environmental impacts of different waste recovery operations. If the waste hierarchy is to be followed in Aalborg Kommune without the application of LCA as an assessment tool, then incineration would always be the chosen technology as it is the technology that is encouraged by the national waste strategy, despite the environmental benefits of alternatives.

The LCA that is presented here is simple in that it only compares two different technologies; anaerobic digestion and incineration. If the assessment were to be expanded to include other alternatives, it is possible that the environmental impacts of household waste management could be reduced even further.

The conclusion is therefore that LCA, as a tool for environmental assessment, is an important tool for municipalities in the process of creating waste management plans and strategies. By conducting a consequential LCA, alternative scenarios can be identified that lead to reduced environmental impacts from waste management, as well as reduced environmental impacts from related industries due to an integrated waste management approach.

6. Discussion

This report aimed to investigate the use of LCA as a tool in waste management planning at a municipal level. It was applied to the case of household food waste in Aalborg Kommune, Denmark to assess the environmental impacts of incineration compared to anaerobic digestion as an alternative energy recovery operation. Therefore this discussion can be split into two parts:

- *A discussion of the LCA that was conducted in this report; and*
- *A discussion of the use of LCA on a municipal level for waste management planning.*

6.1 Incineration versus Anaerobic Digestion in Aalborg Kommune

6.1.1 An Unexpected Result

Before the LCA was conducted, it was hypothesised that an anaerobic digestion scenario for household food waste would prove to give better environmental outcomes than the current incineration scenario, particularly in relation to global warming impacts. This prediction was based on a literature study and other similar LCA studies comparing incineration and anaerobic digestion which generally show an environmental benefit for anaerobic digestion. There are several possible explanations for this unexpected result.

Firstly, other LCA studies that compare incineration and anaerobic digestion usually assume that the anaerobic digestion plant does not already exist. In the incineration scenarios of these LCAs the manure stream is not utilised for energy, and is instead placed directly onto land where methane is then directly released to the atmosphere and contributes to global warming (Prapaspongsa et al., 2010). In this LCA the goal was to assess the environmental impacts of the household food waste alone, and therefore it was assumed that the anaerobic digestion plant already existed and was being fuelled with pig manure. While the combustion of the biogas is also a process which contributes to global warming, the product of combustion, carbon dioxide, has a much lower global warming impact than methane (GWP_{100} of CO_2 = 1, GWP_{100} of CH_4 = 21). It is therefore reasonable to conclude that this difference would lead to a result which shows a decreased environmental benefit from anaerobic digestion in this LCA compared to previous LCA studies.

Secondly, the case of Aalborg Kommune is a special one, in that the incineration plant is one of the most efficient incineration plants in Europe, with an efficiency of between 96% and 97% (Green account 2009). This efficiency is higher than the most efficient biogas turbines, which generally have an efficiency of between 80% and 90%. Also, the Reno-Nord incineration facility is quite unique in that none of the ash and slag is landfilled. Most of the ashes are used to replace gravel in road construction, while the remainder is solidified in cement and used to fill-in and stabilise old salt mines in Germany. The result is that the incineration of waste at the Reno-Nord facility in Aalborg leads to more positive environmental impacts than the incineration of waste at the average Danish waste incineration plant.

Thirdly, some discrepancies were detected in the results in connection with the unit process "Disposal food waste, to anaerobic digestion" which indicate that this process does not represent the reality of the situation. This could be due to a mistake in data entry that was not detected, or could be due to a difference in the way the different Ecoinvent processes for the anaerobic digestion of organic waste and manure were constructed. With more time and more detailed knowledge of the Ecoinvent databases, this problem would have been investigated further.

6.1.2 Technological and Planning Alternatives

Due to time restraints there were many technological alternatives that could not be investigated within this LCA study, but which are recommended to be included in a more comprehensive LCA. The following section outlines some of the technological alternatives that were not covered in this study.

Non-biogas options

Other than mixed municipal waste incineration and anaerobic digestion, several other technologies are also possible for household food waste. These include drying the waste before incineration to achieve a fuel that has a higher burn efficiency, home composting and centralised composting. However, after investigating the results of other LCA studies which investigated these options, it was decided that the potential for environmental benefits that can be gained through anaerobic digestion is greater than the potential for these other technologies. For this reason it was decided to focus on anaerobic digestion as an alternative technology to mixed municipal waste incineration. However, as this LCA has shown, the results of an LCA study differ according to the way in which the scenarios are constructed and the specific circumstances of each case (see chapter 6.1.1). Therefore it is recommended that future LCA studies include as many alternative technologies as is possible given the time and resource constraints.

Sharing heat with neighbouring cities

This LCA study assumed that all the energy that is produced in the municipality of Aalborg is used within the metropolitan area of Aalborg-Nørresundby, which is the largest city in the municipality. However, further benefits could be gained if the biogas plant was placed near to another city which could utilise all the energy produced by the plant. This would have a benefit for the city in which the biogas plant is situated as it would replace fossil fuels that are currently used to produce heat. A potential benefit could also be seen in the city of Aalborg-Nørresundby as energy input (in the form of food waste) would be diverted away from the incineration plant, meaning that the other heat producers would be able to sell more of their excess heat to the grid, giving both an environmental benefit and an economic benefit.

Another technology that could be investigated for sharing heat between different cities is the possibility of connecting the Aalborg district heating system with smaller district heating systems through underground pipes. Current pipe insulation technologies already allow for heat to be transported over long distances with minimum energy losses. At the city of Kolding in southern Denmark, a 12.5 km transmission pipe carries heat from the city to a small town called Lunderskov, which if not for the pipeline would need to rely on fossil fuels as a heating supply (Energy Map, 2010). Connecting the Aalborg district heating network to small towns surrounding the city would help to alleviate the problem of excess heat from Aalborg Portland and Nordjyllandsværket going unutilised in the summer months and could result in both environmental and economic benefits.

Expanding the biogas scenario to give new opportunities

As the amount of biogas that is produced increases, more technological options for the use of the biogas become economically feasible. One of these technologies is a plant to ‘upgrade’ the biogas. Biogas is a mixture of mostly methane and carbon dioxide, but also contains contaminants such as water, particles and hydrogen sulphide. A biogas upgrading process will remove these contaminants as well as raising the calorific value of the gas by removing carbon dioxide (Bekkering, Broekhuis & Gemert, 2010).

Gas that has been upgraded can then have many uses. In Germany and Sweden, upgraded biogas is added to the natural gas network, where it is supplied to homes and businesses for heating and cooking purposes. Another alternative is to compress the upgraded biogas for use in transport. In the city of Malmö, Sweden, biogas from household food waste is utilised to fuel the city’s fleet of busses (Malmö Stad, 2010).

The Reno-Nord facility is jointly owned by five Danish municipalities and currently accepts waste from all of these municipalities. It could therefore be possible to create a biogas plant that accepts food waste from all of these municipalities. Aalborg Kommune has in the past examined the possibility of collecting household food waste separately for anaerobic digestion together with manure. The result of the study was that it would lead to an environmental benefit, particularly in relation to global warming, but that the cost would be too high (Jørgensen, 2003). Perhaps an expansion of the system to include a larger waste stream would be more economically feasible. Also, it is important to note here that the removal of the household food waste from the municipal solid waste mixture does not significantly affect the performance of the incineration plant (personal correspondence with Thomas Lyngholm of Reno-Nord).

6.2 LCA as a Tool for Municipal Waste Management Planning

Both the EU and Danish legislation recommend the application of life cycle thinking (LCT) during the planning of waste management strategies. The EU regulation states that the waste hierarchy should be followed, unless LCT shows that a deviation from the hierarchy would lead to more positive environmental outcomes, while the Danish legislation states that municipalities should meet increasing waste production by increasing capacity for incineration unless LCT shows that an alternative strategy/technology can deliver better environmental outcomes (see chapters 3.3 and 3.4). It is therefore reasonable to assume that LCA is a tool that municipalities should be aware of and capable of using.

The LCA performed in this study showed that from a household food waste perspective there is no environmental benefit to anaerobic digestion over incineration. However, from a pig manure perspective anaerobic digestion does deliver significant environmental benefits and the incorporation of an organic waste stream such as food waste improves the economic efficiency of biogas production. The results of this LCA can therefore be interpreted to support the argument that LCA can, and should, be used to assess and plan integrated waste management strategies. As an example, the LCA study presented in this report could be expanded to investigate other organic waste streams which could give more desirable results than the household food waste stream such as waste from food production, the service industry and agricultural silage.

> "When applying the waste hierarchy… Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking" (European Parliament and The Council, 2008, Article 4, Paragraph 2).

However, LCA is a complicated methodology which relies on the LCA practitioner to make a series of assumptions, each of which can have a significant impact on the result of the LCA study, as was shown in the sensitivity analysis in chapter 5.4.1. These assumptions need to be made over a broad range of topics, and it is not reasonable to assume that the knowledge required to make such assumptions is held by workers in all Danish municipalities. In addition to the knowledge requirements, the conduction of an LCA study also requires the practitioner to become familiar with one of the LCA software packages. While being an invaluable tool in the LCA process, these programmes tend not to be 'user-friendly' and require the practitioner to become familiar with the interface. Therefore it is recommended that municipalities be provided with assistance, either from their national government, or directly from the EU, in how to apply the LCA tool to waste management.

7. Conclusion

This report has shown LCA to be a valuable tool which can help the municipality of the City of Aalborg to plan an integrated waste management strategy that gives preferable environmental outcomes than the strategy suggested by the national waste strategy. The consequential approach to LCA allows municipalities to directly compare the actual environmental impacts of different alternative scenarios and technologies. Through system expansion it also encourages the LCA practitioner to think of waste management as a process that can be integrated with other sectors.

While the waste hierarchy has proven to be a good guide for the planning of waste management strategies, LCA has the ability to tailor that guide to fit the individual situation of each municipality. In this way, the application of LCA methodology in conjunction with the waste hierarchy can help municipalities to identify the waste management technology that will result in the best possible environmental outcome.

However, the LCA process has also proved to be a difficult and demanding process and it is perhaps not reasonable to assume that municipalities are capable of performing a detailed LCA without some form of guidance.

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Appendix A - Parameters for Calculations

Scenario 0

Process/Parameter	Unit	Value	Reference
DB of manure	% of WB	7.74	Wesnæs et al, 2009
VS of manure	% of DB	76	Poulsen et al, 2008
DB of food waste	% of WB	20	Jørgensen, 2003
VS of food waste	%of WB	17.5	Jørgensen, 2003
Biogas yield (household food waste)	m^3 ton^{-1} HFW	110	Jensen & Christensen, 2003
Biogas yield (pig manure)	m^3 ton^{-1} PM	25	Christensen, 2007
Methane content of biogas	%	65	Christensen, 1998; Danish Energy Authority, 2005
Energy content of biogas	kWh m^{-3} biogas	6.5	Christensen, 1998
Efficiency of electricity production in gas engine-generator	%	38	Poulsen & Kuligowski, 2007
Efficiency of heat production in gas engine	%	40	Poulsen & Kuligowski, 2007
Anaerobic digestion plant, electricity consumption	kWh ton^{-1} biomass	6	DEA, 2005
Anaerobic digestion plant, heat consumption	kWh ton^{-1} biomass	34	DEA, 2005

Scenario 1

Process/parameter	Unit	Value	Reference
DB of manure	% of WB	7.74	Wesnæs et al, 2009
VS of manure	% of DB	76	Poulsen et al, 2008
DB of food waste	% of WB	20	Jørgensen, 2003
VS of food waste	%of WB	17.5	Jørgensen, 2003
Biogas yield (pig manure)	m^3 ton^{-1} PM	25	Christensen, 2007
Methane content of biogas	%	65	Christensen, 1998; Danish Energy Authority, 2005
Energy content of biogas	kWh m^{-3} biogas	6.5	Christensen, 1998
Efficiency of electricity production in gas engine-generator	%	38	Poulsen & Kuligowski, 2007
Efficiency of heat production in gas engine	%	40	Poulsen & Kuligowski, 2007
Anaerobic digestion plant, electricity consumption	kWh ton^{-1} biomass	6	DEA, 2005
Anaerobic digestion plant, heat consumption	kWh ton^{-1} biomass	34	DEA, 2005
Energy content of household foodwaste	GJ ton^{-1}	4	Reno-Nord, 2009
Efficiency of electricity production in incineration oven	%	25	Reno-Nord, 2009
Efficiency of heat production in incineration oven	%	71	Reno-Nord, 2009