

November 2002

**Nordtest Project nr. 1537-01**

# **Guidelines for the use of LCA in the waste management sector**



**Linuhönnun**  
consulting engineers



<b>Type of report:</b> Technical report	<b>Nordtest project number:</b> 1537-01
<p><b>Project managers:</b> Helga J. Bjarnadóttir, Linuhonnun Guðmundur B. Friðriksson, Linuhonnun</p> <p><b>Authors:</b> Guðmundur B. Friðriksson, Linuhonnun Tommy Johnsen, DNV Helga J. Bjarnadóttir, Linuhonnun Hege Sletnes, DNV</p> <p><b>Review group:</b> Göran Finnveden, ESG Anna Björklund, ESG Michael Hauschild, IPL</p>	<p><b>Institution:</b> Linuhonnun Consulting Det Norske Veritas (DNV) The Environmental Strategies Research Group (ESRG) at Stockholms University. The Department of Manufacturing Engineering and Management (IPL) at the Technical University of Denmark</p> <p><b>Financed by:</b> Nordtest Linuhonnun Consulting Det Norske Veritas FENUR, Iceland ORIO, Norway</p>
<b>Title (Original):</b> Guidelines for the use of LCA in the waste management sector	
<p><b>Abstract:</b> This report contains guidelines for the application of the life cycle assessment (LCA) methodology in the waste management sector. The guidelines follow the general methodological structure of LCA described in the ISO 14040 series. The focus is on mixed municipal waste and less focus is put on pure material recycling processes. Main focus is put on the most common municipal waste management scenarios in the Nordic countries and the guidelines are supported with case studies in appendices. Research groups and projects, working on LCA in the waste management sector are listed and described in the guidelines and reference is made to further information. The appendices to the guidelines are three and contain real life LCA case studies for waste management in Iceland and Norway.</p>	
<p><b>Key words:</b> LCA, guidelines, municipal waste, waste management, functional unit, system boundaries, inventory, allocation, impact assessment, interpretation, case studies.</p>	
<b>Technical group by Nordtest:</b> Environment and natural resources	
<b>Language:</b> English	<b>Pages:</b> 96 + 86 in appendices

Date: 01.12, 2002

Signature:



Helga Jóhanna Bjarnadóttir, Project manager.

## 1 SUMMARY

This report contains guidelines to the application of life cycle assessment (LCA) in the waste management sector. Focus is put on the most common municipal waste management scenarios in the Nordic countries and the guidelines are supported with case studies in the appendices. In an LCA study the environmental aspects and potential impacts throughout a product's life, from raw material extraction through production, use and disposal are analysed. Provided all upstream and downstream impacts are equal, the life cycle of waste starts when products are disposed of in the trash bin and ends when the waste material is degraded or brought back to the technological system through recycling and replaces other products. LCA in the waste management sector can be applied in order to compare the environmental performance of alternative waste treatment systems and identify focus areas for system performance improvement. It can also help to improve product development, e.g. eco-design, environmental labelling and declarations and introduce regulations that promote better alternatives.

The guidelines follow the general methodological structure of LCA described in the ISO 14040 series. Prioritised issues are system boundaries, inventory data, allocation and impact assessment. The focus is on mixed municipal waste and less focus is put on pure material recycling processes.

How to define the functional unit in an LCA for waste management and what life cycle stages should be taken into consideration when defining the system boundaries of a study are defined. Cut-off criteria that are common to use to limit life cycle systems both within a defined system and also with respect to start and end of the waste life cycle are listed and discussed. Guidelines to questions such as how far do we follow products from recycling, how far do we follow products replaced by products from recycling and how long do we take into account emission and resource consumption related to a landfill are provided.

If an LCA study involves specific waste treatment processes, attempts should be made to collect and apply data that are as specific as possible for the process in question. In the case of more generic studies, such as e.g. a basis for political decisions, generic data should be applied. In the guidelines, parameters and to a certain extent, data that are commonly applied in inventory of LCA for waste management are presented. The treatment alternatives: Incineration, landfilling, aerobic composting, anaerobic digestion and biocell are discussed separately. Inventory data of interest related to these treatment alternatives are listed. Typical process flow charts are drawn and critical issues related to emission and resource consumption are discussed and guidelines given. If energy is recovered from incineration plants or when incinerating collected landfill gas or biogas, energy sources in other systems are substituted with the recovered energy. Steps that should be followed when identifying substituted energy sources, are listed and guidelines given on how to credit the waste management system by avoided impact of the energy source substituted. Anaerobic digestion and aerobic composting produce products that can be used as fertilisers. The products can replace artificial fertiliser, although there are great uncertainties related to what extent the artificial fertilisers are replaced. Guidelines are given for calculations on how much artificial fertiliser is substituted, avoided impact related to production of artificial fertiliser and data for pollutants in sludge and compost. Problems related to allocation in LCA

for waste management (i.e. in multi input recycling and open loop recycling) are discussed and guidelines given.

The general methodology on how to perform quantitative life cycle impact assessment is described in numerous methodology reports. Hence it is not described in any details in this report. LCA applied for municipal waste management usually includes the same environmental impacts as LCA studies in general. Based on the Danish UMIP study and the Nordic Guidelines on Life-Cycle Assessment applicable impact categories are listed. The toxicity impact category is an important category for LCA applied in the waste management sector but needs further development within that sector /5/. Characterisation models for the toxicity impact category are listed and recommendations made in the guidelines. Normalisation and weighting are optional elements in the life cycle impact assessment. Many weighting methods exist, but no methods have been identified that are particularly developed for application in the waste management sector. The newest and most commonly used weighting methods applied in the Nordic countries are listed in the guidelines. It is emphasised that weighting is a controversial issue and there is no consensus within the Nordic countries or other international forums on recommended weighting methods.

The interpretation phase of an LCA requires an analysis of the results of the LCA, conclusions and recommendations according to the ISO standard. In the guidelines questions are listed related to the waste management sector, to assist fulfilling these requirements.

Several groups are working on LCA in the waste management sector, developing new models and performing LCA studies. Some of these groups and projects are listed and described in the report and references given for where to seek further information. Findings of LCA in the waste management sector are discussed. The results of these studies can however, in most cases, not be generalised as results of LCA studies are site dependent and depend on assumptions and choices made. The discussion however provides ideas about what kind of conclusions can be drawn from LCA studies in the waste management sector.

In appendices to the guidelines are case studies of LCA for waste management in Iceland and Norway. Appendix 1 contains a comparative LCA screening study for waste management in Reykjavik, Iceland, where landfilling with gas collection, composting in containers and waste treatment in biocell were compared. Appendix 2 contains a descriptive LCA case study for waste management in South Iceland where the land is sparsely inhabited. In appendix 3 are summaries of three Norwegian LCA case studies for municipal waste and sludge treatment.

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**THE GUIDELINES INCLUDE THE FOLLOWING APPENDICES AS SEPARATE REPORTS:**

**APPENDIX 1** Icelandic comparative case study – landfill, biocell, compost.

**APPENDIX 2** Icelandic descriptive case study – landfill without gas collection.

**APPENDIX 3** Summary of Norwegian case studies.

## **2 INTRODUCTION**

### **2.1 Background**

Solid waste management is currently the subject of many debates in the Nordic countries. This debate is driven by consumer and legislative pressure. Legislators have been active in establishing a legislative framework aiming to exploit the inherent resources (energy and materials) in waste.

European Community (EC) directives and documents such as the Packaging and Packing Waste directive, the Landfill directive, Incineration directive and working document on the Treatment of Biowaste, all have in common the waste management hierarchy. That is waste minimisation at source, reuse, recycling, incineration with energy recovery and landfill and limitation of environmental impacts of the waste treatment alternatives. To demonstrate the performance of management alternatives in the decision-making process, authorities, communities, industry and waste management companies should use environmental assessments in addition to the evaluation of technical and economical aspects.

The application of life cycle assessment (LCA) to products and services has become a useful tool in decision-making processes and system performance documentation. The interest of using LCA in the waste management sector is increasing. In the Nordic countries several projects have been performed that gives methodological solutions on how to apply LCA to waste treatment practices. This is briefly documented in the Nordtest state-of-the-art report on LCA in the waste management sector /5/. However, the report also highlights the need for a consensus in the Nordic countries on a range of important issues. Although the LCA methodology is standardised through the ISO 14040 series /1/-/4/, there are several issues that make LCA in the waste management sector complicated. In order for LCA to assist in decision-making, it is important that the challenging issues are solved within a common framework. A guideline on LCA in the waste management sector will contribute to guide LCA practitioners in such a way that important topics are taken into account.

This guideline document has been developed by Linuhonnun Consulting Engineers (Iceland) and Det Norske Veritas (Norway). The project team was composed of Helga J. Bjarnadóttir (LH), Guðmundur B. Friðriksson (LH), Tommy Johnsen (DNV) and Hege Sletnes (DNV).

The project was financed by Nordtest, Linuhonnun Consulting Engineers, Det Norske Veritas, Orio (Norway) and Fenur (Iceland). In order to incorporate expertise from other Nordic countries and in order to spread the results, it was decided to include in the project an independent critical review group. Specialists from Sweden, Finland and Denmark were contacted and active members of the critical group were Göran Finnveden and Anna Björklund, (ESRG at Stockholms University, Sweden) and Michael Hauschild (IPL at the Technical University of Denmark). They gave valuable comments on both the guidelines and the appendixes.

## 2.2 Objective

The objective of the project is to develop a guideline that can help decision-makers in the municipal waste management sector to perform LCAs and use the results in the decision-making process. The geographical scope is the Nordic countries.

It must however be noted that the data given on waste composition in this report must be regarded as a snap-shot at a given time in any Nordic country. In the mean time the waste management policy might have changed and subsequently waste composition. Therefore, given data should be regarded more as a guide on format and potential references rather than the numbers themselves.

## 2.3 Scope

As a basis this study refers to the ISO 14040 series, relevant studies identified in the state-of-art report /5/ and other studies that are relevant in an LCA in a waste management perspective. LCAs applied to Nordic waste management scenarios will be used to make examples practical. The following main tasks will be performed and reported:

- Short introduction to the general LCA methodology and applications.
- A literature survey will be made as an updated complementary input to the identification of relevant studies in the Nordtest state-of-the-art report.
- A guideline will be written focusing on how to carry out the most critical parts of an LCA study for the most common waste management scenarios, including examples from case studies.
- Examples will be established based on case studies carried out before and during (Icelandic case study) the project period. In addition to be used as practical examples, the case studies also has the purpose to build and transfer LCA competence to Iceland, where no such studies have been performed to date in the waste management sector.

The following limitations are valid for the study:

- Experience will mainly be drawn from Nordic studies. Studies from countries outside Scandinavia will only be mentioned for reference purposes. This is due to both time restrictions and because applied technology is regarded to be on similar levels.
- This guideline document is written for studies with the objective to identify and assess the environmental key issues of the treatment processes of municipal waste from the waste collection system and to the point where the waste ceases to exist through decomposing at landfills, composting or bio-reactor plants, incineration or recycling into a new product system. However, many of the recommendations can be transferred to other waste streams as well. In any case, one should be careful to apply data from the guideline directly without first checking the relevance for the specific waste stream and treatment technology under study. Product specific LCAs and related waste streams will not be treated.
- The application of LCA to municipal waste streams will be limited to a given amount of mixed waste. This means that the functional unit is given as weight (ton) or volume (m<sup>3</sup>) waste, and that the pre-disposal life cycle stages of the products generating the waste is not included. Further, this means that product



design, production efficiency and degree of consumption will not influence the results.

- Work environment is not treated as impacts in the study.
- Only the operational stage of the life cycle of waste treatment plants is considered. Construction and the end of life stages are not included.

## **2.4 Use of the guideline**

The guidelines might be used as a guide when performing an LCA or as a checklist/baseline when validating an LCA. It should be used in combination with more general LCA guidelines or standards such as the ISO 14040 series in combination with recent general methodological development documents.

The guideline will provide assistance in the following:

- It will give a brief introduction to managers in the waste management sector on what LCA is and how it can be applied to the benefit of the decision-making process.
- It will work as a checklist for LCA practitioners on the most central issues of LCA in the waste management sector.
- Provides baseline data and information for critical review or validation purposes.

The guideline does not address the planning stage of an LCA as this is properly treated in more general guidelines and standards.

### 3 LIFE CYCLE ASSESSMENT AND APPLICATIONS

#### 3.1 The concept of life cycle assessment

Generally, life cycle assessment (LCA) can be defined as a method that studies the environmental aspects and potential impacts of a product or system from raw material extraction through production, use and disposal. The general categories of environmental impacts to be considered include resource use, human health and ecological consequences.

The result of an LCA is an environmental profile that expresses the performance of the total system life cycle and single life cycle stages. It has become a recognised tool in decision-making within industry and public administration. As a consequence, several international, national, industry branch and company specific LCA databases are established to provide data efficiently. Data on waste treatment processes still tend to be missing or are of low quality. However, the situation is improving due to projects carried out among other in the Nordic countries that latest 2-4 years. Figure 3-1 shows a general life cycle system.

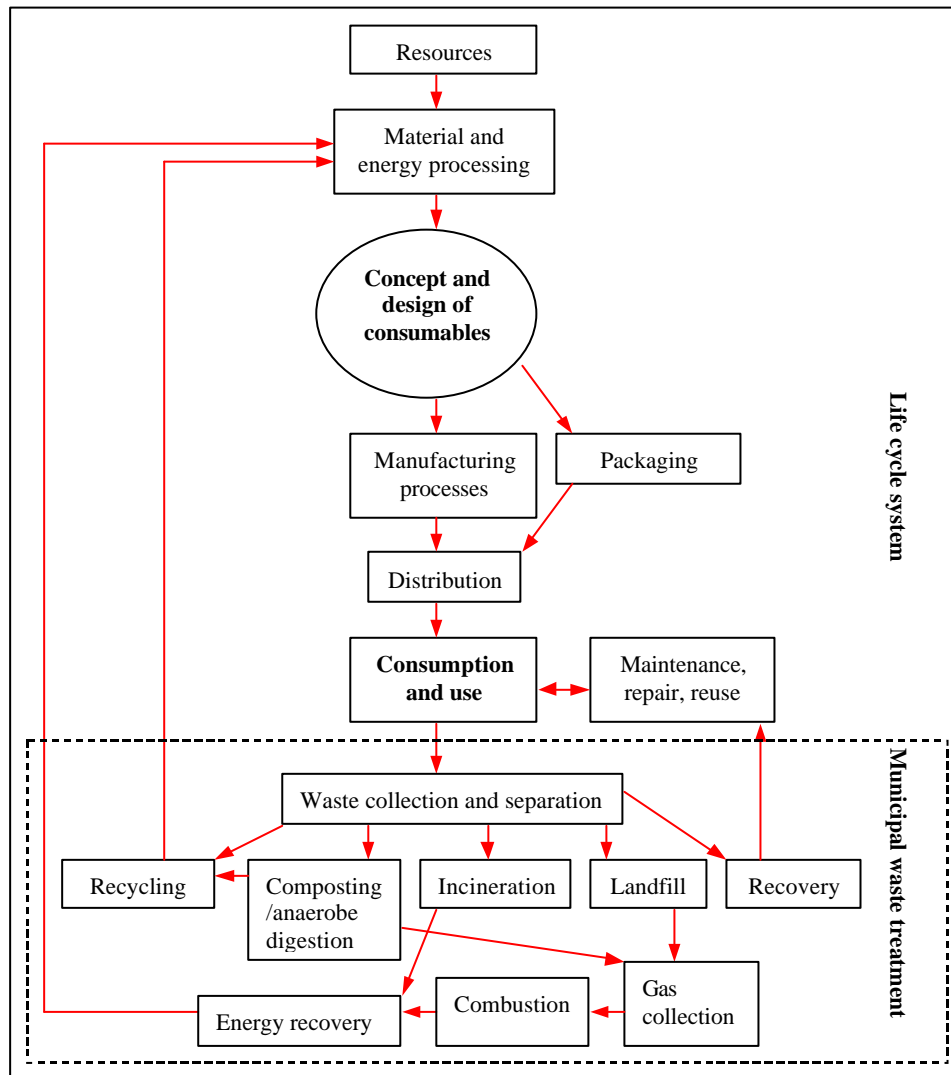
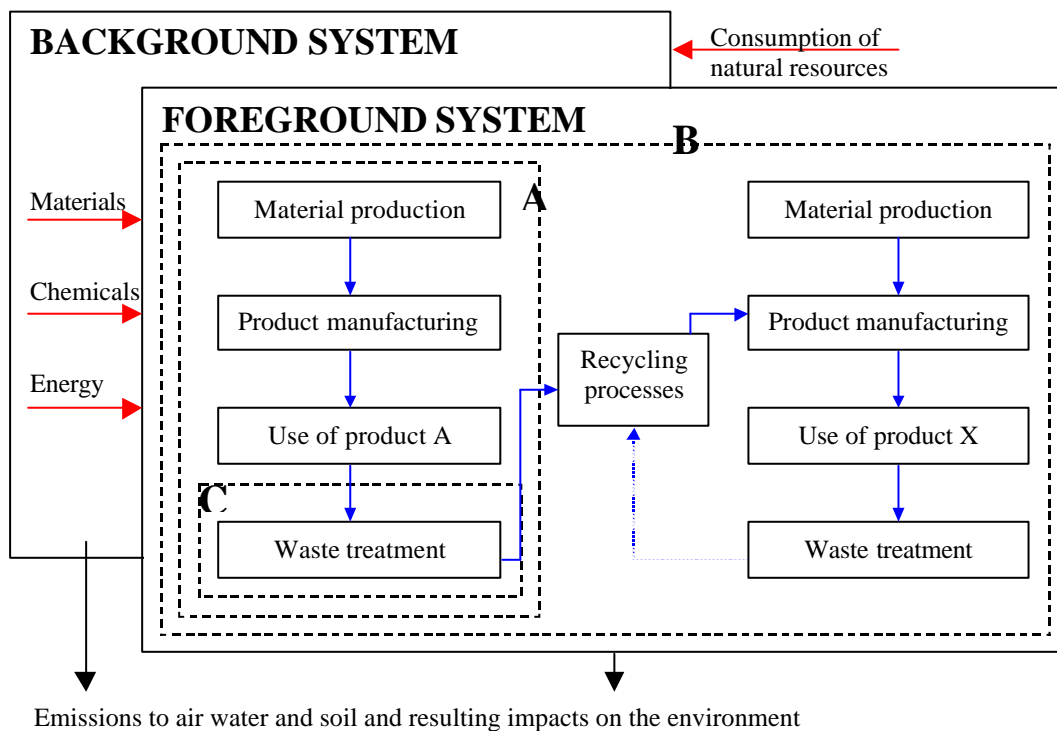


Figure 3-1 Schematic system life cycle

As can be seen from Figure 3-1, the environmental impacts of the municipal waste system depend on three different system characteristics:

1. **The concept and design of the products** that end up as waste have influence on the type and amount of material that the products consist of, life-time of the products, to what degree the products are recyclable and non-hazardous, and to what degree they can be dismantled into recyclable fractions.
2. **Consumption patterns** influence the municipal waste flow because it is the consumers who buy the consumables that flow through the system and who partly decides the lifetime of the consumables.
3. **The municipal waste treatment** decides to what extent waste shall be distributed between the treatment alternatives and the technology and efficiency of the treatment options.

LCA that focuses on waste gives different system boundaries depending on the goal and scope of the study. Figure 3-2 shows examples of three different levels of system boundaries. The foreground system illustrates the main processes to be analysed, while the background system is other processes that are influenced by the foreground processes.



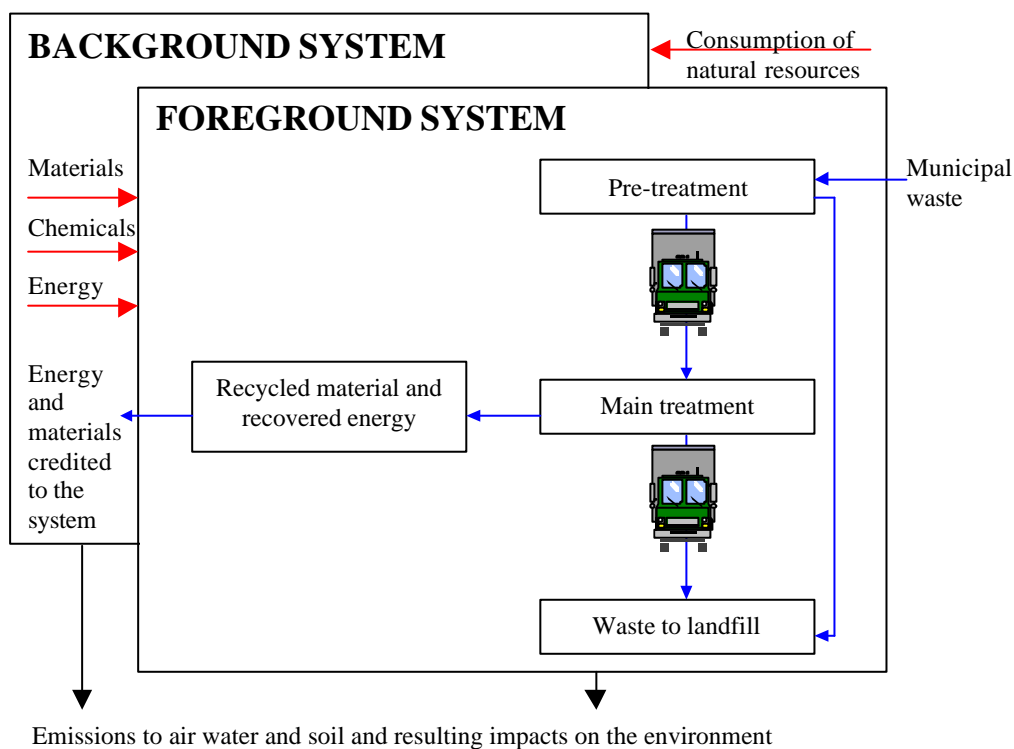
**Figure 3-2 Different system boundaries for LCA**

For the following description, note that:

1. System within the dotted line marked A is referred to as alternative A.
2. System within the dotted line marked B is referred to as alternative B.
3. System within the dotted line marked C is referred to as alternative C.

Alternative A shows system boundaries for an LCA of product A. The waste treatment after product use is included within the system boundaries as this life cycle stage will itself require energy and materials and cause impacts on the environment. Traditionally, several studies have located the waste treatment outside the system boundaries (A minus C) reporting only the amount of waste leaving the system boundaries (and in some cases type of treatment). In case of recycling of waste, system boundaries can be extended as shown in alternative B. In LCAs evaluating waste treatment options, the system boundaries can be set where the waste is introduced into the system (alternative C). This is however only possible when it is presumed that all preceding processes are the same for all options, or that they do not influence on the waste composition.

The third point following Figure 3-1 and alternative C related to Figure 3-2 expresses the same system –the municipal waste treatment system- and are the focus of this document. The life cycle of waste starts when products are thrown in the trash bin and ends when the waste material is disposed and degraded and/or is brought back to the technological system through recycling and energy recovery. A coarse generic illustration of such a system is given in Figure3-3.



**Figure 3-3 System boundaries for waste treatment options**

### 3.2 Life cycle phases and work process

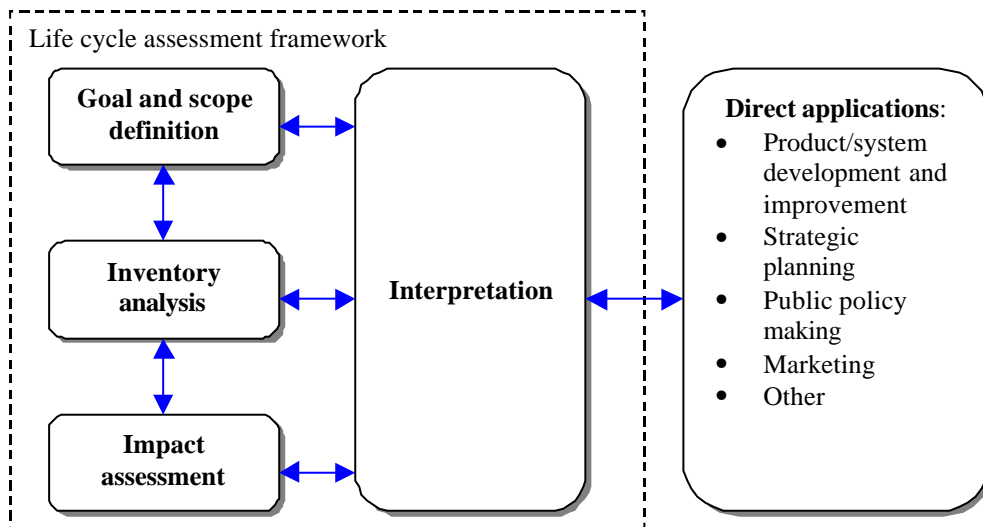
The general methodological structure of LCA, which is used as basis in this guideline, follows the ISO 14040 series:

- ISO 14040:1997 – Principles and framework

- ISO 14041:1998 – Goal and scope definition and inventory analysis
- ISO 14042: 2000 – Life cycle impact assessment
- ISO 14043: 2000 – Life cycle interpretation

The names of the ISO publications more or less reflect the main phases of an LCA. The phases are given below and illustrated in Figure 3-4.

- **Goal and scope definition**, where the goal and scope of the study are defined.
- **Inventory analysis**, which involves compilation and quantification of inputs and outputs, for a given life cycle system.
- **Impact assessment**, which aims at understanding and evaluating the magnitude and significance of the potential environmental impacts of a life cycle system.
- **Interpretation**, in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the goal and scope in order to reach conclusions and recommendations.



**Figure 3-4 Phases of an LCA**

An LCA study does not always need to use impact assessment. In many cases inventory data alone are sufficient for an evaluation. The term LCI (life cycle inventory) is used to indicate that a study has excluded the impact assessment phase.

It is beneficial to perform the LCA in at least two iterative steps. The first time one goes through the LCA phases. First, a key issue identification should be carried out. A rather broad system should be defined and rough data can be used. Dependent on the outcome of a sensitivity and uncertainty assessment, a more detailed study should be performed with revised system boundaries and focus on high quality data going through all the phases again this time with specific focus on the points identified during the first iteration.

It is referred to the ISO 14040 series documents for further general details about the contents of each life cycle phase. For details related to assessment of municipal waste is referred to chapter 3 in this document.

### **3.3 Applications**

LCA results may be useful inputs to a variety of decision making processes. Life cycle assessment in a waste management perspective is specifically targeted towards:

1. Identification of the most environmentally significant processes during the waste treatment chain.
2. Identification of the most significant environmental burdens during a waste management scenario.
3. Identification whether improvement proposals result in local optimisation (shift of environmental burdens to other sites), or if they are environmentally for the better for the whole waste management system.
4. Assessment of the environmental performance of a waste management scenario in a life cycle perspective. Assessment of several scenarios can be used to compare the performance of alternative systems or with defined criteria.

Applications of LCA are presented in the following.

#### **Strategic planning and decisions**

LCA can be applied to compare the environmental performance of alternative systems that shall fulfil a specific service function. This can be e.g. industrial production systems, transport systems or municipal waste treatment systems. The later application example will be the focus of this guideline.

LCA can help organisations responsible for municipal waste flows, or suppliers of waste treatment systems, to understand the pros and cons of their own systems, and it can identify focus areas for system performance improvement, data quality improvement and reporting.

#### **Product development**

LCA ensures that the whole product life cycle is taken into account. This means that an overall product environmental performance improvement can be achieved. By combining LCA with product quality assessment, improved environmental performance can be achieved without compromising the overall quality of the product. A life cycle approach lies inherently in the eco-design concept. Eco-design is promoted through several large industry corporations, designer organisations and through the New Approach legislation in EU (product focus) such as the *Directive on Electrical and Electronic Equipment (EEE)* which is under preparation. Regarding waste management, eco-design principles adopt goals such as:

- Design for cleaner production, including less production waste.
- Design for durability.
- Design for longevity.

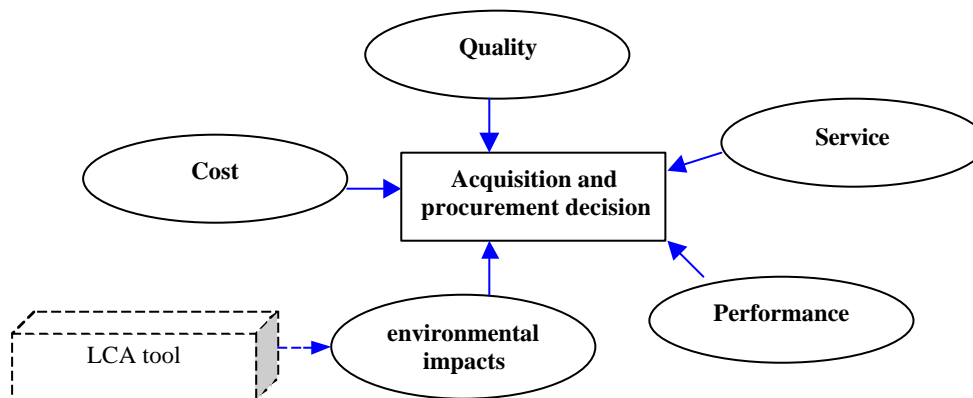
- Design for reuse and recycling (simple disassembly, reduced material complexity, use of recyclable materials, component recovery through closed loop re-manufacturing and secondary application).

The eco-design concept is well documented and guidelines exist both general and for specific product groups (see. e.g. the new publication *Sustainable Solutions. Developing Products and Services for the Future /62/*). ISO has its own Work Group TC 207/WG 3 named *Integrating environmental aspects into product development (DFE)*.

### **Acquisition and procurement**

Traditionally, acquisition and procurement processes balance the functional performance of products against factors such as cost, quality and service. LCA can play an important and synergistic role with existing processes. LCA will identify alternatives that provide decreased environmental burdens. This is particularly relevant for large consumers such as large companies, public administration and development projects.

In a waste management perspective, LCA will identify products with low degree of waste generation through their life cycle.



**Figure 3-5 Acquisition and procurement decision strategy**

### **Product environmental labelling and declaration**

Product environmental labelling and declarations have the goal to:

- Stimulate changes in consumer behaviour that will ultimately lead to meaningful and measurable improvement in the environmental aspects of consumer products.
- Communicate accurate, verifiable, and non-deceptive environmental information to consumers to help them make product choices.
- Educate consumers about the environmental aspects of products.

LCA of products can in this context be used to:

- Give background information that enables the labelling program to set labelling criteria which ensure that labelled products can be called “environmentally preferred” in a meaningful way. Input to Type I environmental labelling (see ISO 14024).
- For specific environmental claims, ensure that the attribute to be communicated is environmentally relevant in the context of the product’s life cycle. Input to Type II environmental labelling (see ISO 14021).
- For product information programs, ensure that meaningful and environmentally relevant information about the life cycle is provided to the consumer. Input to Type III environmental labelling (see ISO 14025).

E.g. the EU eco-label award scheme and the Swedish and Norwegian environmental product declaration programs require LCA.

### **Policy and regulations**

LCA can be used in pilot applications that primarily involve assessing technological alternatives for research development and for rulemaking.

E.g. can LCA, in a waste management perspective, be used to assess the environmental burdens of waste treatment alternatives and, combined with findings from other studies, introduce research programs, regulations and/or incentives that promote the better alternatives.



## 4 GUIDELINE FOR LCA APPLIED FOR RESIDUAL MUNICIPAL WASTE AND SLUDGE TREATMENT ALTERNATIVES

### 4.1 Prioritised topics for the guideline

In the Nordtest document on status of LCA in the waste management sector, prioritised research and development areas are identified /5/. These areas are also prioritised issues in this guideline. The prioritised issues are:

- System boundaries: Limitations of the system to be studied.
- Allocation: Substitution of energy and material by recycling and recovery.
- Inventory data: Emissions from landfill, incineration and biological treatment; emissions from compost and sludge used in agriculture; how to take into account long term emissions.
- Impact assessment: Identification of impact categories of particular interest for waste management studies; characterisation factors for toxicological impacts.

The SETAC-Europe LCA Working Group “Data Availability and Data Quality”, subgroup “Energy, Transport and Waste Models” has finalised a report with recommendations and references concerning waste (and energy/transport) /18/. The report identifies waste incineration, landfill, composting/digesting and recycling as the main waste treatment processes.

In this guideline the focus is on mixed municipal waste. Less focus is put on pure material recycling processes, e.g. for paper, plastics, glass and metals. Although, treatment of biowaste is included because the treatment alternatives for this fraction are not as established. Prioritised processes are incineration, landfill and composting/digestion.

### 4.2 Function and functional unit

Definition of the functional unit is a part of the *Goal and Scope phase* of the LCA methodology. The primary purpose of the *functional unit* is to provide a reference to which the input and output data are normalised (in a mathematical sense). Therefore the functional unit shall be clearly defined.

Having defined the functional unit, the amount of product necessary to fulfil the function unit must be quantified. The result of this quantification is *the reference flow*.

Comparison between systems shall be made on the basis of the same functional unit, and the functional unit should to the extent possible reflect all functions of the product. If two different waste treatment systems are being compared the functional unit should be *ton waste of a specified composition*.

The calculation could be made based on the average annual amount of waste treated. This period of time reflects all activities that cause environmental impacts, including non-continuous activities like maintenance. A longer period can be selected if activities that are important in an environmental perspective occur less frequently than once per year (e.g. accidents).

The reference flow will be the amount of waste treated over the defined period of time.

The environmental impacts caused during the defined period of time is then normalised by the reference flow. The result will then be environmental impacts per ton waste.

The functional unit should also reflect waste quality by defining the waste composition that the study is relevant for.

Summarised, the functional unit for municipal waste should then take into account:

- The period of time to which the environmental impacts and waste generation should be related. Note that this is *not* the same as the time perspective of the emissions (which can be centuries after the treatment) and the resulting impacts (which can be centuries after the emissions' occurrence).
- Amount of waste generated
- Composition of waste. One cannot compare treatment alternatives if the composition of waste that enters the system boundaries is significantly different.

An example of application of a functional unit for municipal waste can be (random numbers is used).

- 35 000 ton/year mixed municipal waste is treated.
- Composition is specified.
- 3 years are the period of time where all planned non-continuous activities are included. The resulting reference waste flow is 105 000 ton waste.
- Emissions and resource consumption are estimated for the reference flow based on quantification models.
- Environmental impacts are quantified and divided (normalised) by 105 000 ton, and all results are presented per ton waste.
- The results are valid for the specified waste composition and time horizon.

## **4.3 System boundaries**

### **4.3.1 Unit processes and input and outputs of unit processes**

The system boundaries define the *unit processes and input and outputs of unit processes to be included* in the system to be modelled.

This guideline is limited to LCA studies where the products generating municipal waste are fixed with respect to design, materials, mass/volume and consumption. With these limitations, life cycle stages and unit processes that should be taken into consideration are listed in Table 4-1. The table also gives comments and recommendations related to each issue.

**Table 4-1 Life cycle stages and unit processes to be taken into consideration**

Life cycle stage/unit process	Comments/recommendations valid for studies on the full function of a waste treatment system or process.
Household and/or industry distribution of waste on reception facilities	Waste bins where the waste has different destinations and/or treatment. Can be excluded from the system if common for all treatment alternatives under study.
Collection and transportation	Processes for transporting waste to treatment facilities, waste treatment products to final consumption should be included. As transport processes usually give small contributions to the total life cycle impacts, they can be excluded for ancillary materials, if not already included in ready-made cradle-to-gate inventory data for the ancillary materials. Transportation for collection of the waste will normally be important.
Production and use of fuel, electricity and heat	Important to include. See comments in next row.
Manufacture of ancillary materials	Flows are divided into <i>primary flows</i> and <i>secondary flows</i> . The primary flows are the materials that the product is built up from. The secondary flows are auxiliary materials and energy that enables an activity to be performed. Several tiers of auxiliary flows may extend further and further from the main sequence. The analyst should set criteria on how many tiers of auxiliary flows will be included. The criterion is typically set from 0-2 tiers of auxiliary flows. 0 tier means that a material flow is only identified by the input amount and not by the upstream life cycle. 1 tier means that the material flow used in a process unit is included by its upstream life cycle, but the materials used in the upstream life cycle flow is not. It is common to use ready-made cradle-to-gate data for secondary flows (cradle-to-gate is the part of the life cycle including everything from resource extraction to ready-made product, but not use and disposal). The selection of tiers is then not a relevant issue.
Waste treatment processes	Waste treatment systems consist of the degradation system and other processes like pumps, cutting equipment, pre-heating etc. It is important to include both environmental impacts related to the degradation process itself and supporting processes.
Recycling/recovery of materials and/or energy	Important to include. <ol style="list-style-type: none"> <li>1. Energy recovery from incineration.</li> <li>2. Energy recovery of bio-gas from anaerobic digestion.</li> <li>3. Energy recovery of landfill gas.</li> <li>4. Recovery of soil improvement material from composting and anaerobic digestion.</li> <li>5. Recovery of materials from recycling processes.</li> </ol>
Manufacture, maintenance and decommissioning of capital equipment	Usually of little importance. Should only be included on request, or if the capital equipment itself is the product subject to an LCA.
Additional operations such as building lighting and heating	Usually of little importance. Should only be included on request.

It is an iterative process to identify the inputs and outputs from the process units that should be included in the study. The initial selection is typically made using data that can easily be made available. The most significant process units and inputs/outputs to focus upon in a more detailed study should be identified through established *criteria* and *sensitivity analysis*.

Criteria that are common to use to limit life cycle systems are given in Table 4-2 /2/, /11/.

**Table 4-2 Criteria for limiting system**

Type of criteria	Criteria quantification
Cut-off based on <i>mass relevance</i> . I.e. all inputs to a process unit that cumulatively contribute more than a defined percentage to the total mass input are included.	Always cut off the flow with the lowest contribution first, then the second lowest contribution. Continue this process until the defined percentage cut-off criterion is reached. Typical cut-off criteria are 1 - 5%.
Cut-off based on <i>energy relevancæ</i> . I.e. all inputs to a process unit that cumulatively contribute more than a defined percentage to the total energy input are included.	Always cut off the flow with the lowest contribution first, then the second lowest contribution. Continue this process until the defined percentage cut-off criterion is reached. Typical cut-off criteria are 1 - 5%.
If independent expert judgement or quantification of <i>environmental relevance</i> allows for it.	Input and output that contribute more than an additional defined percentage to the estimated quantity of each individual data category are included. Typical cut-off criteria are 1 - 5%. E.g. flows that contribute to less than 5% of the total CO <sub>2</sub> emissions are excluded (if CO <sub>2</sub> is the only selected data category).*

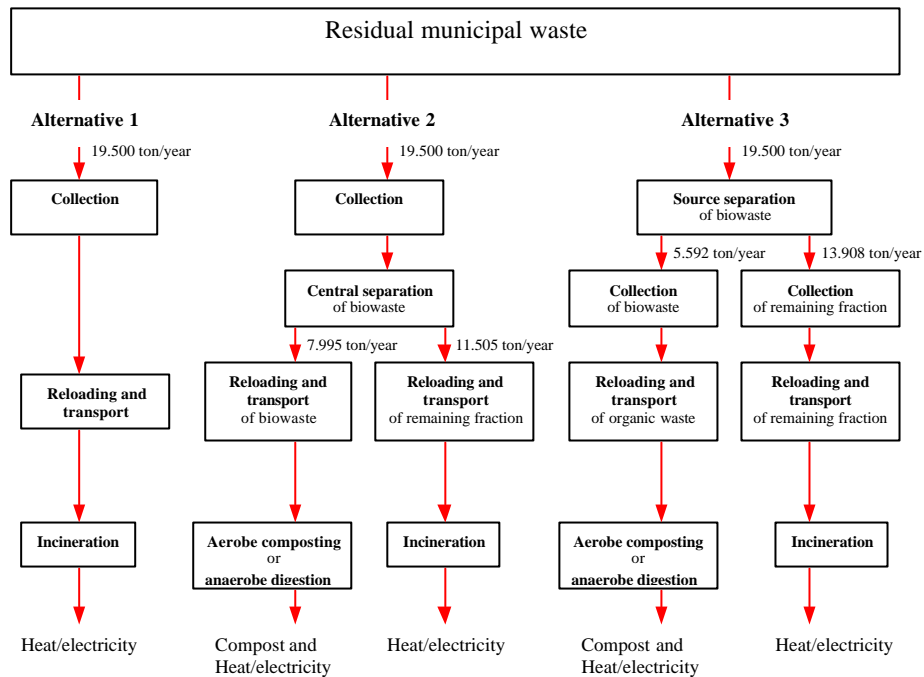
\*For the chemical-related toxicity categories you can not apply a fixed weight or volume-based cut-off criterion since some substances are so potent that even minute quantities can contribute significantly to the overall toxicity impact (e.g. the toxic metals).

As an example of input/output limitations we can use a process unit consisting of a waste treatment process, represented by incineration. Input data are as follows:

- Waste: 750 GJ/yr (96,8%)
- Oil: 20 GJ/yr (2,6%)
- El. power: 5 GJ/yr (0.7%)

With an energy based cut-off criterion of 1 % the el. power input is excluded. With a criterion of 3% only el. power is excluded as the sum of oil and el. power is above 3%. With a cut-off criterion of 5% both oil and el. power are excluded as inputs.

For better understanding of the system under study a flow diagram should be prepared. Figure 4-1 shows an example of a flow diagram for alternatives for treatment of municipal waste from a Norwegian community after source and central separation. Production and use of fuel, electricity and heat and manufacture of ancillary materials are not illustrated even though included in the case study.



**Figure 4-1 Example of a flow diagram**

A description should be related to the flow diagram which explains the activities taking place within each process unit (box in the flow diagram), the type of inputs and outputs of each process unit and the locations at which the activities are taking place.

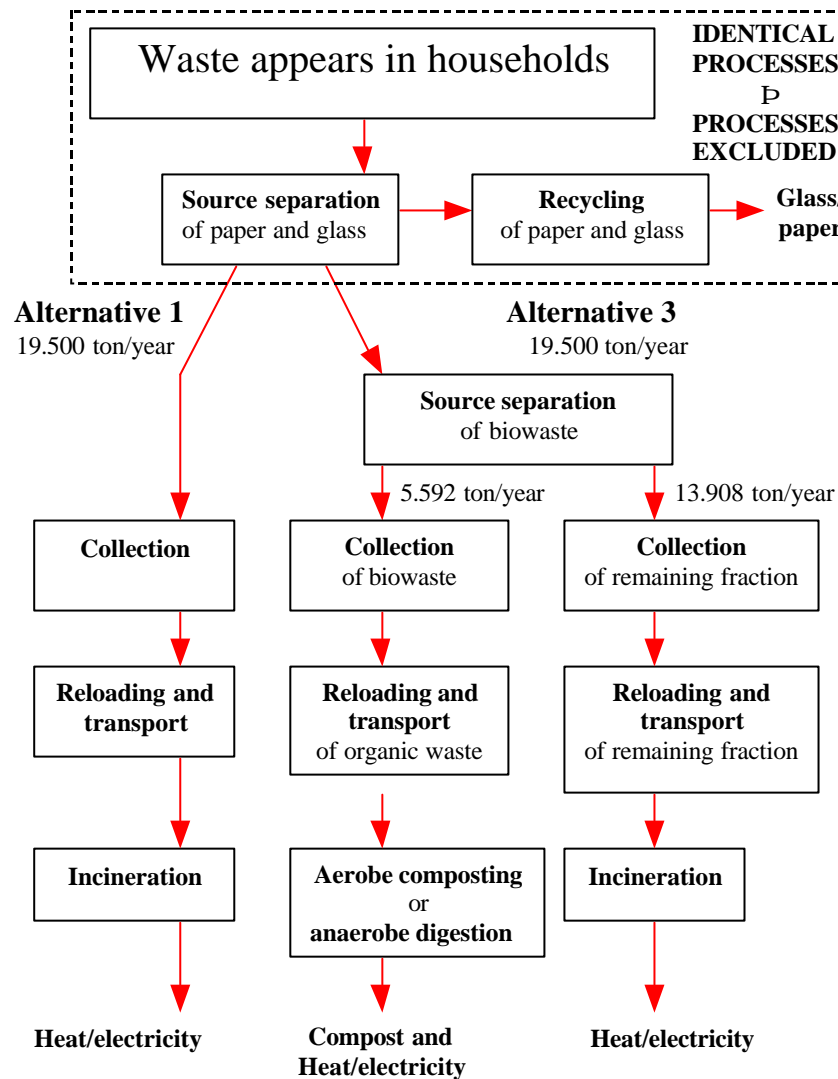
### 4.3.2 Upstream and downstream system boundaries

The upstream system boundaries are the boundaries that define where the technical system boundaries shall start, i.e. the cradle of each material or energy flow. The downstream system boundaries are the boundaries that define where the technical system shall end, i.e. the process that is regarded as the grave for any material flow. Processes might occur with the material after the downstream boundaries, but they are preferably insignificant or they are so long-term and unknown that uncertainty makes it difficult to include.

In the previous sub-section it was described how to set boundaries within a defined system. In this section focus will be on how to limit a system with respect to start and end of the waste life cycle.

The starting point should be the point at which the waste appears, e.g. from households. For comparison of systems it is of vital importance that the systems are defined with the same starting point and the same composition.

The systems can be further limited by excluding those parts, subsequent to the point when waste appear, which are identical in all systems. This is illustrated in Figure 4-2 where the process units within the dashed square are common for both alternative systems. These processes are therefore excluded from the systems to be studied.



**Figure 4-2 Illustration of waste life cycle upstream cut-off**

The end of the waste life cycle can also seem somewhat blur. It is therefore important to provide a description that clearly defines the downstream end of the waste life cycle. Typical questions to be raised are:

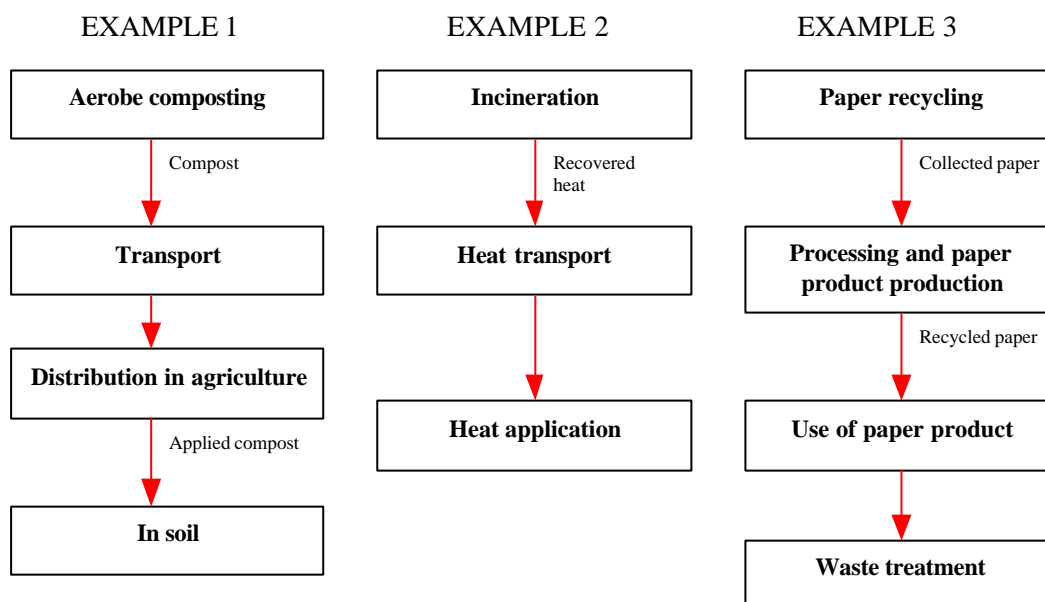
- How far do we follow products from recycling (e.g. compost)?
- How far do we follow products replaced by products from recycling (e.g. fuel oil replaced by recovered heat from waste incineration)?
- For how long do we take into account emissions and resource consumption related to a landfill?

### 4.3.3 Products from recycling and recovery

As a minimum the products from recycling should be followed until the product is at a level where it can be regarded to replace an alternative product. If an earlier cut-off is practised, the system under study can gain more benefit from the replacement than it should have.

The product from the recycling process may also introduce large or new environmental impacts during the use stage. The recycled product use should then be included within the system together with credits for substituting the use of the replaced product.

As an example we use compost, recovered heat and recycled paper. These products can replace respectively fertiliser, oil and pulp based on wood. An illustration of the life cycle processes of the products from recycling/recovery is given in Figure 4-3.



**Figure 4-3 Illustration of examples of life cycle of products from recycling**

Cut-off can be introduced at several levels for each of the examples in Figure 4-3. Ideally, all products from recycling/recovery should be followed until they cease to exist. However, there can be arguments for introducing a cut-off at an earlier stage. Cut-off at a stage preceding the point where the product ceases to exist can be used if:

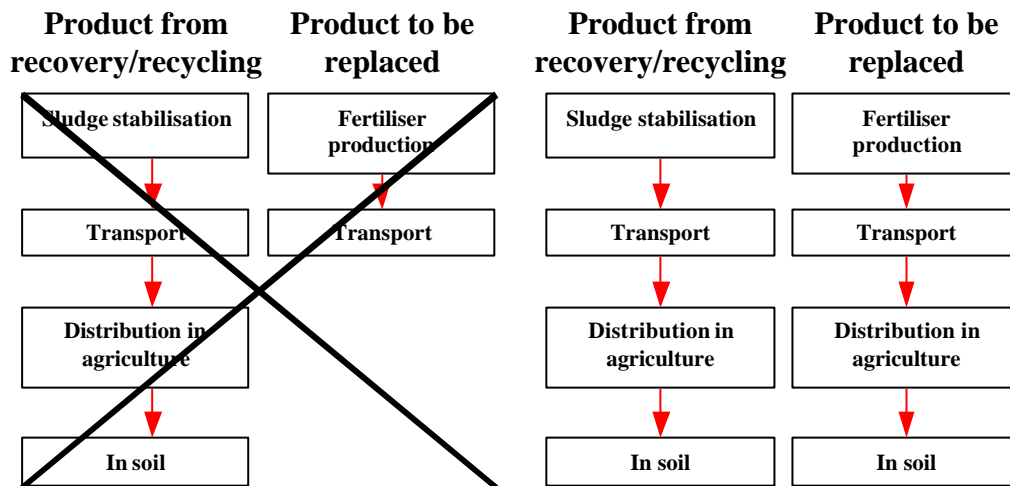
- The environmental impacts of the remaining life cycle are of the same type and magnitude as the product to be replaced.
- The remaining life cycle gives insignificant environmental impacts compared to the total life cycle impacts.
- Data for the remaining life cycle is not available but it can be assumed that one of the previous two bullet points applies.

In all cases the reason for the chosen cut-off must be argued for.

#### **4.3.4 Products replaced by products from recycling and recovery**

It is of major importance that the product to be replaced by a recycling product and the recycled product has system boundaries that involve the same life cycle stages and are based on the same cut-off criteria. If not, the life cycle inventory analysis and impact assessment will under or over estimate the environmental burdens caused by the life cycle system. It is crucial to avoid this when making comparative studies.

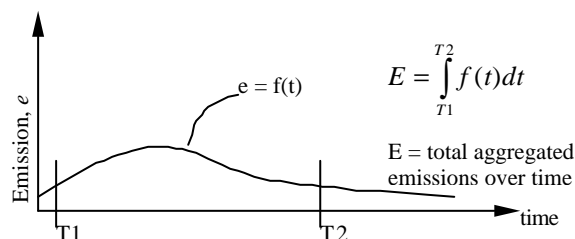
E.g. if a soil improvement product derived from treatment of sludge to a certain extent replaces fertilisers, it is important that the sludge product is analysed to the same level as the artificial fertiliser. A bias would lead to a higher/lower environmental burden for the overall life cycle system than in an ideal situation where both products are described and analysed on the same level. This is illustrated in Figure 4-4. We here see that it is wrong to include all process levels for the product from recycling, while the product to be replaced includes less process levels. If the environmental impacts from the product from recycling is followed until the product is in the soil, the same should account for the product to be replaced.



**Figure 4-4** Example of system for product to be replaced

### 4.3.5 Time aspect for landfills and soil products

Waste in landfills and soil improvement products will have an impact on the environment that lasts for a long period of time. This is the case for e.g. leakage of metals and gases from degradation such as methane. The challenge to be dealt with here is to select an appropriate time interval and the time dependent emission function to be integrated over the selected time interval (see Figure 4-5).



**Figure 4-5** Integration of environmental impacts from landfill over time

The selection of a time interval is an ethical question based on the fact that by limiting the exposure time, effects on future generations will be omitted.

The ISO 14040/41 standards do not give any specific recommendations. However SETAC recommends that the emission  $E$  should be integrated over an infinite time



period (from  $T1=0$  to  $T2=\infty$ ). If this is not possible a time interval of 100 years should be applied. Third priority is any other time interval.

In Nordic LCA studies on waste, both the infinite time approach and more limited time intervals are applied. Often without any discussion of the consequences of the selected approach.

In the Danish LCA-LAND study, 100 years is used to estimate emissions from 5 different waste component categories at landfills. The model is limited to landfills in Denmark, Germany and the Netherlands. The model can be found online at <http://www.ipt.dtu.dk/>.

The Swedish ORWARE model describes an average Swedish landfill and divides the time for emissions into the *surveyable time period* and the *remaining time period*. The surveyable time period is until the major part of  $CH_4$  has ceased (100 years), and the remaining time period is when all components have been released to the environment.

A clear recommendation on best practice will not be given here, although some basic decisions must be taken and made clear in an LCA report.

- Decide time intervals for different substances and processes.
- Give arguments for the selected time intervals.
- Make sure that the selected approaches are consistent.
- Discuss consequences for the results if other approaches are selected.

Normally, landfill data are not developed specifically for each study. That is usually a too comprehensive task. In stead readymade data are used, like e.g. the LCA-LAND data. It is then a satisfactory argument to use the approaches of the data source. But again it is emphasised that the approaches must be consistent throughout the study.

## **4.4 Inventory data**

### **4.4.1 General**

If an LCA study involves specific waste treatment processes, attempts should be made to collect and apply data that are as specific as possible for the processes in question.

In the case of more generic studies, such as e.g. a basis for political decisions, generic data should be applied. However, it is important that the generic data represent the temporal and spatial boundaries of the study.

In the following sub-sections parameters, and to a certain extent data, that are commonly applied in life cycle assessment of waste are presented. Focus will be on energy use and recovery and emissions to air water and soil. Information on other environmental aspects is given in section 4.4.10.

### **4.4.2 Waste composition**

For all treatment alternatives for municipal waste the environmental impact from the treatment is partly a function of the composition of the waste. The collection of inventory data for waste composition is defined by the scope of the study. There are three alternative approaches for collection of inventory data:

1. To collect data on composition of the waste and the emissions caused by the treatment from the geographical area under study. This enables calculation of emission factors that are specific for the waste flow in question. Different local waste separation regimes can lead to large variations in waste composition.
2. To use average “default” waste composition. This allows for the use of already developed related average emission factors. Such an approach is recommended in less comprehensive screening studies.
3. Not use waste composition, but limit the study to “average” municipal waste. This will limit the study to be process specific and does not allow for calculations that shall reflect how changes in waste composition affect the LCA results.

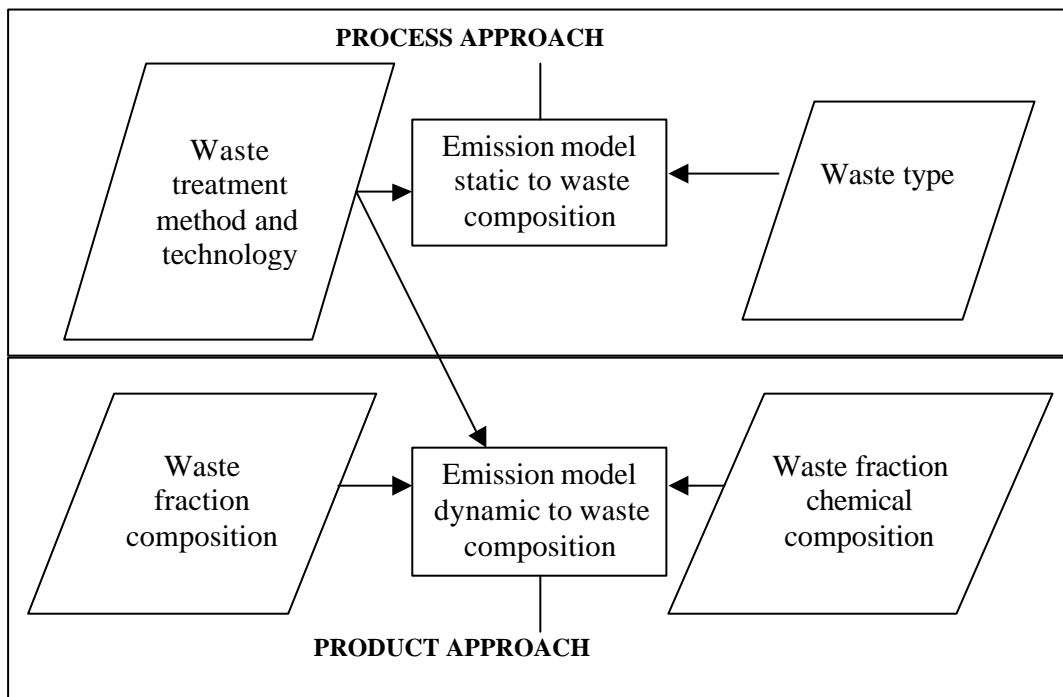
Data for composition of waste with respect to waste fractions is developed on national level in many countries, for specific waste treatment plants and for specific municipal waste management companies (see e.g. table 3.3 for different waste fractions). It is important to make sure that the collected data reflect the source separation that is valid for the study. E.g. if an LCA is to be performed of the treatment chain related to a municipal waste flow with source separation of paper, it is important to collect composition data that reflect such a separation regime.

Composition is also related to the content of the basic chemical compounds such as carbon (C), nitrogen (N), sulphur (S), chloride (Cl) and metals. The contents of these compounds in the municipal waste partly decide the amount of pollutants emitted to air, water and soil. By developing factors for emissions to air, water and soil related to treatment method and technology a model that predicts emissions can be developed. However, such a model is not able to reflect changes in waste fractions. To be able to do that the content of chemical compounds must be given per waste fraction, like in /9/ or /15/.

## Process and product approach

These two phrases are used to describe two different emission modelling approaches.

- The **process approach** uses ready-made emission and resource consumption factors for different waste treatment methods and underlying technological variations. Data might also be developed for different types of waste. I.e., if you define waste treatment method, technology and waste type, then a ready-made factors that fits with the definition are applied.
- The **product approach** uses waste treatment method specific models that calculate emission and resource consumption factors based on waste composition (waste fraction composition and contents of the waste fractions).



**Figure 4-6** Illustration of inputs to models predicting waste treatment emission factors

### 4.4.3 Incineration

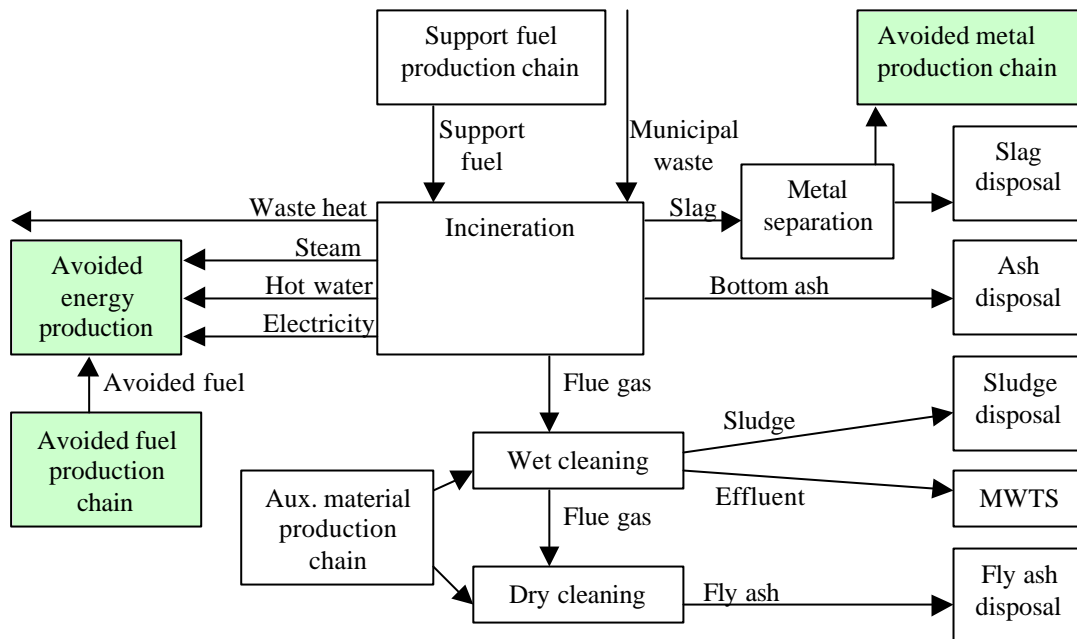
#### 4.4.3.1 System description

Data of interest related to waste incineration are:

- Type of technology. This influences how pollutants are distributed on emissions to air and water and residuals. The technology can be separated based on type of flue gas cleaning systems and furnace types.
- Waste distributed on waste fractions (applies for the whole study). Data for the specific waste in question are sometimes available, but in most cases generic data must be applied.
- Waste fraction physical and chemical data (applies for the whole study).. Combined with data on how waste is distributed on waste fractions, this allows for development of product specific emission factors. Data for the specific waste in question are sometimes available, but in most cases generic data must be applied.
- Amount and type of support fuel. Some type of fossil fuel is usually incinerated to generate enough heat to during waste incineration start-up and to keep the incineration process stable.
- Type and amount of auxiliary materials. These materials is applied in the flue gas cleaning. Relevant auxiliary materials can be  $\text{Ca}(\text{OH})_2$ , NaOH, coke, ammonia, limestone, urea and waste water treatment chemicals.
- Overview of the range of pollutants decided to be studied.
- Emission to air and water. Can be collected from specific plants or estimated from models based on waste composition and technology. Emission to water presumes that a wet flue gas cleaning system is installed.
- Process specific energy consumption and emissions such as operation of vehicles and machinery.
- Incineration residues and residue contents. Can be given specifically for the defined plant(s). or estimated based on models taking into account waste composition and incineration technology.
- Potentially recovered energy from a specific plant. Is estimated based on models that take into account heating values and dry matter in waste components and efficiency of the installation.
- Type of energy substituted by recovered energy.
- Recovered energy. Should be based on data valid for the defined plant(s).

The different topics listed above are described in further detail in the following chapters in this guideline. An overview of a system model for incineration is given in Figure 4-7. Note that some process units are given at a coarse level. These can be further refined (e.g. the deposition boxes, the production chain boxes and the incineration process itself). Further, emissions, resource consumption and energy use flows are not shown for the process units (except incineration). Finally, transportation is excluded.

All the flows in the system will be relative to the municipal waste flow entering the system. This municipal waste flow is the whole, or a share of the reference flow resulting from the defined functional unit.



**Figure 4-7 Process flow chart for the incineration system**

#### 4.4.3.2 Emission of CO<sub>2</sub>

CO<sub>2</sub> emissions are estimated from the carbon content of the incinerated material. The carbon content contributes to emissions such as CO<sub>2</sub>, CO, CH<sub>4</sub>, non-methane volatile organic compounds (NMVOC) and carbon in soot. The relative distribution of carbon between the different components depends on the operation of the incineration plant. CO<sub>2</sub> is by far the component that binds most of the carbon (above 97%) /10/.

Exhaust gas cleaning or incineration technology does not influence CO<sub>2</sub> emissions. It is therefore common to differentiate CO<sub>2</sub> emissions on waste composition only.

Emission of CO<sub>2</sub> from incineration of biological waste material does not contribute to net emissions of greenhouse gases and should therefore not be accounted for. It is therefore necessary to separate between fossil carbon and biological carbon.

Calculation of net CO<sub>2</sub> emissions from waste incineration is based on the fossil carbon content of the waste (kg fossil carbon/kg waste), multiplied by the amount of CO<sub>2</sub> generated per amount of carbon (kg CO<sub>2</sub>/kg fossil carbon).

The fossil carbon content of different waste fractions is estimated in several Nordic studies. Table 4-3 gives data based on two selected Nordic studies.

**Table 4-3 Carbon content in waste fractions (dry matter)**

Reference /9/, g C /kg waste			Reference /15/, g C /kg waste		
Waste fraction	Fossil C	Biological C	Waste fraction	Fossil C	Biological C
Food waste	0	434	Food, garden waste	0	500
Newspaper	8	440	Wood	0	495
Corrugated cardboard	0	500	Other degradable	0	400
Mixed cardboard	170	400	Newspapers, magazines	0	422
PE	856	0	Milk cartons	125	375
PP	855	0	Mixed cardboard	0	422
PS	889	0	Other paper	0	433
PET	640	0	Napkins, coffee filters	0	458
PVC	401	0	Diapers	0	500
			Plastic foil	644	0
			Hard plastic packaging	656	0
			Other plastic	590	0
			Textiles	278	278
			Fine matter	75	75
			Vacuum cleaner bags	150	150
			Other combustible	400	93

Further, /9/ and /15/ give the following amount of CO<sub>2</sub> generated per amount of carbon:

- /9/: 3,67 kg CO<sub>2</sub>/kg fossil carbon (equivalent to 100% conversion)
- /15/: 3,49 kg CO<sub>2</sub>/kg fossil carbon (takes into account conversions to other substances)

Based on the composition of the waste (examples given in section 4.4.2), fossil carbon content of the waste fractions (as given in Table 4-3) and kg CO<sub>2</sub>/kg fossil carbon, the amount of CO<sub>2</sub> per amount of mixed municipal waste is calculated (kg CO<sub>2</sub>/kg waste).

If the composition of the waste is not known or does not fit with the given/available waste fraction carbon content data, average municipal composition figures can be used, at least in a screening study. E.g. Norwegian figures indicate average emissions from incineration plants of 0,29 kg CO<sub>2</sub>/kg household waste (including water content in the waste) and 0,43 kg CO<sub>2</sub>/kg household waste (dry matter) /15/.

#### 4.4.3.3 Emissions to air (not CO<sub>2</sub>)

Other emissions to air vary with age, incineration technology, flue gas treatment technology and composition of the waste. Data can be retrieved in several ways:

1. Process specific data from one incineration plant: This is recommended in cases when the analyst knows that the waste is going to be incinerated in the particular plant where the data is derived from, or in a similar plant. The data are static and they are not able to reflect situations where the composition of the waste is changed.
2. Average process specific data from several incineration plants: This is recommended in studies with a broader geographical scope. E.g. in case of national or regional studies. It is then important that the selected plants represent

the variation in technology in use within the boundaries in question. These data are also static and they are not able to reflect situations where the composition of the waste is changed.

3. Product specific data: Emission data are modelled based on knowledge about waste composition. Should be applied for system development purposes, where the effect of system changes shall be quantified (e.g. the effect of introducing source separation of a material).

Emissions to air from a waste incineration plant applied in an LCA of waste should be given as weight pollutant emitted per weight waste incinerated (e.g.  $g\ NO_x/kg\ waste$ ). When deriving plant specific data, these are usually given at one of the formats listed in Table 4-4 (example with  $NO_x$  as pollutant is used). How to estimate  $g\ NO_x/kg\ waste$  from the given format is also given in the table.

**Table 4-4 Formats for emission to air data and related estimation to derive at wanted format**

Format	Estimation	Comment
$g\ NO_x/m^3\ exit\ gas$	Multiplied with exit gas rate at same conditions ( $m^3\ exit\ gas/h$ ) and divided by waste flow ( $kg\ waste/h$ ).	At specific conditions for ambient pressure and temperature, and exit gas $O_2$ content. Exit gas rate are usually measured at existing plants and can be estimated for new plants
$g\ NO_x/h$	Divided by waste flow ( $kg\ waste/h$ ).	
$g\ NO_x/kg\ waste$		Wanted format

It should be possible to retrieve plant specific data on emissions to air for that are regulated by the authorities, as these data are publicly available. Usually the regulated parameters are those with limit values according to EU directive on the incineration of waste /12/. The directive gives the minimum requirements that *new* waste incineration plants have to comply with. Existing plants have to comply with the directive within the end of 2005. The directive gives requirements as concentrations in the exit gas at defined conditions. The requirements of the directive can be regarded as a worst case for emissions to air from a waste incineration plants that must be compliant with the directive or related national legislation.

Limitations on which emissions that shall be taken into account are made in the scope of the LCA. If there are no arguments for restricting the number of pollutants, the parameters regulated in the EU directive should at least be taken into account in addition to  $CO_2$  in the scope when studies include waste incineration. The parameters are:

- Dust (can be further specified by dividing into particle size;  $PM_{10}$ ,  $PM_{2,5}$ )
- TOC (can be further specified into chemical components or groups of these)
- HCl
- HF
- $SO_2$
- $NO_x$
- CO
- Cd+Tl
- Hg

- Metals (includes Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V)
- Dioxins/furans

Table 4-5 gives emission measurements made in 1999/2000 at an existing waste incineration plants in Norway /13/. It is seen that there are great variations in the emission factors, mainly due to different pre-treatment, incineration and cleaning technologies. All plants incinerate mixed municipal and industry waste. Still, there might be large differences in waste compositions probably also affect the emission factors.

**Table 4-5 Emission to air from waste incineration in Norway, 1999/2000 /13/**

	Unit	Frevar	BiR	Nir	Ålesund	Heimdal	Klemets-rud	Brobekk
Start year		1984	2000	2000	1987	1986	1985	1987
Waste flow	ton/yr	70000	90000	30000	37000	90000	160000	100000
Relative to waste								
Dust	g/ton	2,1	7	2,29	42,9	91,1	14,3	79,5
Hg	g/ton	0,001	0,01	0,008	0,11	0,11	0,273	0,088
Metals*	g/ton	0,69	0,07	0,1	0,64	0,4	23,4	9,14
CO	g/ton	252	32,5	1,14	1	333	250	0,22
TOC	g/ton	1,4	2	3,43	0,56	28,9	3,19	19
HF	g/ton	0,28	0,7	1,14	4,82	0,48	1,95	2,29
HCl	g/ton	2,8	4,5	11,4	0,08	0,08	146	42,3
SO <sub>2</sub>	g/ton	21	14,5	74,3	155	5,56	78,4	386
NO <sub>x</sub>	kg/ton	2,54	0,67	0,41	1,53	1,47		2,26
Dioxins	mg/ton	0,029	0,06	0,046	2,23	4,11	11,7	13,9

\* Includes Cd, Hg, Tl, As, Pb, Cr, Cu, Mn and Ni

If it is preferred to model the emissions to air, in stead of using data from existing plants like those in Table 4-5, the model developed by the Danish part of the EUREKA project on technical data for waste incineration can be applied /10/. Here emission factors are established for the relevant compounds for a range of cleaning technologies, given that the waste content of C, N, S, Cl, and metals are known.

By selecting data from specific plant as those listed in Table 4-5 (or other plants), a *process specific* data collection approach is applied. The benefit of such an approach is that it is easy to derive updated data. By using the approach from the EUREKA project, both a product specific and process specific approach is selected. This approach requires that the contents of the waste are known and the flue gas cleaning technology to be applied.

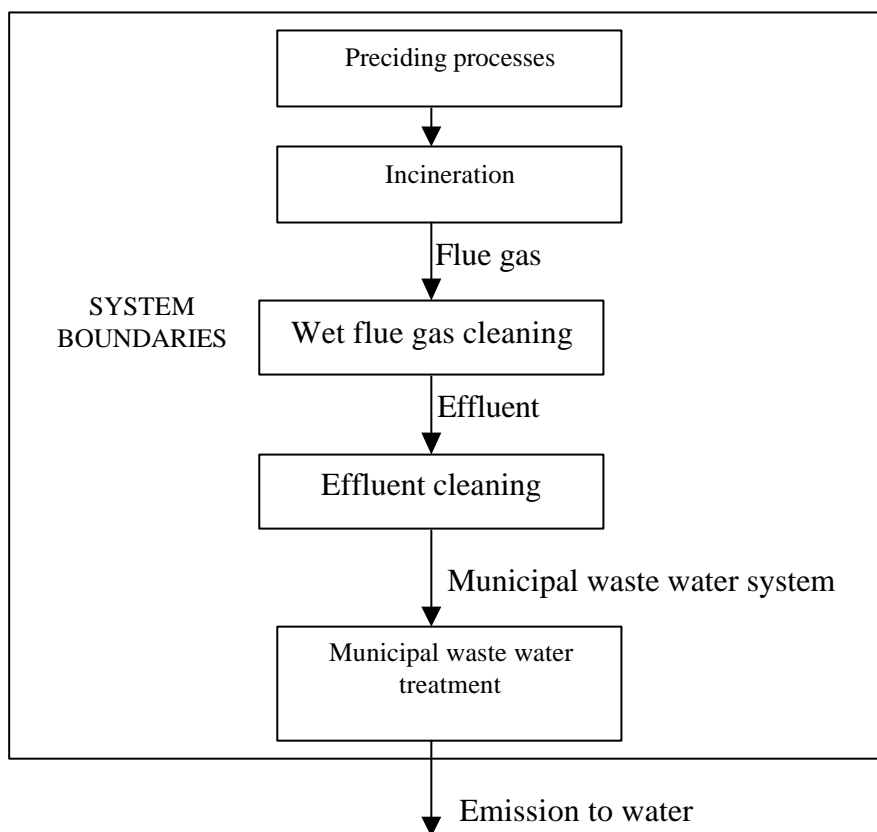
A product specific approach is also applied in the Swedish ORWARE project /9/. This model is however simpler than the EUREKA model because there are less possibilities for variation in technology.

#### 4.4.3.4 Emissions to water

Emissions to water from waste incineration are only related to plants that have wet exhaust gas cleaning systems. The wastewater is then released to the municipal waste



water system and treated at the local wastewater treatment plant (see Figure 4-8). Some studies only follow the emissions until after the effluent cleaning. This is acceptable if there are no subsequent treatment, but if treatment is present it should be included so that the actual effluent to the recipient is quantified.



**Figure 4-8 Illustration of flows, process units and system boundaries from incineration to emission to water**

In general, no studies are identified during the preparation of this guideline that quantify the contribution from effluent cleaning to the total emissions from municipal wastewater treatment plants to natural water resources. However, plant specific data can be derived for emissions that leave the plant into the municipal waste water system. These data must only be used combined with careful evaluations and discussions about how the effluents affect the local wastewater treatment plant and their fate after the treatment.

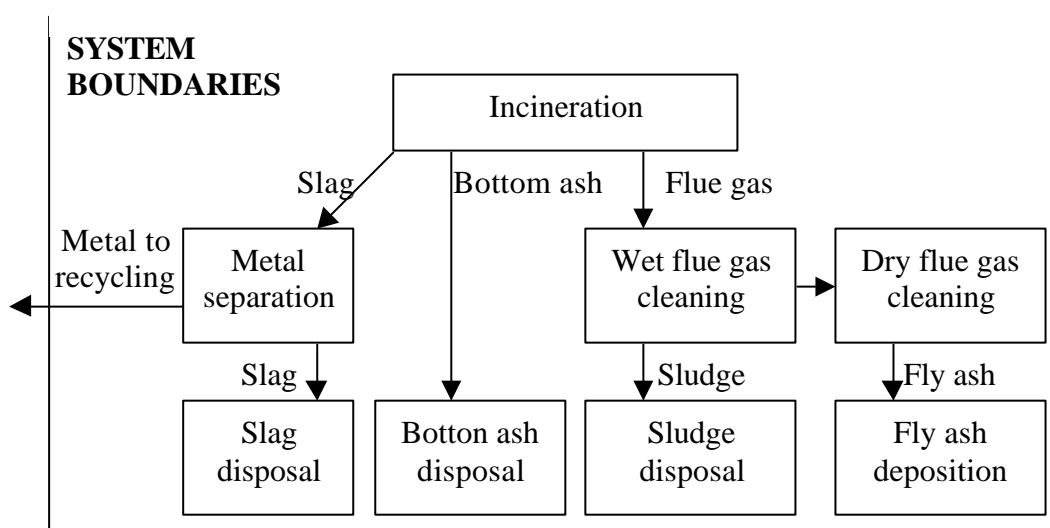
In the same way as for emissions to air, the EU directive on incineration of waste /12/ can give input to the scope on pollutant to include in the study when wastewater from exhaust gas cleaning is involved as a process in the system. The requirements are given for suspended substances, Hg, Cd, Th, As, Pb, Cr, Cu, Ni, Zn and dioxins and furans as mg/l wastewater.

If data for these compounds are collected they should be applied by multiplying with the amount of wastewater emitted per ton waste incinerated (l waste water/ton waste). The compound emitted through the wastewater emissions can then be expressed as mg/ton waste.

#### 4.4.3.5 Incineration residues

Incineration residues come in the form of slag (unburned materials), bottom ash (ash collected at bottom of kiln), sludge (from wet flue gas cleaning system) and fly ash (collected at dry flue gas cleaning systems). The type and amount of residues generated are of course very much dependent on the technology applied at the incineration plant.

The incineration residues contain metals and dioxins/furans that may leak into the environment if not handled properly. The residue fractions with the highest concentrations of toxic compounds are usually regarded as hazardous waste (e.g. fly ash) and should be treated accordingly. Process units that should be taken into account when quantifying the environmental impact of residues are illustrated in Figure 4-9.



**Figure 4-9 Illustration of flows, process units and system boundaries from incineration to final disposal of residues**

In many LCAs the system boundaries are set in a way that incineration residues are only quantified as “waste”. By using such an approach much information is lost. This might be information such as collection and recycling of metal contents of the slag, and how the remaining residues are deposited and what impacts to the environment that are caused by this deposition.

To be able to quantify the potential environmental impact of incineration residues a process approach or a product approach can be selected, as for all other flows in and out of the incineration plant.

In a process approach the amount of residues are measured (kg residue/ton waste), together with the content of chemical compounds (g compound/kg residue). Then the leakage and land occupation can be estimated based on leakage rates and land occupation factors for different deposition methods. This approach is not able to reflect changes in the waste composition.

In a product approach the amount of residue and its contents of basic chemical compounds are modelled. The modelling takes into account waste fraction distribution, content of chemical compounds in the waste fractions, and an

input/output mass balance for different technologies. The product approach is able to reflect changes in the waste composition.

Parameters that should be taken into account regarding the environmental impact of deposition of residues should at least be those toxic compounds regulated by authorities. In addition land-use is an important parameter in many LCAs.

The most comprehensive Nordic work on modelling the environmental impact of incineration residues is probably the LCA-LAND project (ref. <http://www.ipt.dtu.dk/ap/lceresearch.htm>). The model is developed for landfills and can be applied for deposited incineration residues. It is based on a large number of assumptions and approximations concerning landfill properties, waste product properties and characteristics of various kinds of environmental protection systems (e.g. landfill gas combustion units and leakage treatment units). The model is useful for estimation of emissions from waste products disposed in landfills and it has been made operational in the computer tool LCA-LAND. In the model, waste products are subdivided into five groups of components: general organic matter (e.g. paper), specific organic compounds (e.g. organic solvents), inert components (e.g. PVC), metals (e.g. cadmium), and inorganic non-metals (e.g. chlorine,) which are considered individually. The assumptions and approximations used in the model are as far as possible scientifically based, but where scientific information has been missing, qualified estimates have been made to fulfil the aim of a complete tool for estimation of emissions. Due to several rough simplifications and missing links in the present understanding of landfills, the uncertainty associated with the model is relatively high.

#### **4.4.3.6 Recovered energy**

Recovered energy ratio is the exploited energy from the incineration plant divided by the energy produced by the plant that can potentially be exploited. Energy is exploited as steam used in industrial processes, hot water used in district heating and electricity production.

The recovered energy ratio is varying considerably from plant to plant and over the year. Annual variation is usually a result of variations in ambient temperature which influence the need for district heating. However, the energy recovery can be optimised by adjusting the amount of waste incinerated. This requires an intermediate storage of the waste during the summer season.

In Sweden the recovered energy is close to 100% due to a comprehensive use of district heating using hot water.

In Norway the energy recovery lies around 70% on average (varied from 50-84% in 1999/2000 for existing plants) /13/. Norway does not have much district heating, and therefore the potential for energy recovery is lower than e.g. in Sweden. Although, increased district heating is a national target. Steam to industrial processes is the most important form of energy recovery in Norway.

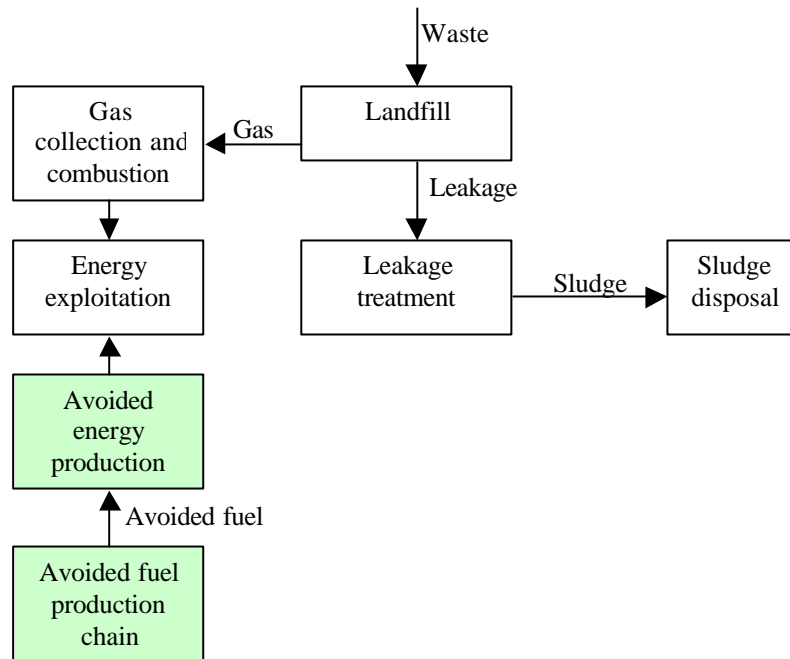
## 4.4.4 Landfills

### 4.4.4.1 System description

The landfill system is relevant to apply to both to the direct municipal waste flow, and to residual waste flows resulting from other treatment methods, such as incineration and biological treatment. Data and information normally applied in LCA landfill emission models are:

- Overview of landfill technologies applied in the temporal and spatial boundaries of the study. This is mainly related to types of leakage water prevention (e.g. membranes of different leaking potentials) collection and treatment and collection, combustion and energy exploitation of landfill gas.
- Distribution of main waste flow on waste fractions (applies for the whole study).. The main waste flow should be separated on waste fractions that act differently in the landfill and give significantly different type and magnitude of emissions and gas production.
- Waste fraction contents (applies for the whole study).. This gives the substances available for pollutant and product generation.
- Overview of the range of pollutants decided to be studied.
- Time period for estimation of emissions. Some emissions can occur over a very long period of time. The time period is a temporal cut-off.
- Product specific models for potential generation of pollutants and distribution of pollutants on environmental compartments. The models must match the time periods selected for generation of pollutants and generation of impacts.
- Share of leakage water and gas collected and treated. Duration of collection and treatment might be relevant in the future as models depending on duration might be developed.
- Leakage water and landfill gas treatment technology emission factors.
- Process specific energy consumption and emissions such as operation of vehicles and machinery.
- Recovered energy, which is estimated based on models that take into account produced gas, share of gas collected, heating value of gas and the efficiency of the installation(s).
- Type of energy substituted by recovered energy.

A process flow chart for a landfill is given in Figure 4-10. Note that some process units are given at a coarse level. These can be further refined (e.g. the avoided energy and related production chains). Further, emissions, resource consumption and energy use flows are not shown for the process units. Finally, transportation is excluded.



**Figure 4-10 Process flow chart for the landfill system**

A particular pollutant emitted to an environmental compartment after a specific emission treatment ( $E_{pollutant,treatment,compartment}$ ) can be expressed as:

$$E_{pollutant,treatment,compartment} = (M \cdot C \cdot F \cdot G \cdot A \cdot R)_{pollutant,treatment,compartment}$$

Where:  $M$  is the waste flow input to the landfill (kg/functional unit)

$C$  is the content of the basic substance in the waste forming the pollutant (g substance/kg waste)

$F$  is the share of the basic substance going to the compartment of interest (g compartment/g substance)

$G$  is the generation potential of the pollutant from the basic substance (g pollution pot./g substance)

$A$  is the share of the pollutant that is treated (g treated/ g pollution pot)

$R$  is the emission reduction factor for the pollutant after treatment (g removed/ g treated)

Pollutants that are not treated are given by:

$$E_{pollutant,non-treatment,compartment} = (M \cdot C \cdot F \cdot G \cdot (1 - A))_{pollutant,non-treatment,compartment}$$

The sum of the two equations above expresses the total emission of a pollutant to a given compartment.

However, note that some pollutant emissions can not be modelled this way. E.g. amount of VOC and BOD to treatment should rather be related to the amount of waste, rather than a basic substance generation potential.

As an example let us define the following task: Calculate landfill emission to water given that:

- 10000 kg waste is delivered to landfill per functional unit (FU) (M=10000 kg/FU).
- Focus on cadmium (Cd). The Cd content of the waste is 0,1 mg/kg waste (C= 0,1 mg/kg).
- Cd in waste is released to water as Cd, i.e. pollutant equals the substance (G=1 mg/mg).
- 10% of the Cd ends in landfill waste water after 100 years. The remaining Cd remains in the landfill. (F=0,1).
- 80% of the landfill wastewater is treated. (A=0,8).
- The landfill wastewater treatment reduces the Cd content of wastewater with 90%. The removed Cd ends in treatment sludge (R=0,1).

The emission to water from the landfill is then given by:

$$\begin{aligned}
 E_{\text{cd,water}} &= E_{\text{cd,water,treatment}} & + & E_{\text{cd,water,non-treatment}} \\
 &= (10000 * 0,1 * 0,1 * 1 * 0,8 * 0,1) & + & (10000 * 0,1 * 0,1 * 1 * (1-0,8)) \\
 &= 10 & + & 20 \\
 &= \underline{30 \text{ mg/FU}}
 \end{aligned}$$

The Danish LCA-LAND model /31/ is a product specific landfill model, based on a large number of assumptions and approximation concerning landfill properties, waste product properties and characteristics of various kinds of environmental protection systems (landfill gas combustion and leakage treatment). This is probably the most comprehensive work in Europe related to product specific emissions from landfills. The model can be used as a basis to establish emissions per ton waste from waste composition and the waste fraction's content of pollutants.

The model calculates emissions to air, water, what remains in the landfill after 100 years and recovered energy. It takes into account all the input data given in the bullet list above, except the latter one related to substituted energy. Most of the input parameter can be varied. The only standard parameters are:

- The time period.
- Fraction of leakage treated at landfills with leakage treatment units (80%).
- Fraction of gas collected at landfills with combustion plants (50%).
- Fraction of precipitation entering landfills equipped with water stopping top covers (5%).
- Fraction of precipitation entering landfills without water stopping top covers (50%).

The model contains default values for The Netherlands, Denmark and Germany. It can be applied for other countries and regions as well as long as the necessary input data are available. LCA-LAND should be regarded as a model which processes input data given by the analyst into inventory results, not a data source.

#### 4.4.4.2 Emission of CO<sub>2</sub> and CH<sub>4</sub>

Main focus has been placed on the bulk emissions to air, which is the greenhouse gases methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>). It is commonly assumed that approximately the first months there are aerobic conditions in the landfill, which means that CO<sub>2</sub> is formed. After that there are anaerobic conditions, which means that CH<sub>4</sub> is formed in addition to CO<sub>2</sub>.

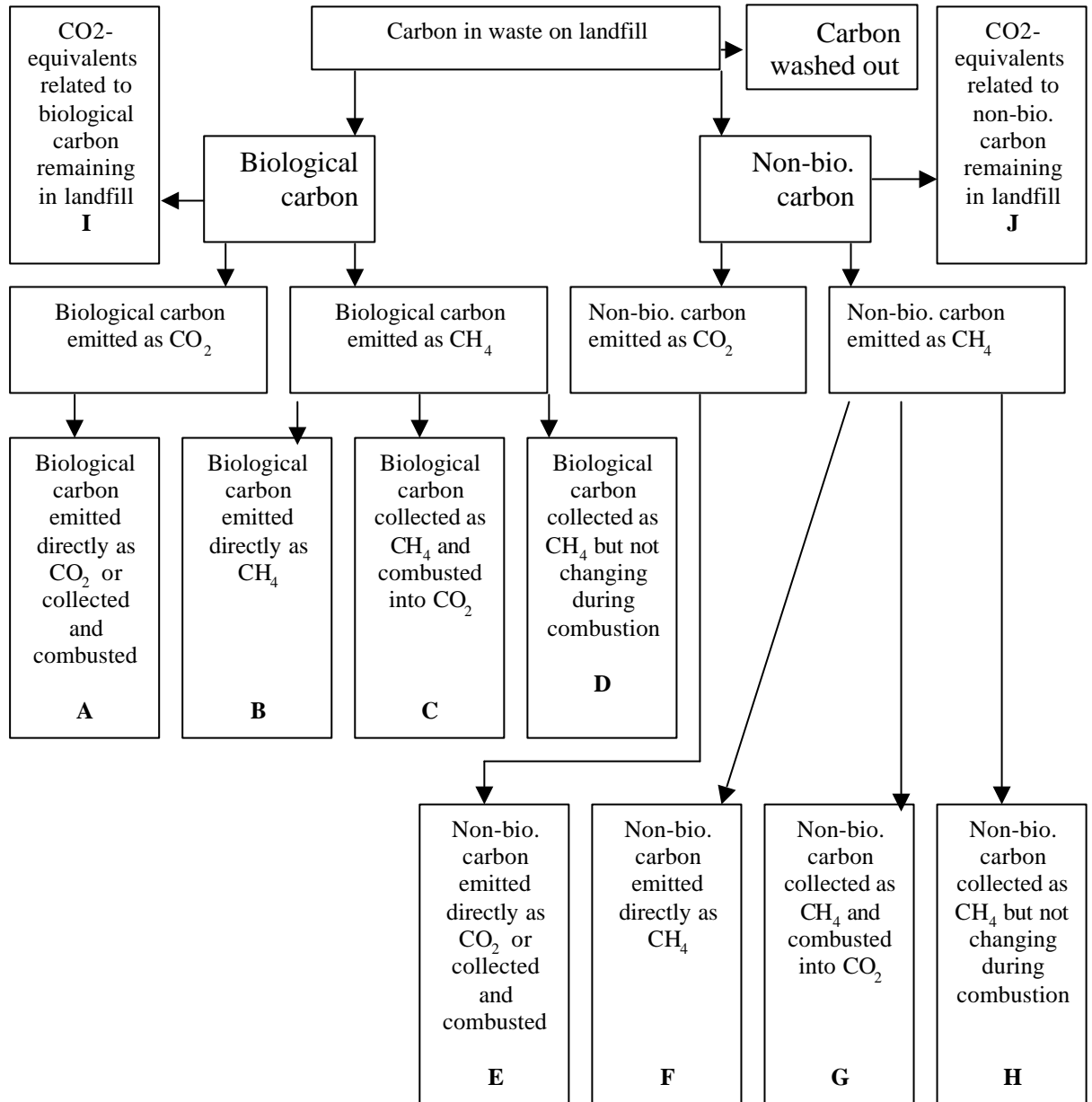
As discussed in section 4.3.5, the time period taken into account partly decides the CH<sub>4</sub> and CO<sub>2</sub> generated per ton waste. As a starting point the carbon content in the waste flow available for degradation decides the potential emissions of CO<sub>2</sub> and CH<sub>4</sub>. This should be specified during the waste composition data collection (ref. section 4.4.2). The total available carbon in the waste, minus carbon washed out with the leakage water, is available for CO<sub>2</sub> and CH<sub>4</sub> generation.

There might also be carbon left in the landfill after the defined emission time frame has run out. In a Swedish LCA study on solid waste /9/ the biological share of these amounts of carbon are transformed in CO<sub>2</sub> equivalents which are regarded to decrease the contribution to global warming (the carbon sink concept). I.e. the landfill is a carbon sink if carbon is not released to air or water, but remains in the landfill for an infinite time. If the carbon had not ended up in the landfill it would have been released and contributed to global warming.

It is important to use a product specific approach to estimate CH<sub>4</sub> and CO<sub>2</sub> generation. This is first of all because biologically based carbon is CO<sub>2</sub> neutral and a product specific approach is needed to keep track of the share of biological carbon.

A share of the landfill gas is often collected and combusted. The combustion transforms most of the CH<sub>4</sub> into CO<sub>2</sub>, although some minor amount can remain throughout the combustion.

Figure 4-11 shows CO<sub>2</sub> and CH<sub>4</sub> emitted from a landfill and which emissions that should be regarded as decreasing, neutral or increasing CO<sub>2</sub> equivalent emissions. Box B and D-H contributes to global warming, while A and C are regarded as CO<sub>2</sub> neutral. It is common to pay less attention to box D and H due to a very small contribution compared to the other boxes. If carbon remains in the landfill after the defined time frame (surveyable time) for emission of CO<sub>2</sub> and CH<sub>4</sub>, it must be decided whether to use the carbon sink approach or not /9/. If the carbon sink approach is used, box I will decrease the contribution to global warming and box J will be neutral. If the landfill is not regarded as a carbon sink, box I will be neutral and box J will increase the contribution to global warming in an infinite time perspective. That is *if* the remaining carbon is taken into account at all. If the remaining carbon is *not* taken into account, the contribution from box I and J will be zero.



**Figure 4-11 CH<sub>4</sub> and CO<sub>2</sub> emissions from landfill**

The biological carbon content of different waste fractions and the related CO<sub>2</sub> and CH<sub>4</sub> emissions are given in Table 4-6 /15/. It is assumed that the biological carbon content is to equal the bio-available content. This is not always the case, e.g. lignin is biological but not bio-available. The approach applied does therefore not take into account the carbon that remains in the landfill (non-available biological carbon). Further, in the bio-available definition chemical reactions involving carbon are included in addition to the biological degradation. In sum this might overestimate the potential for gas development.

It is recommended to perform sensitivity studies on how to deal with the remaining carbon. Alternative scenarios could be:

- Not to include remaining carbon (as in Table 4-6).
- To use the carbon sink approach.



- To assume that all carbon in landfill is emitted in an infinite time perspective.

**Table 4-6 Greenhouse gas emissions (kg/ton waste fraction) from landfill /15/**

Waste fraction	Dry matter (%)	Bio-available carbon (% of C)	Total potential <sup>1</sup>		After CH <sub>4</sub> combustion <sup>2</sup>		Contribution to global warming <sup>3</sup>	
			CO <sub>2</sub> (kg/ton)	CH <sub>4</sub> (kg/ton)	CO <sub>2</sub> (kg/ton)	CH <sub>4</sub> (kg/ton)	CO <sub>2</sub> (kg/ton)	CH <sub>4</sub> (kg/ton)
Food, garden waste	30	100	269	99,4	400	49,7	0	49,7
Wood	80	100	739	252	1072	126	0	126
Other degradable	25	100	179	66,3	267	33,2	0	33,2
Newspapers, magazines	90	100	714	240	1031	120	0	120
Milk cartons	90	75	634	213	916	107	0	107
Mixed cardboard	90	100	714	240	1031	120	0	120
Other paper	90	100	733	246	1059	123	0	123
Napkins, coffee filters	60	100	530	169	753	84,4	0	84,4
Diapers	30	100	289	92,1	411	46,1	0	46,1
Plastic foil	90	5	53	19,0	78	9,5	0	9,5
Hard plastic packaging	90	0,1	1	0,3	1,4	0,2	0	0,2
Other plastic	100	0,1	1	0,4	1,5	0,2	0	0,2
Textiles	90	50	466	159	677	79,6	0	79,6
Fine matter	50	50	70	23,9	102	12,0	0	12,0
Vacuum cleaner bags	100	50	280	95,5	406	47,8	0	47,8
Other combustible	75	20	138	47,3	201	23,7	0	23,7
Glass	100	100	9	3,3	13,4	1,7	0	1,7
Iron	100	10	8	2,9	11,8	1,5	0	1,5
Other metals	100	0,1	0	0	0,0	0,0	0	0,0
Other non-combustible	100	0,1	0	0	0,0	0,0	0	0,0

1. 57% of carbon is emitted as CH<sub>4</sub> for food, garden waste and glass, while 50% for the remaining waste fractions. Only CO<sub>2</sub> is generated the first half year. Complete degradation of bio-available carbon in the landfill. Degradation of other types of carbon like lignin and those used in plastics are not taken into account and are assumed to be remaining in the landfill.
2. 50% of the methane is collected and combusted. 0,054 kg CO<sub>2</sub> is emitted per MJ methane combusted. Methane has here a heating value of 49 MJ/kg (2,65 kg CO<sub>2</sub> pr. kg CH<sub>4</sub>).
3. All CO<sub>2</sub> has its origin from bio-available carbon and is therefore not accounted for.

Due to the great variation in degree of flaring and energy recovery of landfill gas, it is important that the system under study reflect the actual technology applied in the geographical and temporal scope of the study.

#### 4.4.4.3 Emissions to air (not CO<sub>2</sub> and CH<sub>4</sub>)

Pollutants are emitted to air from landfills through direct evaporation from the landfill and through landfill gas combustion off-gases. Although methane and carbon dioxide are the bulk constituents, landfill gas typically contains in the order 120-150 trace components, constituting approximately 1% of volume (according to USEPA). The wide range of trace compounds that may be present are mainly determined by the types of waste deposited. It is therefore a benefit to apply product specific models as a basis for estimating emissions to air from landfills.

There is lack of data on emissions to air directly from landfills. Limited process information exists for evaporation of metals, volatile organic compounds (NMVOC), dioxines and other toxic pollutants. For most pollutant there is not enough data to establish product specific models.

For combustion off-gases better background data exist. But it is not identified studies that attempt to relate landfill gas to waste fractions and waste fraction contents (except for CO<sub>2</sub> and CH<sub>4</sub>). Hence, it is not possible to establish product specific models for emission from landfill gas combustion either.

Information that has been gathered about toxic emissions emitted directly to air from landfill is given below.

- Dioxines directly from landfill: No data are found.
- Dioxines from landfill fires: 1 mg TEQ/ton mixed waste /30/. This figure must be combined with landfill fire frequency if taken into account. Often accidents are excluded from an LCA study.
- Hg directly from landfill: Measurements at Grønmo landfill in Oslo, Norway indicate that 1% of Hg in waste to the landfill is emitted to air. Studies carried out in Sweden indicate 0,01-0,2 g/ton waste (average Swedish waste to landfill) /13/. Note that both these studies are 10-15 years old.

Pollutants that are typically emitted from landfill gas combustion are given in Table 4-7 with examples of emission factors per kg gas combusted. These should not be regarded as default values, only examples, based on measurements from a single landfill with a simple flare technology.

Based on the amount of landfill gas generated per ton waste (e.g. as given in Table 4-6), and the share going to combustion/flaring, it is possible to calculate the figures in Table 4-7 into emissions per kg waste.

**Table 4-7 Emission factors for landfill gas combustion/flaring /15/**

Parameter	Unit per kg gas	Mixed waste
CO	g	39,7
NO <sub>x</sub>	mg	162
SO <sub>2</sub>	mg	931
PM	mg	882
PAH	mg	1,23
Hg	µg	5,88
Dioxins	pg	539

If other emissions than CO<sub>2</sub> and CH<sub>4</sub> from landfill are to be included in an LCA study, efforts should be made to collect more relevant data than those given above, where the main focus should be placed on the toxic compounds.

#### 4.4.4.4 Emissions to water

It is particularly leakage of nutrients and metals that have negative impacts on the environment.

Parameters that typically are measured in leakage water are listed below /13/. According to the Norwegian State Pollution Control Agency (SFT) the first 11

parameters should be measured 4 times per year and the remaining ones 2 times per year. It should therefore be possible to at least derive process specific data for these parameters (if included in the study scope).

- Amount of leakage water
- Chemical oxygen demand (COD)
- Tot-N
- Ammonia
- Mercury (Hg)
- Lead (Pb)
- Cadmium (Cd)
- Iron (Fe)
- Chloride (Cl)
- Sodium
- Borium
- Biological oxygen demand (BOD)
- Arsene (As)
- Phenol
- Aromates
- Tot-P
- Potassium
- Sulphate
- Aluminium
- Polyaromatic hydrocarbons (PAH)
- Chlorinated organic compounds
- Zinc
- Chromium (Cr)
- Copper (Cu)
- Nickel (Ni)

Environmental authorities in the other Nordic countries might have other focus parameters and measurement criteria. Note that short-term measured data cannot be used to model long-term emissions. However if measured data are collected over many years from many sites and the waste composition is roughly known, one could use the measured values to see if there are large differences between model outputs and the measurements.

To be able to quantify leakage from landfill using a product approach one must:

- Select the period of time for which emissions shall be quantified (ref. section 4.3.5).
- Gather data on generated leakage rates for all components for the selected time interval.
- Gather data for the type and share of pollutants removed from water by leakage treatment.
- Calculate leakage to the environment (g pollutant/kg waste) based on waste composition, leakage rates and share of leakage collected in wastewater treatment systems and reduction factors for wastewater treatment.
- Finally the equation given in section 3.4.4.1 can be applied.

The selected time period is the same as for all pollutants (usually 100 years).

In ORWARE and LCA-LAND it is assumed that 80% of the leakage from landfills are collected and treated. In Norway in 1995 about 50% of all waste at landfill had leakage water treatment. This figure rises to 70-100% in the more populated areas around the Oslofjord (ref. <http://www.ssb.no/>).

If a leakage treatment system is in place, not necessarily all leakage water is collected and treated. As for landfills without leakage treatment, direct emissions must be taken into account.

Due to the great variation in collection system for leakage water, it is important that the system under study reflect the actual technology applied in the geographical and temporal scope of the study.

To estimate leakage to soil and water from a landfill in an LCA, it is recommended to use a product based model to estimate the maximum emissions (no leakage water collection). Then process specific figures, representative for the geographical and temporal boundaries of the study, should be applied for the share of leakage water that is collected and the efficiency of this treatment. The efficiency of the treatment varies with substance and treatment technology.

Future landfills might be located close to the sea. In this way drinking water resources (ground water) are protected and leakage treatment considered less important. This means that we will have higher emissions from landfills in the future but that the resulting impacts will be of lower concern. E.g. risk assessment will show lower risks but a life cycle impact assessment will show higher impacts. This illustrates the importance of not looking solely on LCA results when considering environmental performance. Parallel evaluations based on different methodologies are often necessary. It also illustrates the need to continuously develop the "waste-LCA methodology", in this case to integrate risk into the assessment.

#### **4.4.4.5 Energy recovery**

Energy recovery related to landfills is relevant when the landfill gas is collected and incinerated with energy recovery. The energy can be exploited both as heat, electricity or mechanical energy, as other types of fuels.

The main component of landfill gas is CH<sub>4</sub> (about 50%). As an approximation it is common to assume that the energy recovery is related to CH<sub>4</sub> alone.

The energy recovered based on a product specific approach can be estimated from:

- The amount of CH<sub>4</sub> produced by the waste flow in question. This is calculated based on the waste composition as all waste fractions have their own specific CH<sub>4</sub> generation potential based on bio-available carbon and defined period of time where CH<sub>4</sub> generation takes place.
- The degree of CH<sub>4</sub> collected and incinerated.
- The net heat value of the CH<sub>4</sub>.
- Energy losses from combustion to delivered energy.

New landfills are usually required to have gas collection and flaring systems, while there are several old landfills that are lacking such systems.

- In Norway in 1995 approximately 25% of all landfills had gas collection system (ref. [www.ssb.no](http://www.ssb.no)).
- In Sweden in 1998 approximately 25 % of all landfills had gas collection (ref. <http://www.environ.se/>)

Most LCA studies assumes that in case of a landfill gas collection system, approximately 50% of the gas is collected and combusted. Assuming that the Norwegian and Swedish figures are valid for the present situation in Nordic countries (the values are probably higher as the large sites with much gas production probably has gas collection), about 13% of all landfill gas is collected with a variation within countries ranging from 0-50%.

The net heat value of CH<sub>4</sub> is typically 50-55 MJ/kg (depending on the conditions under which the gas is incinerated).

As a example on how estimate recovered energy we assume the following:

- Paper is sent to landfill.
- 240 kg CH<sub>4</sub> per ton paper is generated.
- 80% of the landfill gas (and CH<sub>4</sub>) is collected and incinerated.
- It is assumed that only CH<sub>4</sub> gives energy in the incineration process.
- CH<sub>4</sub> has a heat value of 50 MJ/kg.
- The efficiency of the incineration and energy recovery process is 90% (10% energy loss).

The recovered energy, which in a life cycle perspective substitutes another energy carrier, is estimated to be:

$$240 \cdot 0,8 \cdot 50 \cdot 0,9 = 8640 \text{ MJ/ton paper.}$$

## 4.4.5 Aerobic composting

### 4.4.5.1 System description

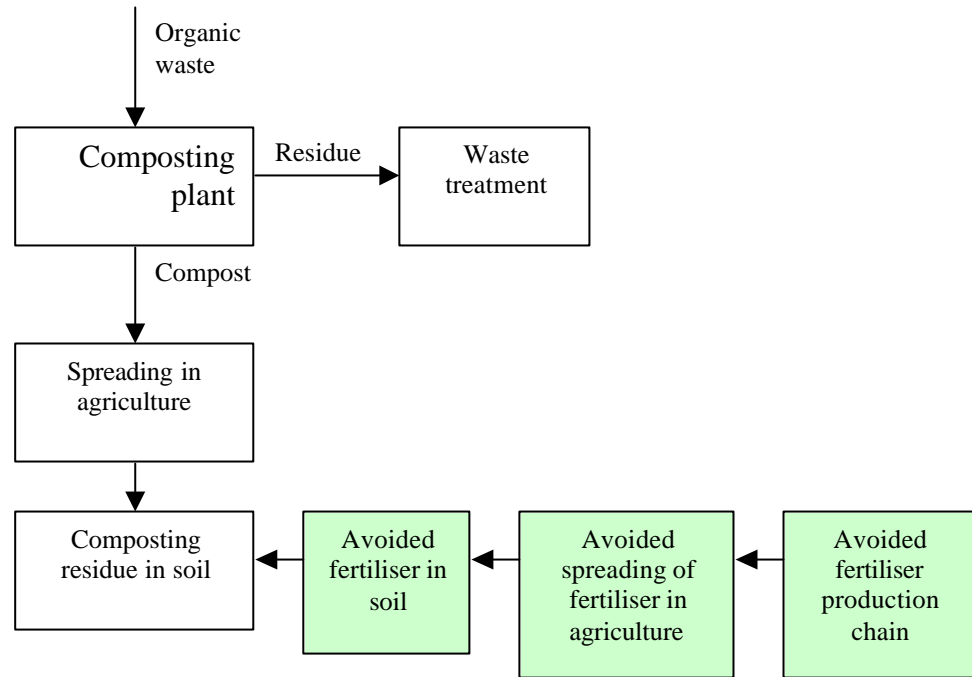
The composting system is relevant to apply to organic waste, although some small non-organic fractions can be expected due to fractions passing through source- or central separation. Data and information normally applied in a LCA composting model are:

- Overview of composting technologies applied in the temporal and spatial boundaries of the study. The technology usually includes pre-treatment (disintegration and mixing of the organic waste), some type of composting process(es) and post treatment (e.g. stabilisation, sifting and maturing). Also different types of air and water emission purification technologies are applied.
- Distribution of main waste flow on waste fractions (applies for the whole study).. The main waste flow should be separated on waste fractions that act differently in the composting process and give significantly different type and magnitude of emissions and gas production.
- Waste fraction contents (applies for the whole study). This gives the substances available for pollutant and product generation.
- Overview of the range of pollutants decided to be studied.
- Product specific models for potential generation of pollutants and distribution of pollutants on environmental compartments, residues and compost.
- Share of air and water emissions collected and treated.
- Efficiency of emission treatment.
- Process specific energy consumption and emissions such as operation of vehicles and machinery.
- Compost and residue generation.
- Amount and type of fertiliser substituted by produced compost based on compost quality.
- Amount and type of auxiliaries and related cradle-to-gate data.

Composting is modelled in several studies. Although some exceptions exist, most of the models are process specific based on one the following assumption:

- That the waste fraction composition does not change and that the waste composition for which process data is collected, are representative for the waste flow composition under study. This is e.g. the case if only one waste fraction is treated (food waste)-
- If the waste composition changes, all organic waste behaves approximately similarly (contain the same pollutants and have the same potential to generate products, product characteristics and emissions).

A process flow chart for composting is given in Figure 4-12. Note that some process units are given at a coarse level. These can be further refined (e.g. the composting plant). Further, emissions, resource consumption and energy use flows are not shown for the process units. Finally, transportation is excluded.



**Figure 4-12 Process flow chart for the aerobic composting system**

#### 4.4.5.2 Emission of CO<sub>2</sub> and CH<sub>4</sub>

As long as the waste that is degraded is organic waste and sufficient oxygen access is secured, generation of CH<sub>4</sub> is small. Nonetheless, specific data should be collected to document whether the CH<sub>4</sub> level is insignificant. Studies have shown that CH<sub>4</sub> can constitute over 10% of the air emissions from a closed and controlled composting plant.

It has also been documented that 1,5-2% of the biologically available carbon are emitted as CH<sub>4</sub> during composting of green waste /33/.

The same study says that about 80% of the carbon is emitted as CO<sub>2</sub>. The waste contained 30% carbon (weight), which gives a CO<sub>2</sub> emission factor of 880 kg/ton green waste.

The emitted CO<sub>2</sub> is regarded to be greenhouse gas neutral.

For the remaining carbon other carbon-related emissions must be estimated during the selected period of time for emission generation. After that, it must be decided whether the carbon sink approach is used, if it will be emitted during a infinite period of time, or whether it is excluded from the further estimates and evaluations (as for carbon remaining in landfills).

#### 4.4.5.3 Emissions to air (not CO<sub>2</sub> and CH<sub>4</sub>)

The approach for establishing product related emissions to air are similar to what is valid for emissions from landfill. The potential for generation of a pollutant is based on the contents of the waste flow and distribution factors for emissions to air and water and what remains in the compost and residue.

However, this study has not identified such models except for nitrogen /9/. This means that it is only possible to establish product specific models for these substances and related emissions.

If no product specific models are identified, process models must be applied. Process emissions to air from composting are available from measurements performed at composting plants. It is important that the measurements from plant technologies that are representative for the system under study are applied as there can be great variations. It is emphasised that little data exist, mainly due to the fugitive characteristics of the emissions. Performed measurements are mainly related to substances generating odour, and they are measured as concentrations. However, some data are developed. Air emissions from the composting process are given in Table 4-8. Figures for other emissions than the ones listed in the table have not been identified by this study.

**Table 4-8 Process specific emissions to air from composting**

Parameter	Unit	Mixed organic waste		Green waste (garden waste)	
		Bio-reactor, gas treatment unknown /32/	Various techn. without gas treatment /34/	Wood box without gas treatment /33/	Various techn. without gas treatment /34/
NH <sub>3</sub>	kg/ton waste	0,024	1,3	0,16	0,38
N <sub>2</sub> O	kg/ton waste	0,08	-	0,17	-
TOC	kg/ton waste	0,9	-	-	-
CO	kg/ton waste	-	-	0,27	-
VOC	kg/ton waste	-	0,80	-	1,7

To what extent emission control is efficient depends on the composting and control technology. In-vessel composting methods can collect approximately 100% of the air emissions for purification. This is not possible for more open methods. Efficiency data can be collected from scientific studies and from control equipment suppliers. Biological filters are perhaps the most common emission purification technology. An American study estimates the efficiency of such filters to be 75% and 90% for captured NH<sub>3</sub> and VOC respectively /34/.

#### **4.4.5.4 Emissions to water**

Water leaches from the compost as a result of the water content in the waste. In addition it comes from watering the compost and/or from rainwater. The heat in closed composting vessels can evaporate water that is condensed in colder areas and released. The amount of water generated will depend on several factors, but a rough estimate is 250-300 kg water per ton waste /32/. The concentration and amount of pollutants washed out with the water depends on the concentration of substances in the waste and the amount of water emitted.

Water emissions to ground, groundwater and surface water can more or less be avoided by appropriately designed composting facilities.

In case of central composting, the run-off water is collected and purified in a local wastewater treatment unit, or sent to the municipal water collection and treatment system.

In case of home composting, it is assumed that insignificant amounts of pollutants emitted in run-off water as long as the waste is garden waste.

Based on the above emissions to water from composting is regarded as a minor problem.



No product specific models have been identified in this study related to emission to water. Table 4-9 shows process specific emissions factors without water treatment. These emissions will be significantly reduced if water treatment is applied. To derive more relevant figures, pollution reduction factors can be applied according to e.g. municipal sewage treatment plants.

**Table 4-9 Emission factors for run-off water from composting /32/**

Parameter	Water in waste (mg/litre)	Condensed water (mg/litre)	Rain water (mg/litre)
COD	20.000-100.000	500-2.000	500-2.500
BOD <sub>5</sub>	10.000-45.000	100-1.000	100-1.200
TOC	5.000-18.000	<50-500	<50-500
P <sub>tot</sub>	50-150	<1	<1-50
NH <sub>4</sub> -N	50-800	<5-100	15-300
NH <sub>3</sub> -N	<5-190	<1	<5-150
Cl <sup>-</sup>	2.000-10.000	-	30-500
K <sup>+</sup>	1.000-7.300	-	-
Zn	1-8	0,2-0,6	<1-2
Pb	0,01-0,02	<0,1	<0,1-0,2
Ni	0,07-2,6	<0,04	<0,05-1
Co	0,01-0,2	<0,05	<0,05-0,2
Cd	0,01-0,2	<0,02	<0,05-0,2
Hg	-	<0,0005	-

#### 4.4.5.5 Compost

Data for the amount of compost generated for various presumptions are shown in Table 4-10.

**Table 4-10 Amount of compost generated**

Waste to composting	Technology	Compost	Additives	Ref.
Organic fraction of household waste	Reactor composting in closed room	590 kg pure compost per ton waste	340 kg wood per ton waste is added as stabilising substance.	/7/
Organic fraction of household waste	Reactor composting in boxes	450 kg pure compost per ton waste	170 kg wood per ton waste is added as stabilising substance.	/7/
Organic fraction of household waste	Open string technology	350 kg pure compost per ton waste	290 kg wood per ton waste is added as stabilising substance.	/7/
Sludge	Open string technology	600 kg pure compost per ton waste	400 kg wood per ton waste is added as stabilising substance.	/8/
Food waste	Open string technology	500 kg pure compost per ton waste	-	/9/

The amount of residues that are separated as non-compost is 50-300 kg per ton waste. This material flow should be subject to further waste treatment and should be treated as such in an LCA study /7/, /8/.

Compost quality, how to estimate the amount of substituted fertiliser, content of toxic compounds and leakage of these are treated in section 4.4.9.

## 4.4.6 Anaerobic digestion

### 4.4.6.1 System description

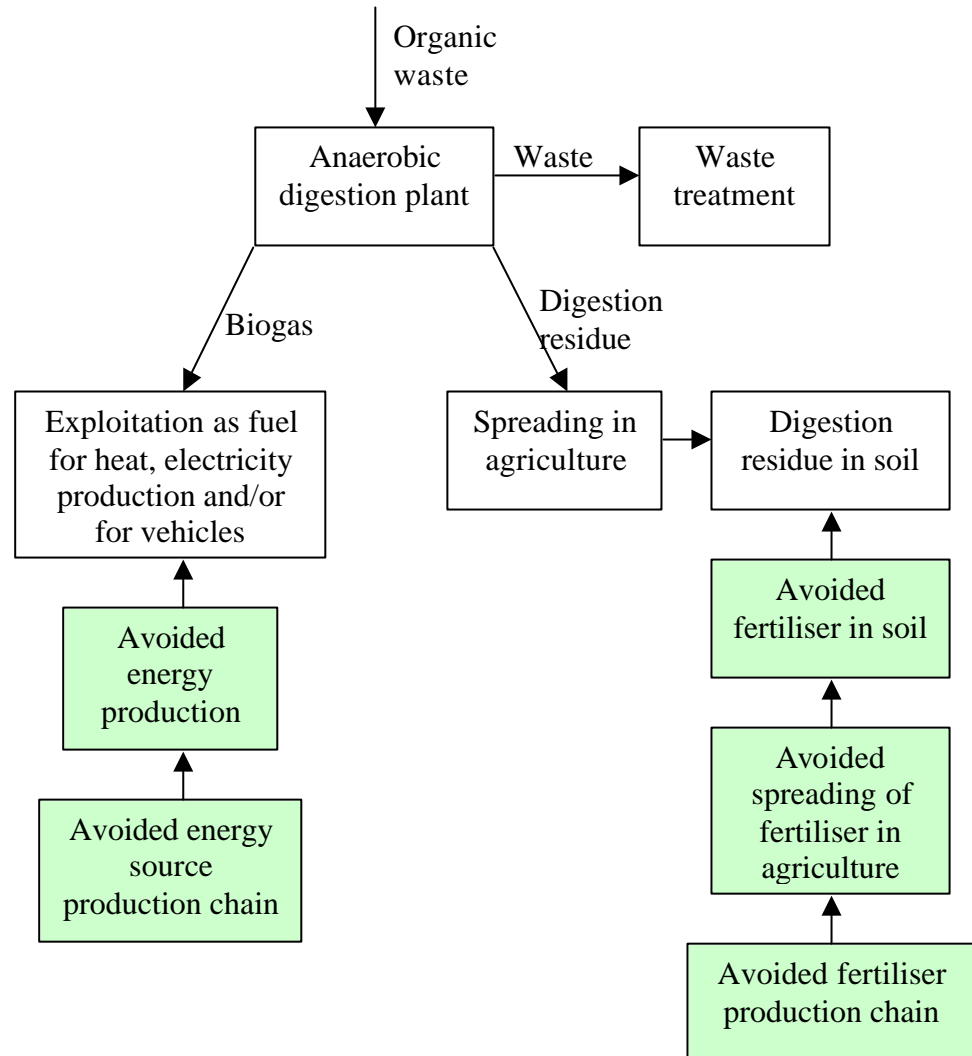
The anaerobic digestion system is relevant to apply to organic waste, although some small non-organic fractions can be expected due to fractions passing through source- or central separation. Data and information normally applied in an LCA anaerobic digestion model are:

- Overview of technologies applied in the temporal and spatial boundaries of the study. The technology usually includes pre-treatment (disintegration, mixing and pre-heating of the organic waste), some type of digestion process(es) and post treatment (e.g. stabilisation, sifting and maturing). Also different types of air and water emission purification technologies are applied.
- Distribution of main waste flow on waste fractions (applies for the whole study).. The main waste flow should be separated on waste fractions that act differently in the process and give significantly different type and magnitude of emissions and gas production.
- Waste fraction contents (applies for the whole study). This gives the substances available for pollutant and product generation.
- Overview of the range of pollutants decided to be studied.
- Process specific energy consumption and emissions such as operation of vehicles and machinery.
- Product specific models for potential generation of pollutants and distribution of pollutants on environmental compartments, residues and compost.
- Share of air and water emissions collected and treated.
- Efficiency of emission treatment.
- Compost, residue and energy generation (or any other generated product).
- Type and amount of fertiliser substituted by produced compost based on compost quality.
- Type and amount of energy substituted by recovered energy.
- Amount and type of auxiliaries and related cradle-to-gate data.

Relevant waste fractions for anaerobic digestion are organic waste such as food waste, paper and cardboard, garden waste, edible oil and fat and sludge.

Micro-organisms digest the waste and/or sludge in a controlled environment without any presence of air. This process produces biogas (mainly methane), which can be collected and exploited. The residues can be further treated to become compost.

An overview of a system model for anaerobic digestion is given in Figure 4-13



**Figure 4-13 Process flow chart for the anaerobic digestion system**

Related to the figure, note that some process units are given at a coarse level in the figure. These can be further refined. The following is not reflected:

- E.g. the bioreactor plant can be split into processes such as pre-treatment (homogenisation and thermal treatment), dewatering, digestion and composting. The thermal treatment process is for sterilisation purposes and to improve the digestion process.
- Transportation processes, emissions, resource consumption, auxiliary material use and energy use flows are not shown in the figure.
- A liquid phase can be separated from the waste flow in the dewatering process. This liquid can be used as a carbon source for biological wastewater treatment plants. This potential product, and the product that presumably is substituted (e.g. ethanol), is not included in the figure.

The bioreactors can be divided into wet and dry processes. The wet process mixes the waste with so much water that it can be pumped through the process (typically 15% dry matter). On the negative side this requires energy, water, larger reactor volumes and produces more effluent. The dry process has typically 30-35% dry matter.

Process temperature is used to regulate the digestion time, hence also the reactor capacity or volume. It is in this respect common to separate between mesophilic (30-40<sup>0</sup>C) and thermophilic (50-60<sup>0</sup>C) processes. Experience from a bioreactor plant in Finland using a wet process gives 10 days digestion time for a thermophilic process and 20 days for a mesophilic process /7/.

Table 4-11 gives some typical data collected from various bioreactor treatments of household waste. Note that this process includes separation of the organic fraction from the mixed residual household waste.

**Table 4-11 Typical process data for anaerobic digestion**

Environmental parameter	Unit (per ton waste)	Plant 1 /7/	Plant 2 /7/	Plant 3 /9/	Plant 4 <sup>#</sup> /29/
Technology	-	wet mesophilic	dry mesophilic	wet mesophilic	wet thermophilic
Waste type	-	organic waste	organic waste	organic waste	Sludge
Electricity consumption	MWh	0,05	0,038	0,009	
Heat consumption	MWh		0,025	0,138	0,94
Waste water	m3	0,56			
Reject for other treatment	ton		0,22		
Produced compost	ton	0,67	0,69	0,86	0,58
Produced biogas	m3	130	145	99	370

<sup>#</sup> All data are given per ton dry substance entering the plant Note that the process requires more energy than the others because it contains thermal hydrolysis. This gives a quicker process and better compost quality.

There are significant technical differences from plant to plant, and as seen from the table, this leads to significant differences in the performance of the plants. It is therefore important to use plant specific information for the waste type defined by the system description and within the geographical and spatial boundaries defined in the scope of the study.

Also, the compost product could be of varying quality. This will quantitatively not be taken into account unless the “in soil” environmental impacts are taken into account. As a minimum requirement such differences must be described qualitatively in comparative studies.

Based on experience from LCAs carried out for anaerobic digestion plants, the aspects influencing the environmental performance the most are the amount of recovered energy and the amount of composting residue substituting fertilisers. In addition comes the emissions caused by the plant and the consumption of energy and materials such as e.g. lime added to sludge to improve compost quality. In the latter case it is important also to include the production chain for the added materials.

#### 4.4.6.2 Emission of CO<sub>2</sub> and CH<sub>4</sub>

The main purpose of anaerobic digestion is to generate biogas that can be exploited as an energy source. The process takes place in a closed and controlled environment with no access to air where bacteria digest the organic waste. As the biogas is collected and combusted, it is transformed mainly into CO<sub>2</sub>, but CH<sub>4</sub> will also be present in the off-gas. As the waste flow is approximately 100% organic, all CO<sub>2</sub> emissions are greenhouse gas neutral.

CH<sub>4</sub> might also be emitted due to fugitive emissions during biogas storage.

Emissions of CH<sub>4</sub> and CO<sub>2</sub> are also related to the pre- and post-treatment processes, which requires fuel and/or electricity as heat and mechanical energy sources.

The heat consuming processes at the anaerobic digestion plant is often supplied with energy from the recovered biogas.

Both the type and magnitude of fuel and electricity consumption will be plant specific.

#### **4.4.6.3 Emissions to air (not CO<sub>2</sub> and CH<sub>4</sub>)**

Other emissions to air are (as for CO<sub>2</sub> and CH<sub>4</sub>) related to:

- Direct emissions from the degradation process.
- Combustion of fuel supplied to the plant.
- Production of electricity supplied to the plant (common for all processes within the same geographical boundaries).
- Combustion of the biogas (either at the site or it can be exported as a fuel, e.g. for buses).

Emission factors for fuel can be derived from onsite measurements or from generic data related to similar transport means or machinery.

Emission factors for biogas combustion are available from e.g. specific sites combusting biogas and from the companies responsible for biogas a bus fuel (e.g. bus companies in Uddevalla, Sweden or Fredrikstad, Norway).

#### **4.4.6.4 Emissions to water**

The water content of the waste/sludge is usually undergoing several processes and chemicals might be added. Hence, it is difficult to estimate the content of pollutants in water based on the waste/sludge composition. The excess water can be exploited as a carbon source and as source very little reject water is generated. Potential reject water is usually treated in wastewater treatment plants. The amount of reject water and the contents of pollutants are impossible to quantify without also specifying the applied technology. Therefore, no generic data is given here, and it is recommended to only apply data that is specific for the relevant technology.

#### **4.4.6.5 Energy recovery**

The energy provided by the CH<sub>4</sub> from the digestion system per functional unit (FU) will vary a great deal depending on technology. Hence, it is difficult to give generic figures for a geographical area unless data are collected from a representative share of the relevant plants in the area. Generally, the recovered energy is calculated by:

$$E = G \cdot H \cdot R \cdot M$$

E is the recovered energy (MWh/FU)

G is produced biogas (m<sup>3</sup>/ton waste)

H is heating value of the biogas (MWh/m<sup>3</sup>)

R is share of produced energy that is exploited, subtracted what is used by the process itself ( $(MJ_{\text{exploited}} - MJ_{\text{internal use}})/MJ_{\text{produced}}$ )

M is the amount of waste (ton waste/FU)

How the recovered energy is distributed on heat and electricity production and what type of energy that is substituted is of course specific for the selected plants that are representative for the temporal and spatial boundaries of the study.

An anaerobic digestion plant operating with high temperatures, such as e.g. plants with thermal hydrolysis as pre-treatment, may require so much energy that all the biogas is used as energy for internal heat production. If we look at the biogas production in Table 4-11 and assume a biogas heat value of 6 kWh/m<sup>3</sup>, the energy efficiency of the plants (1-1 relationship between consumed energy and produced energy) is in the range 0,58-0,94. Note that low energy efficiency is not necessarily negative. It can indicate that there is more focus on compost quality and by-products that require high treatment temperatures.

#### **4.4.6.6 Compost and other products**

As for all the other parameters related to anaerobic digestion, also the products vary a great deal. This is both the amount of product and the type of products. Some plants are focused on biogas generation and others on soil improvement products and other by-products (e.g. carbon source). Again data should be quantified based on a process specific data for relevant technology.

Compost quality, how to estimate the amount of substituted fertiliser, content of toxic compounds and leakage of these are treated in section 4.4.9.

## 4.4.7 Biocells

### 4.4.7.1 System description

In principle biocells are anaerobic digestion (bioreactors) carried out in batches, usually under less controlled ambient conditions. It can also be seen as an improved landfill, especially with respect to biogas collection and treatment of leakage.

Compared to a landfill biocells have:

- More efficient biological turnover
- Better collection of biogas
- More efficient land use
- Low production of leakage water
- Better quality of leakage water

Note that even though bioreactors usually have better performance data than biocells, it usually also calls for larger investments. Also, biocells can be more technically feasible than bioreactors when the input is residual waste not only containing organic waste.

The biocell system is relevant to apply to mixed municipal waste, preferably with a high organic content. Data and information normally applied in an LCA biocell model are:

- Overview of technologies applied in the temporal and spatial boundaries of the study.
- Distribution of main waste flow on waste fractions (applies for the whole study).. The main waste flow should be separated on waste fractions that act differently in the process and give significantly different type and magnitude of emissions and gas production.
- Waste fraction contents (applies for the whole study). This gives the substances available for pollutant and product generation.
- Overview of the range of pollutants decided to be studied.
- Process specific energy consumption and emissions such as operation of vehicles and machinery.
- Product specific models for potential generation of pollutants and distribution of pollutants on environmental compartments, residues and compost.
- Share of air and water emissions collected and treated.
- Efficiency of emission treatment.
- Residue and energy generation (or any other generated product).
- Type and amount of energy substituted by recovered energy.
- Amount and type of auxiliaries and related cradle-to-gate data.

Little information has been derived that gives inventory data for biocells. However, some information is given below based on the only identified Nordic study on this waste treatment alternative /37/. This study includes collection of experience data and information and a LCI model (applied in ORWARE).

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Compared to a landfill biocells have:

- More efficient biological turnover
- Better collection of biogas
- More efficient land use
- Low production of leakage water
- Better quality of leakage water

Note that even though bioreactors usually have better performance data than biocells, it usually also calls for larger investments. Also, biocells can be more technically feasible than bioreactors when the input is residual waste not only containing organic waste.

In general the system model for a biocell is the same as for landfill. The differences are related to the input and output data. The main purpose of the biocell is to recover as much biogas as possible. To do so it is more common to add auxiliary materials than it is for landfill. Such materials, that should be included in an LCA, are typically:

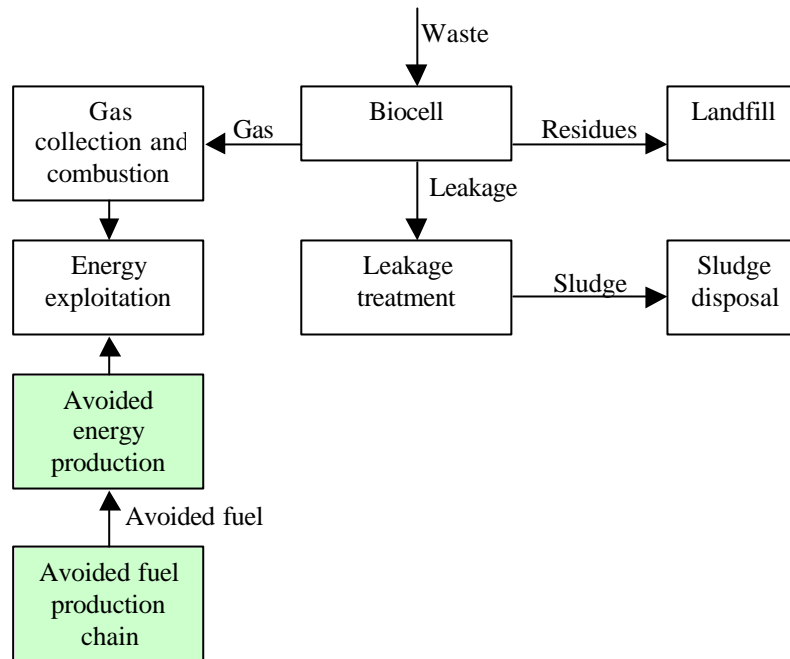
- Water and air injection.
- Phosphorous, to optimise degradation (1-2 kg/ton household waste).
- Pre-combusted waste (ash), to establish anaerobic conditions at the bottom of the cell. A decision must be taken on whether the ash shall be regarded as a product, a resource or waste. If it is regarded as a product the production of ash (incineration process) should be allocated to the system. If it is regarded as a resource, no production impacts are allocated. If it is perceived as waste, the system should be credited the reduced amount of waste. To make such a decision, the analyst could evaluate the monetary flow related to the ash. If the biocell company buys the ash it should be regarded as a product. If the company get paid for receiving the ash, it should be regarded as waste. If the ash is free it should be regarded as a resource (not limited).

An overview of a system model for biocell is given in Figure 4-14. It can be argued that the fraction remaining after opening the biocell can be used as soil improvement products. In that case the system should include this post-treatment of the product and the production chain of the substituted product. The main reason for not including it here is that the acceptance for such a product is unlikely due to the content of pollutants and lack of data. Inclusion of the relevant processes would be more or less based on speculations.

Note that some process units are given at a coarse level. These can be further refined (e.g. the avoided energy and related production chains). Further, emissions, resource consumption and energy use flows are not shown for the process units. Finally, transportation is excluded.

All the flows in the system are relative to the waste flow entering the system. This municipal waste flow is the whole or a share of the reference flow resulting from the functional unit.





**Figure 4-14 Process flow chart for the biocell system**

As for all other treatment alternatives the data applied to the model can be based on a product or process approach or a combination of these. The process approach uses plant specific data, but does not have the ability to reflect changes in the waste composition in the calculated results. The product based approach gives this opportunity, but should be calibrated against process data representative for the spatial and temporal scope of the study to minimise errors.

As for landfill, which takes place over a long period of time, the emissions can be divided into surveyable time emissions and remaining time emissions (ref. section 4.3.5). However, the surveyable time could be set similar to the biocell lifetime (from closing to opening). The remaining time would then be relevant for the biocell residues if sent to landfill.

#### 4.4.7.2 Emission of CO<sub>2</sub> and CH<sub>4</sub>

Biocells are constructed in such a way that methane tends to oxidise when passing through the protection layer. It is indicated that the methane emissions are less than 10% of the formation (i.e. less than 10 m<sup>3</sup>/ton mixed household waste, based on the figures given in section 4.4.7.6).

Experience data from operation of 12 Swedish biocells for 5 years gives the following results, which must be multiplied with the biocell lifetime (10-15 years):

- CH<sub>4</sub>: 3-10,3 m<sup>3</sup>/yr/ton (average 5,7 m<sup>3</sup>/yr/ton). Less than 10% of this is emitted.
- CO<sub>2</sub>: 2,9-7,6 m<sup>3</sup>/yr/ton (average 4,9 m<sup>3</sup>/yr/ton). All is emitted. The major part of the CO<sub>2</sub> is non-fossil based. The fossil/non-fossil CO<sub>2</sub> must be estimated based on the waste fractions and their degradation within the biocell lifetime.

In general, the different categories of CH<sub>4</sub> and CO<sub>2</sub> emissions as described in Figure 4-11 for landfill, also apply for biocells.

The methane gas formation will of course vary with the ambient conditions, technical conditions and the waste composition. The ORWARE biocell model enables differentiation between household waste mix, sludge and ash and slag from incineration.

Experience shows that the biogas production does not increase proportional to the content of fast biodegradable waste such as food and garden waste. In order to obtain high rates of biogas production under the whole treatment period, the amount of fast biodegradable waste must be limited.

#### **4.4.7.3 Emissions to air (not CO<sub>2</sub> and CH<sub>4</sub>)**

No data or information has been identified. However, there are reasons to believe that the potential substances are the same as for landfill. Although, in smaller amounts due to the closed environment and less mass transport of gases and micro pollutants.

#### **4.4.7.4 Emissions to water**

Typically 0,3 litre leakage water is produced per kg household waste (compared to 2 litre/kg for landfill and 0,1 liter/kg for bioreactors).

Both less leakage water and lower concentration of pollutants in the water result in less leakage impacts compared to a traditional landfill. The main reason for less water generation is due to less intrusion of water into the biocell. The level of pollutants is lower because the bottom layer consists of pre-combusted material and anaerobic conditions are established here. The layer then acts as an anaerobic filter for the leakage water, degrading dissolved carbon substances. Experience data shows 30-85% reduction of COD concentration versus a traditional landfill.

#### **4.4.7.5 Biocell residues**

As previously mentioned it can be argued that the fraction remaining after opening the biocell can be used as soil a improvement product. However, the acceptance for such a product is unlikely due to the content of pollutants and lack of data. In a future perspective, with improved source separation and subsequent improved waste quality, this usage could be possible.

A more probable usage is as top/side covers at landfills or new biocells. However, this might require further stabilisation to avoid potential odour problems.

The residues might also end up as landfill waste, with related environmental impacts.

#### **4.4.7.6 Energy recovery**

Some characteristics for biocell energy recovery are:

- The period of time that methane is produced is 10-15 years.
- For mixed household waste ~200 m<sup>3</sup>/ton biogas is generated (~250 m<sup>3</sup>/ton including air intrusion). About 100 m<sup>3</sup>/ton is methane gas.
- Typically 60-70% of the methane gas is collected in a biocell.
- An LCA must consider how the gas is exploited and what type and magnitude of energy sources that is substituted by the energy recovery.

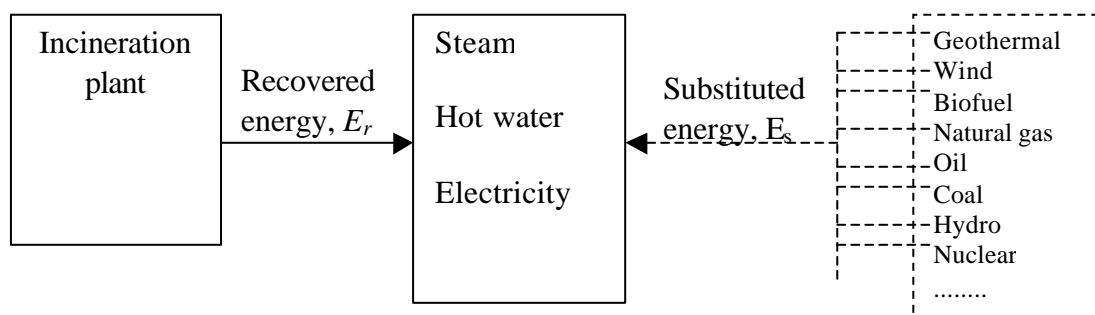
#### 4.4.8 Substituted energy

Energy sources in other systems are substituted when recovered energy from the system under study are exploited and replaces other energy sources. This is relevant for energy recovered from incineration plants, energy recovered when incinerating collected landfill gas, energy recovered through use of collected biogas from anaerobic digestion, and energy recovered when using biogas from biocells.

##### 4.4.8.1 Substituted energy sources

The amount of energy substituted equals the amount of energy from the waste treatment that is exploited.

The distribution of substituted energy sources is illustrated in Figure 4-15.



**Figure 4-15** Illustration of distribution of substituted energy

First of all it must be decided whether to use a retrospective or a prospective approach (should be defined in the scope). In a retrospective study the historic and present energy supply situation is used as a basis. The following steps should be followed when identifying substituted energy sources in a historic/present perspective:

- Quantify how exploited energy is distributed on steam to industrial processes, hot water to district heating and electricity production.
- Check with the companies that use/produce steam what would be the alternative energy source(s) if the steam is not provided. If several energy sources are relevant the distribution of these in a long term must be quantified.
- Check with the electricity producers, what will be the energy source for electricity production, if additional electricity is needed.

In a prospective study future energy supply scenarios are defined. In general, the marginal energy source should be applied and the retrospective and prospective approaches can lead to different marginal energy carriers.

In a short-term perspective, at an existing plant, the marginal energy carrier is usually the lowest priced energy source that is technically and legally feasible. In most cases this involves some kind of fossil fuel (oil, coal, natural gas). However, also other energy forms might be relevant, especially if energy is recovered in the form of electricity.

In a long-term perspective the marginal energy source will be the energy source taken out if energy consumption is reduced, or the energy source installed if the energy consumption is increased. This is perhaps more a result of political goals, rather than short-term economic considerations.

Whether to use a short- or a long-term perspective will depend on the goal and scope of the study. E.g. to analyse future scenarios (prospective approach) a long-term perspective should be preferred.

In many studies where electricity is replaced, the present form of producing electricity is selected as the energy form to be replaced. This is not the marginal energy form (although it can be). The energy form can be the energy source mix used for electricity production in the nation in question. The energy mix used for electricity production in the Nordic countries in 2000 according to Nordel (<http://www.nordel.org/>) are given in Table 4-12.

**Table 4-12 Total electricity generation by energy source, and net imports and exports 2000, TWh (ref. NORDEL statistics at <http://www.nordel.org/>)**

	Denmark	Finland	Iceland	Norway	Sweden
Net imports	0.7	11.9			4.7
Geothermal power			1.3		
Wind power	4.2	0.1		0.0	0.4
Other *	3.8			0.4	
Biofuel	1.7	13.2			3.6
Natural gas	8.0	8.0		0.2	0.5
Oil	0.1	1.5			2.8
Coal	16.4	8.4			1.9
Nuclear power		21.6			54.8
Hydropower	0.0	14.4	6.4	142.1	77.8
Net exports (negative value)				-19.0	

\* In Denmark orimulsion (a fossil fuel produced from natural bitumen mixed with water) and refinery gas.

As the liberalised market for electricity in Europe comes into effect through improved distribution nets, it may be difficult to define the energy mix of a region, as energy will flow across national borders. It is then relevant to apply the energy mix used for electricity production on an average European level.

In case of introducing recycling of materials instead of incineration it is important to realise that very often the fuel substituting a specific waste fraction can be another waste fraction. This is because the incinerator capacity is often limited which means that if one waste fraction is recycled instead, another waste fraction (which perhaps is currently landfilled) can be incinerated. The capacity restriction will however vary from region to region. In some areas there might even be over-capacity. It is therefore important to relate such a presumption to the geographical boundaries of the study.

#### 4.4.8.2 Pollution related to substituted energy sources

The pollution and related impacts from energy sources that are substituted by recovered energy should preferably be subtracted from the life cycle inventory of the municipal waste. This is equivalent to a system expansion which is ISO's first recommendation before allocation is investigated. This means that emission data (and

other environmental impact data) for all energy sources (at least the ones listed in Table 4-12) can potentially come into use.

There are several problems related to derive pollution data, both due to great variations in energy plants using the same energy source, and due to the variety and forms of environmental impacts. E.g. combustible energy sources such as fossil fuels have environmental impacts that are traditionally treated in an LCA (emissions to air and water). Hydro and nuclear power give environmental impacts such as land occupation, esthetical disturbance, hazardous waste and human/environmental risk, which are aspects that can be quantified with established methodological models.

Due to the great number of energy producing installations and the variety in technology, it is not reasonable to list plant specific pollution data for substituted energy sources within the frames of this study. However, if the available LCA study scope and resources allow for it, plant specific data should be collected and applied.

Ideally, the whole life cycle of the substituted energy sources should be taken into account. This means that e.g. for oil, coal, natural gas nuclear fuels, extraction, production and distribution should be taken into account in addition to the operational pollution. Such data are available for most energy sources in life cycle inventory databases.

Life cycle assessments have been performed for most fuels and energy sources. Hence, it should not be difficult to obtain generic data. An example of a comprehensive data source is the EU project ExternE. The results of work performed in several European countries (including Denmark, Sweden, Finland and Norway) are presented in reports available online at <http://externe.jrc.es/>.

#### **4.4.9 Substituted fertilisers and fertiliser impacts**

##### **4.4.9.1 What is substituted?**

Both sludge treatment, aerobic composting and anaerobic digestion of organic waste are processes that can produce products that can be used as fertilisers or additions in soil products due to high contents of nutrients.

The products can replace artificial fertilisers, although there are great uncertainties related to what extent the artificial fertilisers are replaced. I.e. how many ton artificial fertiliser is replaced by one ton compost?

The nutrient content of the compost is defined by the content of nitrogen (N) and phosphorous (P). Hence, the compost can replace both artificial N-fertiliser and P-fertiliser. Table 4-13 gives content of nutrients in sludge and compost. The sludge related data are collected from 18 Norwegian sludge treatment plants, while the figures for compost (from municipal waste) are derived from a range of European studies /28/.

**Table 4-13 Content of nutrients in sludge and compost /28/**

Parameter	Sludge (kg/ton dry matter)	Compost (kg/ton dry matter)
NH <sub>4</sub> -N	0,4 - 7,8	0,18 - 0,78
Tot-N	3 - 29	7,9 - 23,3
Tot-P	4 - 22	1,9 - 5,4
Ca	3 - 190	27 - 35,3
K	0,7 - 2,7	5,3 - 14,8

It is more difficult to obtain representative figures for compost than sludge due to a larger variation in composition. The level of available N is lower and the compost will to a less extent replace fertilisers compared to sludge. The homogeneity will be influenced by the organic waste composition, which again is influenced by the composition at the source, the quality of organic waste separation and the treatment technology.

Note that the approach presented here takes into account the nutrition potential of compost as a basis for assessing what products that are substituted and estimation of the amount of avoided artificial fertiliser.

There might be other benefits of artificial fertilisers that are lost due to the substitution, e.g. lime in fertiliser that affect soil acidity. Or vice versa if compost has other benefits that the replaced product has not, e.g. increasing the soil's organic carbon content, added structure to soil and changed water balance. Such additional effects are difficult to quantitatively take into account in an LCA. However, it is important to address these issues when defining the functions of the competing products.

#### 4.4.9.2 How much is substituted?

The amount of artificial fertiliser substituted depends on whether the soil limits the amount of compost with respect to N or P. To decide this, figures for recommended annual doses for N and P in soil can be used (kg/ha-year). The ratio between recommended N-dose and recommended P-dose can be used as a reference value. If the exploitable N/P ratio in compost is larger than the reference value the compost is N-limited and vice versa. As a simplification the total N and P content can be used instead of the exploitable, although it is recommended to use the exploitable content.

$$\frac{N_{comp}}{P_{comp}} \approx \frac{N_{comp,expl}}{P_{comp,expl}} > \frac{N_{limit}}{P_{limit}} \Rightarrow N - limited$$

$$\frac{N_{comp}}{P_{comp}} \approx \frac{N_{comp,expl}}{P_{comp,expl}} < \frac{N_{limit}}{P_{limit}} \Rightarrow P - limited$$

Where:  $N_{comp}$  = The N-content (kg/ton) in the compost

$P_{comp}$  = The P-content (kg/ton) in the compost

$N_{comp,expl}$  = The exploitable N-content (kg/ton) in the compost

$P_{comp,expl}$  = The exploitable P-content (kg/ton) in the compost

$N_{limit}$  = Recommended annual N-dose in soil (kg/ha-year)

$P_{limit}$  = Recommended annual P-dose in soil (kg/ha-year)

A Swedish study presents maximum N-dose = 90 kg/ha-year and P-dose = 15 kg/ha-year, which gives  $N_{limit}/P_{limit} = 90/15 = 6$ . The residue of anaerobic digestion is analysed with an N-content of 7,6 kg/ton and a P-content of 1,1 kg/ton. The  $N_{comp}/P_{comp}$  ratio is then 6,9. This is larger than 6 and the compost is therefore N-limited /9/.

The limit for exploitable N-content in the compost is calculated by:

$$\frac{N_{comp,limited}}{P_{comp,expl}} = \frac{N_{limit}}{P_{limit}} \Rightarrow N_{comp,limited} = \frac{N_{limit}}{P_{limit}} \cdot P_{comp,expl} = 6 \cdot 1,1 = 6,6 \text{ kg / ton}$$

Alternatives to the N- or P-limited approach are to use both the N- and P-content directly or it is possible only to focus upon N or P as a basis for substitution.

### N-limited substitution

Most N in compost is bound up organically, while only a small share is mineral based nitrogen ( $NH_4^+$ ,  $NO_2^-$  and  $NO_3^-$ ). Studies on sludge carried out by Planteforsk in Norway shows that about 80% of mineralised N and 10% of organic N can be exploited the first year, and 10% of the remaining N each year after that. These figures are directly comparable with the nitrogen content of artificial fertilisers /7/.

Based on Table 4-13 and only taking into account the first year of nutrition, the available N is 0,6 – 9,1 kg/ton for sludge and 0,9 – 2,9 kg/ton for compost (dry matter).  $NO_2^-$  and  $NO_3^-$  are assumed negligible. Note that taking only the first year into account is an underestimation. Ideally integration of the nutrition uptake function should be performed over the period of time where the nutrition takes place.

To estimate the amount of N-fertiliser that is replaced, it is necessary to know the N-content of the fertiliser. Figures for N-content of N-fertilisers produced by the worlds largest mineral fertiliser producer (Hydro Agri) are given in Table 4-14 (ref. <http://www.agri.hydro.com/>).

Based on the fact that available N in sludge and compost is 0,5 – 4 kg/ton and the second column in Table 4-14, the amount of sludge or compost to replace 1 ton artificial N-fertiliser is calculated. This is given in the third and fourth column in Table 4-14.

**Table 4-14 Nitrogen content of N-fertilisers supplied by Hydro Agri and the magnitude substituted per ton compost (dry weight)**

Nitrogen fertilisers	Tot-N (kg/ton)	Substitution sludge (kg/ton dry matter)	Substitution compost (kg/ton dry matter)
Calcium nitrate	155	4 - 59	6 - 19
Calcium ammonium nitrate	250 - 280	2 - 36	3 - 12
Ammonium nitrate	340	2 - 27	3 - 9
Urea	460	1 - 20	2 - 6
Nitrogen solutions (mainly UAN)	280 - 320	2 - 32	3 - 10
Ammonium sulphate	210	3 - 43	4 - 14

#### P-limited substitution

To be able to estimate the amount of P-fertiliser that is replaced, it is necessary to know the P-content of the fertiliser. Figures for P-content of P-fertilisers produced by the worlds largest mineral fertiliser producer (Hydro Agri) are given in Table 4-15 (ref. <http://www.agri.hydro.com/>).

Assuming that all phosphorous in sludge and compost are available for uptake, the content given in Table 4-13, and the second column in Table 4-15, the amount of sludge or compost to replace 1 ton artificial P-fertiliser can be calculated. This is given in the column 3 and 4 in Table 4-15.

**Table 4-15 Phosphorous content of P-fertilisers supplied by Hydro Agri and the magnitude substituted per ton compost (dry weight)**

P-fertilisers	P (kg/ton)	Substitution sludge (kg/ton dry matter)	Substitution compost (kg/ton dry matter)
Hydro-P <sup>TM</sup> 8	80	50 - 275	24 - 68
Raw phosphate	160	25 - 138	12 - 34
Hydro-PK <sup>TM</sup> 5-17	47	85 - 468	40 - 115

Note that these fertilisers also contain kalium (latter product) and sulphur that can give additional positive effects.

A study performed by The Norwegian Crop Research Institute (Planteforsk) reveals that 35% of the P in compost from biowaste is bioavailable, and 8% of the P in compost from sludge /36/. This indicates that the assumption made above, saying that all phosphorous is available for uptake, is not valid. Applying this would reduce the values in the table above significantly.

#### **4.4.9.3 Processes related to compost exploitation**

There are mainly two processes related to compost exploitation that are associated with environmental impact. These are, in addition to transport activities, the spreading of the compost and the leakage of pollutants from the compost and into the recipients.

The latter processes is often omitted in LCA applied in the waste management sector, but should ideally be included as there could be significant differences between artificial fertilisers and compost with respect to the contents of pollutants.



### Spreading of compost

The spreading process itself will probably not differ between fertiliser and compost. However, the amount of material that is spread is greater for the compost, and therefore it requires more energy for the transport and spreading. If the spreading of fertiliser and compost can be regarded to be about the same, this process will not have to be taken into account.

The main environmental impact associated with this process is the consumption of fuel and related combustion exhaust gases. Data for emitted exhaust gases per unit fuel are usually easy to obtain (e.g. from spreading vehicle manufacturer) and are therefore not treated any further here.

The fuel is usually diesel. The amount of diesel consumed per ton sludge or compost (F) can be given as  $F = C \cdot L / A$ , where:

- $A$  (ton/ha) is the amount of compost per area. This parameter can be given specifically for the study or national regulations can be used as a maximum area. Remember to take into account the wet fraction if  $A$  is given based on dry fraction.
- $L$  (m/ha) is the driving distance of the tractor/spreader per ha of spreading. This parameter can be estimated based on the working width of the spreader.
- $C$  (MJ/m) is the fuel consumption per driving distance of tractor/spreader. This parameter can be derived e.g. from vehicle manufacturer.

### Sludge and compost in soil

Sludge and compost always contain some pollutants that can be transferred to the soil. The content of pollutant in sludge and compost will of course depend on the pollution level in the origin flows (wastewater and organic waste) and the technology applied to treat these flows. It can be assumed that all the pollutants end up in the soil.

However, note that artificial fertilisers will also contain pollutants that must be considered if the compost pollutants are considered.

Table 4-16 and Table 4-17 give data for pollution level in sludge and compost /28/. The data are from Norway and collected during 1997-2000. The data are mainly for exemplification as these data tend to be very case specific.

The figures for organic pollutants in sludge are gathered from 7 Norwegian municipal wastewater treatment plants. One sample is mixed over a month of sludge production. Five such samples are taken from each plant.

The figures for organic pollutants in compost are gathered from 9 samples of compost from Norwegian household waste

The figures for heavy metals in sludge are gathered from mixed monthly samples from all Norwegian wastewater treatment plants with dehydration of sludge.

The figures for heavy metals in compost are gathered from mixed samples from 9 Norwegian composting plants (two reactors and seven open air plants). Source separated organic waste from households was composted.

**Table 4-16 Contents of pollutants in sludge and composted sludge /28/**

Parameter	Unit	Sludge			Composted sludge
		Average	Min.	Max.	
Dioxins/furanes	ng/kg TS	10,6	3,1	69,3	-
PCB	mg/kg TS	0,05	0,02	0,10	
PAH	mg/kg TS	6,0	0,7	30,3	0,084
Creosols	mg/kg TS	35,5	n.d.	470	
Nonylphenol/-ethoxilates	mg/kg TS	171	22	650	
Phtalates (DBP and DEHP)	mg/kg TS	81	n.d.	192	7,4
LAS	mg/kg TS	85	n.d.	424	116
Cd	mg/kg TS	1			
Pb	mg/kg TS	21			
Hg	mg/kg TS	0,9			
Ni	mg/kg TS	15			
Zn	mg/kg TS	317			
Cu	mg/kg TS	244			
Cr	mg/kg TS	25			

**Table 4-17 Contents of pollutants in compost from organic fraction of municipal waste /28/**

Parameter	Unit	Average	Min.	Max.
Dioxins/furanes	ng/kg TS	4,4	0,5	11,9
PCB	mg/kg TS	0,024	0,003	0,078
PAH	mg/kg TS	1,36	n.d.	3,77
Creosols	mg/kg TS	2	n.d.	22
Nonylphenol/-ethoxilates	mg/kg TS	n.d.	n.d.	-
Phtalates (DBP and DEHP)	mg/kg TS	8,0	n.d.	29,2
LAS	mg/kg TS	85	14	185
Cd	mg/kg TS	0,36	<0,3	0,59
Pb	mg/kg TS	20	<5	37
Hg	mg/kg TS	0,11	<0,05	0,38
Ni	mg/kg TS	10	<2	17
Zn	mg/kg TS	197	46	320
Cu	mg/kg TS	52	24	78
Cr	mg/kg TS	14	<5	20

#### 4.4.9.4 Processes related to substituted fertiliser

Compost can substitute fertiliser. The allocation principle presented in section 4.5.2 required that the system producing the compost will get subtracted the environmental burdens associated with the substituted fertiliser (or the alternative system will have it added).

Environmental burdens associated to artificial fertilisers are related to the whole life cycle of the product. This includes:

- The cradle to gate production chain
- Distribution
- Spreading
- Fertiliser in soil

Note that it is important to set the fertilisers product system cut-off at the right stage. If the compost system does not include the environmental impacts of spreading or compost in soil, neither should spreading and fertiliser in soil be included (and vice versa).

To obtain LCI data for the life cycle of fertilisers is a study in itself. Usually, there are not enough resources available in a waste LCA to develop fertiliser LCI data specifically for the geographical and temporal boundaries of the study. Hence, ready-made data should be applied. Such data are available in various LCA databases, but note the time range and geographical boundaries they represent. There are large differences between types of fertilisers, production technology (old Eastern Europe technology versus modern Western Europe) and national power supply systems (e.g. hydropower versus coal power). One should therefore make sure that applied fertiliser data that comply the scope of the study.

It will be a too comprehensive task for this guideline project to collect and present LCI data for different artificial fertiliser products. For ready made LCI data, or the basis for developing such, it is referred to LCA databases (or the studies providing the basis for the database data), large fertiliser producers (like Hydro Agri) and the European branch organisation European Fertilizer Manufacturers Association (EFMA). The latter has developed several Best Available Technique (BAT) documents for various fertiliser products and for production and application (ref. <http://www.efma.org/index.asp>). Many LCI data can be established based on these documents.

#### **4.4.10 Other environmental aspects than emissions and material consumption**

Waste treatment also has some other obvious environmental disadvantages than emissions, energy and material consumption and waste generation, the most important ones being:

- Land occupation
- Odour
- Noise
- Accidents resulting in emissions (e.g. landfill fires).
- Injuries and fatalities from accidents.
- Esthetical impacts

One problem with these environmental burdens is that they are usually not given in a unit that enables aggregation of contribution from various processes. If they are given in units that can be aggregated, there is often lack of existing representative data, and much project resources must be invested to derive figures.

This study has not identified any LCAs on waste where the environmental burdens above are included. However, methodologies exist in the general LCA literature that enables them to be included (except for esthetical impacts).

- Land occupation is perhaps the environmental burden that is most commonly applied in LCAs of the burdens above. Guideline on how to measure land area occupation is described in section 4.6.1.

- Odour is usually a result of exposure from a range of gases. Odour can then be included as an impact category by including the emission of odour generating gases in the inventory analyses. The problem is that inventory data to a little extent exist.
- Noise is measured in dB(A), but it is not possible to aggregate noise measured in dB (A) from different locations. However, a certain noise level can be transferred to a potential influence area, which can be aggregated.
- Accidents with both environmental and human health consequences are difficult to predict due to great variations in accident frequency. Also, it is not a part of normal planned operation, which is often a presumption in an LCA. However, the Swedish ORWARE model includes a landfill fire model.
- Esthetical impacts are usually not described in quantitative terms and are very site specific. This environmental burden is usually not included in LCAs, but is commonly treated in environmental impact assessments (EIA).

## 4.5 Allocation

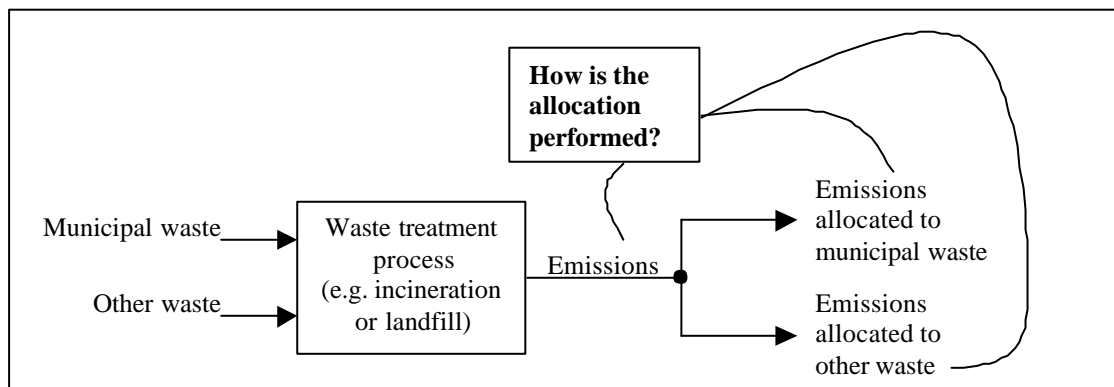
According to the ISO14040 series selection of allocation principle should be performed according to the following hierarchy:

1. System expansion.
2. Allocation applying a relevant technical criterion.
3. Allocation applying an economic criterion.

Allocation is partitioning the input or output flow of a unit process to the product system under study. An allocation principle is as such a principle that describes how the flows shall be partitioned.

With respect to LCA applied for municipal waste, allocation is particularly relevant with respect to:

- How to allocate environmental burdens from waste treatment to specific input waste fractions (multi input problem). E.g. if the flow of interest is municipal waste and this waste is incinerated or sent to landfill together with other types of waste (e.g. mixed industrial waste), how do we allocate the environmental burden from the incineration or landfill to the municipal waste under study? (See Figure 4-16 for illustration.)
- How to allocate the environmental benefit generated by a waste system that produces product that are applied in other systems (open loop recycling). E.g. soil improvement products or heat produced from composting or incineration, how does the waste system under study benefit from the fact that the produced soil improvement can replace fertilisers and heat can replace other energy sources?



**Figure 4-16 Multi input waste allocation problem**

### 4.5.1 Multi input recycling

Multi input recycling can be relevant is the case illustrated in Figure 4-16 or in similar problems related to transportation.

If a product based approach is used in the inventory phase there will be no allocation problem. This because the emissions from the waste treatment is a direct function of

the inputs. However, if a process approach is used to establish data, allocation must be applied.

Related to transportation, where the waste flow under study is transported together with other waste, volume should form the basis for allocation. This is because volume is usually the limiting factor on the capacity of transportation means.

As waste flows usually have approximately the same economic value, economic allocation will usually mean the same as allocation based on mass in situations as those illustrated in Figure 4-16. As an example, assume that the waste treatment process in Figure 4-16 gives 1000 kg NO<sub>x</sub>/year. The mix of input waste per year is 40% municipal waste and 60% other waste on a mass basis. If the system under study only included the municipal waste flow, a mass based allocation approach would allocate 400 kg NO<sub>x</sub>/year to the municipal waste flow. Here may exist a technical criterion which differs if the emission is product specific (i.e. determined by the composition of the product or waste stream and not of the process) as NO<sub>x</sub> is partially in the above allocation example.

Allocation of produced energy to input flows should be based on the energy content of the input flows. Similarly, metal emissions should be allocated to input flows based on their content of these metals, and CO<sub>2</sub>-emissions according to their C-content.

#### 4.5.2 Open loop recycling

The open loop recycling problem is usually solved through system expansion in most LCAs applied for waste. The system expansion approach is illustrated in Figure 4-17.

For illustration purposes, landfill treatment, that result in no form of recycled/recovered products, is compared to composting, that result in a recycled material (soil improvement product).

Note that the composting system also represents other waste treatment alternatives that give recycled/recovered products, such as incineration (heat and electricity) and material recycling (glass, paper, metals etc.).

In the first instance (first row of figure 3-17) the functions of the two waste management options are:

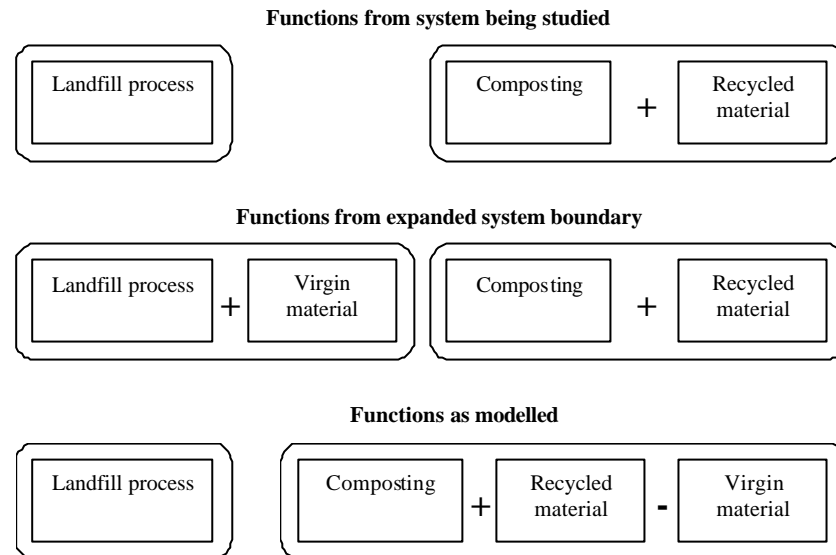
- Waste management through landfill of waste.
- Waste management through composting waste.

A related functional unit to the above functions would be *treatment of X ton waste*. This would however be wrong as it does not reflect the additional function of the composting (material production).

On the second row in the figure a material production function (virgin material) is added to the landfill system to make it equivalent to the recycling system (this is known as system expansion). A related functional unit would be *treatment of X ton waste and production of Y ton material*.

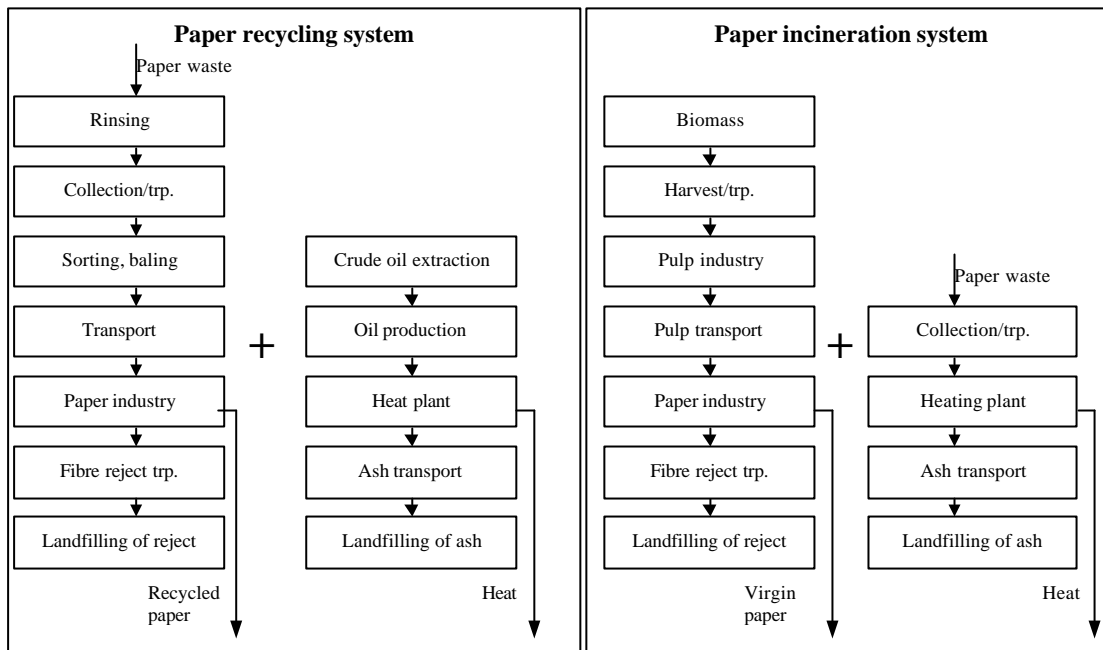
On the third row in the figure the virgin material is credited to the composting function to isolate the waste landfill waste management function. Of course it can be performed the other way around, where the recycled material is moved over and the composting is isolated.

This is known as the avoided product allocation and it is identical to system expansion – the preferred procedure according to the ISO standard for life cycle assessment. The related functional unit would now be *treatment of X ton waste again*. However, due to the system approach the compost system would have a system definition that makes the functional unit correct (in contrast to the first definition).



**Figure 4-17 System expansion methodology**

As a more specific example let us consider the comparison of recycling and incineration of waste paper. It is assumed that the recycled paper replaces virgin paper, while the recovered energy replaces oil combustion. According to Figure 4-17 and the level “functions from expanded system boundary”, the system models could become as illustrated in Figure 4-18.



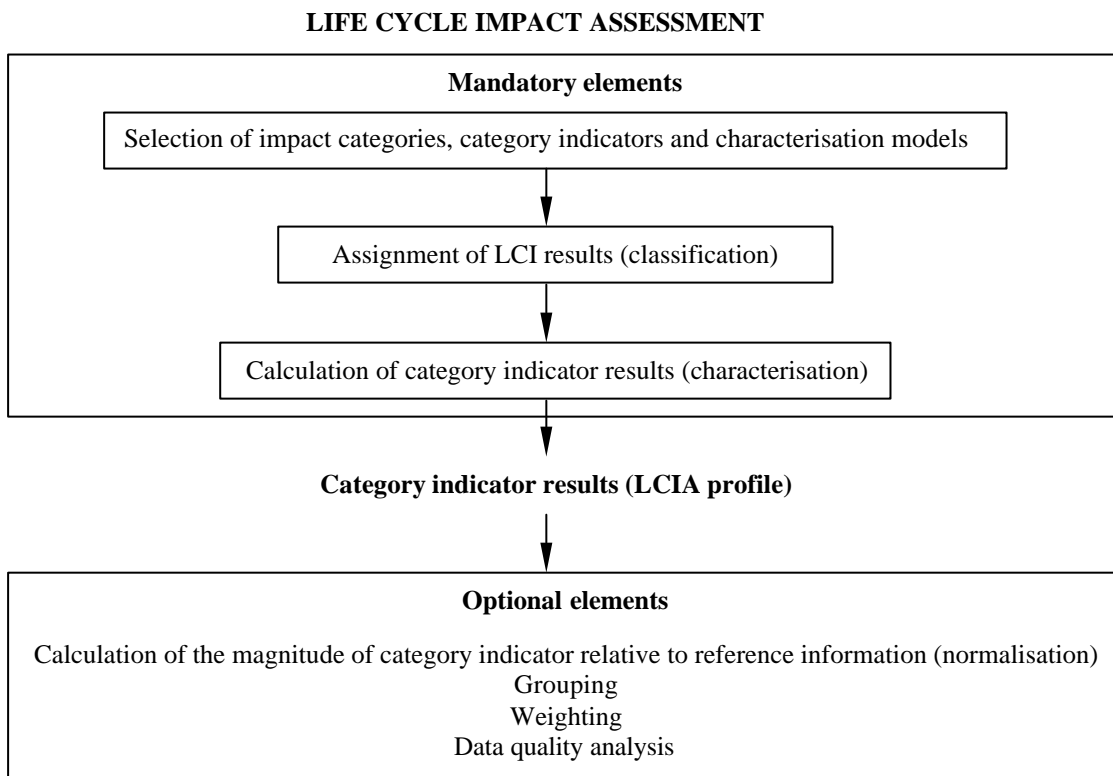
**Figure 4-18** Systems for paper recycling and incineration after system expansion



## 4.6 Impact assessment

The general methodology on how to perform quantitative life cycle impact assessment (LCIA) is described in numerous methodology reports and in ISO 14042. Hence it will not be described in any detail in this report. If an LCIA is carried out, it consists of some mandatory elements and some optional elements /3/.

The mandatory elements (selection of impact categories and impact indicators, classification and characterisation) convert LCI results to indicator results for each defined impact category. The optional elements are normalisation, grouping or weighting and data quality analysis techniques. This is illustrated in Figure 4-19.



**Figure 4-19 Elements of an LCIA /3/**

For the mandatory part of the LCIA, each impact category uses constant characterisation factors to calculate the potential contribution to the impact categories from the components identified in the LCI.

$$S_{ji} = M_i Q_{ji}$$

- $S_{ji}$  Potential contribution to impact category  $j$  from component  $i$
- $M_i$  Amount of component  $i$  from LCI results
- $Q_{ji}$  Characterisation factor for component  $i$  to impact category  $j$

The sum of all  $S_{ji}$  describes the total contribution to impact category  $j$  from all components:

$$S_j = \sum S_{ji}$$

#### **4.6.1 Impact categories, indicators and characterisation models**

LCA applied for municipal waste management usually includes the same environmental impacts as LCA studies in general. Therefore, the same environmental impact categories as those established in generic LCA guidelines should be used. Based on the Danish UMIP study /19/ and the Nordic Guideline on Life-Cycle Assessment /11/ the impact categories listed in Table 4-18 can be applied. Which impact categories to include and how to perform the impact assessment must be defined in the scope of the study. The listed impact categories covers the categories used in most known LCAs applied in the waste management sector, including /6/, /7/, /8/, /9/, /16/ and /20/.

For many of the impact categories the classification and characterisation is quite straight forward, because the impact categories have been in use for a long time, the number of substances which contribute is manageable, and a certain degree of international consensus exists on which indicators to use and how contributions shall be modelled. A selection of approaches is briefly described in the table.

Ozone depletion is hardly ever an issue related to waste management systems in the Nordic countries due to the prohibition of ozone depleting substances. This is confirmed by the findings in /9/.

According to the Nordtest State of the art study /5/ it is especially assessment of toxicity impacts that needs further development with respect to application in the waste management sector. This impact category is treated separately in section 4.6.2.

The impact assessment can stop after the characterisation has been performed, or it can continue with normalisation and/or weighting (sometimes normalisation lies inherently in the weighting method).

Note that new characterisation models and characterisation factors are not developed within a specific waste management decision support projects. This is done in separate research project dedicated to that purpose. Most LCA practitioners use some kind of commercial LCA computer tool. These tools usually have several alternative characterisation models and associated characterisation factors. The LCA practitioners usually select one of the available models in the tool, or put in new models based on available research reports.

Not all components identified in an LCI can be assigned to an impact category. In such cases these substances should be listed separately. Also, there are weighting methods that weight the LCI components directly, rather than estimating the impact category indicator scores first.

**Table 4-18 Commonly used impact categories, indicators and characterisation models**

Impact categories	Commonly used indicator(s)	Characterisation model(s)
Global warming	Global warming potential (GWP) = CO <sub>2</sub> -equivalents.	GWP for substances as defined by the Intergovernmental Panel on Climate Change (IPCC) and given e.g. in /19/.
Ozone depletion	Ozone depletion potential (ODP) = CFC11-equivalents.	ODP for substances as defined by the World Meteorological Organization (WMO) and given e.g. in /19/.
Photo-oxidant formation	Photochemical ozone creation potential (POCP) = C <sub>2</sub> H <sub>4</sub> -equivalents..	POCP for substances for relevant background concentration level of NO <sub>x</sub> as given e.g. in /19/.
Acidification	Hydrogen ion (H <sup>+</sup> ) generation potential expressed as SO <sub>2</sub> -equivalents.	H <sup>+</sup> generation potential taking into account regional/national recipient buffer capacity (removal of nitrates by plant harvesting). See /19/ for Danish adoption.
Eutrophication	Nutrient enrichment of water and soils.	Nitrogen limited recipients. Phosphorous limited recipient. Combined nitrogen and phosphorous limited. All three models with or without N to air. For all models see /11/.
Toxicity for ecosystems and humans	See section 4.6.2	See section 4.6.2.
Abiotic resource consumption	Weight (ton) Volume (m <sup>3</sup> )	Usually the resources are split into renewable and non-renewable resources. The LCI results are transformed from weight to volume or vice versa by using material density.
Biotic resources consumption	Weight (ton) Volume (m <sup>3</sup> )	The LCI results are transformed from weight to volume or vice versa by using material density.
Fresh water consumption	Weight (ton) Volume (m <sup>3</sup> )	The LCI results are transformed from weight to volume or vice versa by using water density.
Land consumption	m <sup>2</sup> m <sup>2</sup> *year	Land areas are usually split into area categories reflecting the present exploitation. See /11/ for examples of land area categorisation.
Materials not followed to cradle	Weight (ton)	All (selected) materials aggregated. Selected materials given separately.
Energy not followed to cradle	Energy content (MJ)	All (selected) forms of energy aggregated. Aggregation within the groups renewable and non-renewable energy.
Waste not followed to grave	Weight (ton) Volume (m <sup>3</sup> )	All (selected) forms of waste aggregated. Aggregation within the groups non-hazardous waste and hazardous waste.
Smell	Potentially affected area (m <sup>2</sup> )	Affected area is based on experience or dispersion modelling combined with smell threshold values. Can be split on area type as for land consume.
Noise	Potentially affected area (m <sup>2</sup> )	Affected area is based on experience or noise modelling combined with noise acceptance criteria. Can be split on area type as for land occupation.

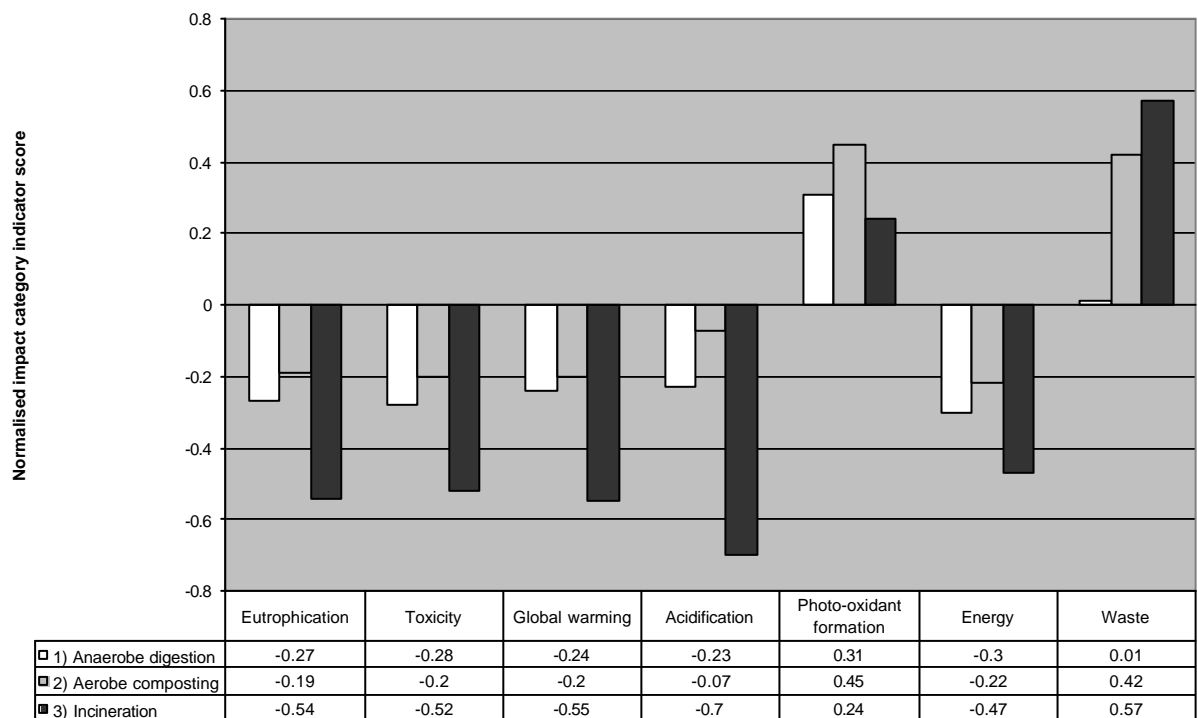
Table 4-19 and Figure 4-20 illustrates an LCIA profile. To be able to present the results in Table 4-19 on a common axis, for each impact category the sum of all three waste treatment system alternatives is set to 1. The alternatives are expressed as their relative contribution to 1. It should be noted that some of the impact scores may be very large and others insignificant - the figure does not tell anything about the relative size of the different impact scores.

7 of the categories in Table 4-18 are included. The profile is related to the comparison of 3 alternative treatment methods for 19500 ton household waste; 1) anaerobic digestion of biowaste and incineration of residues, 2) aerobic composting of biowaste and incineration of residues, 3) Incineration. The negative indicator scores occur due to the environmental benefit of recovered energy and recycled material. Note that the results are only valid for the boundaries, limitations and data applied in the specific study.

It is seen from the figure that 3) incineration is ranked as the best alternative for all impact categories, except waste generation.

**Table 4-19 Example of LCIA profile /7/**

Impact category	Unit	Anaerobic digestion	Aerobic composting	Incineration
Eutrophication	kg PO <sub>4</sub>	-4.98e+04	-3.41e+04	-9.91e+04
Eco-toxicity	m <sup>3</sup> water/air	-2.66e+10	-1.91e+10	-4.97e+10
Global warming	kg CO <sub>2</sub>	-5.97e+06	-4.96e+06	-1.36e+07
Acidification	kg SO <sub>2</sub>	-2.42e+04	7.16e+03	-7.42e+04
Photo-oxidant formation	kg ethylene	8.60e+02	1.24e+03	6.69e+02
Human toxicity	kg body weight	-7.23e+06	-5.17e+06	-1.36e+07
Energy	MJ	-7.32e+07	-5.29e+07	-1.14e+08
Solid waste	kg	1.14e+04	4.11e+05	5.65e+05



**Figure 4-20 Example of LCIA profile /7/**

## 4.6.2 Toxicity

The toxicity impact category is an important category for LCAs applied in the waste management sector. This, because emissions like dioxin, PCB, PAH and heavy metals are toxic and they are generated by a range of relevant processes related to waste management, such as:

- Toxic pollutants emitted to air from incineration and through evaporation from landfills, composting and bioreactors.
- Toxic pollutants leaching from landfill containing municipal waste and incineration residues.
- Toxic pollutant in soil improvement products recovered from composting of biowaste.
- Toxic pollutant emitted during production of consumed energy and auxiliary materials.
- Toxic pollutant emitted during production and use of substituted energy and materials.

The impact category toxicity is often divided into human toxicity and eco-toxicity. The reason for collecting them in a common category is because the toxic impact model regard the recipient as the same and does not include the different fates that the pollutants might have on humans and eco-systems.

The influence that the long release time horizon for metals in landfills has on the toxicity but not on the calculated impact potentials for LCIA is a matter of discussion. The discrepancy is caused by “dilution in time” which means that environmental concentrations below the landfill may be slightly increased for thousands of years. A risk assessment may tell us that this does not cause any significant risk but an LCIA looks at the mass emission which may be very large and hence cause a large impact potential. Dilution in time is an issue particularly for landfills as opposed to most other processes in the life cycle. It gives problems with the traditional LCIA approach based on mass loads and may call for alternative approaches (part of the justification for the distinction between the “short term” emissions (<100 years) and the long term emissions (>100 years) applied for landfills by many researchers.

The toxicity category is very complex. The main reasons for this are a large number of mechanisms, an enormous number of contributing substances, many affected natural resources and the inter-media transport of substances in the eco-system. In addition to dividing into human toxicity and eco-toxicity it is also common to divide eco-toxicity into aquatic, terrestrial and sediment eco-toxicity.

Several characterisation models exist for this impact category. Models applied in identified LCA studies on waste management are:

- Dutch USES-LCA model. This is a multi-media fate model that predicts the environmental concentrations after emission, and compares the concentrations with no-effect concentrations. Separates on aquatic eco-toxicity, terrestrial eco-toxicity, sediment eco-toxicity and human toxicity. See /23/ for further description (report can be downloaded from /22/). Applied in /9/.
- UMIP model for human toxicity. Separates on toxic exposure through air, water and soil. The model takes into account distribution on different environmental

compartments, exposure routes, human intake, transfer to human body and component toxicity. See /19/ for method description. Applied in /9/.

- UMIP model for eco-toxicity. Separates on acute aquatic eco-toxicity, chronic aquatic eco-toxicity and soil eco-toxicity. The model takes into account distribution on different environmental compartments, bioaccumulation and toxicity. See /19/ for method description. Applied in /9/.
- Dutch model for human toxicity and eco-toxicity proposed by the Centre for Environmental Studies (CML), University of Leiden, in 1992 (CML-92). The human toxicity effect factor for each component is equal to the inverse of the human tolerable daily intake (mg/kg body weight). Emissions to air and water are treated separately and then added. The eco-toxicity effect factor for each component is equal to the inverse of a threshold concentration (mg/m<sup>3</sup>) in water. There is thus no consideration of the substance's environmental fate in the model. See /21/ for further description of method. Both categories are applied in /6/, /7/ and /8/. Note that the CML toxicity impact assessment methods have been extensively updated since 1992. The upgrading e.g. includes USES-LCA. See /22/ for overview of updated methods and models.

SETAC recommends that impact assessment of toxicity should take into account /24/:

- The toxicity of the component.
- Differences in human toxicity and eco-toxicity.
- Fate and exposure (not the case CML-92)
- Background concentration dependency (not the case for any of the models)
- Regional geographical differentiation (not the case for any of the models)

Based on the amount of data included in the models, the recommendations of SETAC and what is in use in the latest LCA studies in the waste management sector, it is recommended to use one of the first two models listed above. It is referred to /11/ and /24/ for overview of other models generally applied in LCA studies.

In some studies toxicity is excluded from the LCA study with the argument that no credible methods exist and due to lack of data /16/. This is OK as long it is clearly stated in the scope of that study that the toxicity impact assessment is not included, and as long as the goal of the study can be met without inclusion of chemical impacts in the impact assessment.

As for other impact categories, new characterisation models and characterisation factors for toxicity impact assessment are not developed within a specific waste management decision support projects (ref. last paragraph in section 4.6.1).

As an example, Table 4-20 lists some of the most common metals related to waste treatment processes and relates human toxicity characterisation factor for emissions to air based on the USES-LCA and UMIP methods. Only metals that have given values in both models are included in the table.

The effect factors from the two models cannot be directly compared, as the models for deriving values are different. However, the relative importance of the metals can be compared using a reference metal that equals 1. We use cadmium as a reference metal. All other metals are then given as cadmium equivalents. The results of this calculation are given in column 4 and 5 in the table. In column 6 the ration between

the USES-LCA effect- factors and the UMIP effect factors are given. It shows that there are large differences in the prioritisation of metals in the two models, especially for chromium, cobalt, copper and lead.

This difference may change the ranking of alternative waste treatment solutions. Especially related to human toxicity. There are reasons to believe that similar differences also exist for other components that are toxic to humans and ecology. Due to this, it is recommended to apply both models in an LCA if the project frames allow for it.

**Table 4-20 Human toxicity effect factors for emissions to air /19/, /22/**

	USES -LCA Human health Metals emitted to air Effect factors	UMIP Human health Metals emitted to air Effect factors	USES -LCA given as Cd-equivalents	UMIP given as Cd-equivalents	USES -LCA/ UMIP ratio
Cadmium	1.50E+05	1.10E+08	1.00E+00	1.00E+00	1.00E+00
Chromium III	6.50E+02	1.00E+06	4.33E-03	9.09E-03	4.77E-01
Chromium IV	3.40E+06	1.00E+06	2.27E+01	9.09E-03	2.49E+03
Cobalt	1.70E+04	9.50E+03	1.13E-01	8.64E-05	1.31E+03
Copper	4.30E+03	5.70E+02	2.87E-02	5.18E-06	5.53E+03
Lead	4.70E+02	1.00E+08	3.13E-03	9.09E-01	3.45E-03
Mercury	6.00E+03	6.70E+06	4.00E-02	6.09E-02	6.57E-01
Molybdenum	5.40E+03	1.00E+05	3.60E-02	9.09E-04	3.96E+01
Nickel	3.50E+04	6.70E+04	2.33E-01	6.09E-04	3.83E+02
Selenium	4.80E+04	1.50E+06	3.20E-01	1.36E-02	2.35E+01
Thallium	4.30E+05	5.00E+05	2.87E+00	4.55E-03	6.31E+02
Vanadium	6.20E+03	1.40E+05	4.13E-02	1.27E-03	3.25E+01
Zinc	1.00E+02	8.10E+04	6.67E-04	7.36E-04	9.05E-01

### 4.6.3 Normalisation

To be able to present the impact assessment results on a common axis, to enable comparison and/or to form the foundation for subsequent weighting, normalisation is performed. This means that the impact category indicator results are divided with associated reference values.

$$N_j = S_j/R_j$$

- $N_j$  The normalised indicator score of impact category  $j$
- $S_j$  The total indicator score of impact category  $j$
- $R_j$  Reference value of impact category  $j$

Examples of references used in normalisation are:

- The status of relevant impact categories within the geographical area for which the study shall be representative (e.g. national, European or global) within a specified period of time (usually latest available year). The same geographical area and time frame is applied for all impact categories.
- The status of relevant impact categories within the geographical area that the impact category has an effect (e.g. global reference for global warming and

national reference for acidification) within a specified period of time (usually latest available year).

Note that normalised results do not state which impact categories are the most important for a waste treatment system, although some clue is given when there are magnitudes of difference between different normalised impact scores. To state importance weighting must be performed. The normalisation will only show to which problems the waste system contributes the most.

#### 4.6.4 Weighting

Weighting is the optional step of an LCIA where the different impact categories are weighted so that they can be compared among themselves. The aim is to arrive at a further interpretation and aggregation of the data of the impact assessment. Some weighting methods apply weighting factors directly to the LCI results. The weighting factors are then usually established partly based on an inherent effect factor.

$$W_j = N_j F_j$$

- $W_j$  The weighted category indicator score of impact category  $j$
- $N_j$  The normalised indicator score of impact category  $j$
- $F_j$  Weighting factor for impact category  $j$

Aggregation of impact categories can be carried out after weighting.

$$W = \sum W_j$$

Note that some weighting methods use different weighting models for resources consumption, ecological effects and human health/work environment. In these cases aggregation is only possible within the same type of model if not other is specified.

Many weighting methods exist, but no methods have been identified that are particularly developed for application in LCAs in the waste management sector. Hence, the range of weighting methods available for generic LCA studies are also applicable in the waste management sector.

It will be a too comprehensive task for this guideline to go through alternative weighting methods. Based on availability of weighting methods in LCA computer tools, the newest and most commonly used weighting methods applied in the Nordic countries are:

- Environmental Design of Industrial Products (UMIP) /19/. The method uses a distance to target approach.
- Eco-indicator. Eco-indicator 99 latest version /25/.
- Environmental Priority strategies (EPS). EPS 2000 latest version /26/.

All the above weighting methods require that the impact assessment and normalisation is carried out in a specific way before weighting can be performed. The references given in the bullet list above describes the methods and gives weighting factors.



It is emphasised that weighting is a controversial issue and there is no consensus within the Nordic countries or other international fora on recommended weighting methods. The only recommendation made in several publications is that more than one weighting method should be applied to a study if weighting shall be carried out. This should especially be valid for LCA applied in waste management as comparison results often are made public and can generate a lot of basis for discussion.

## 4.7 Interpretation of results

The interpretation phase of an LCA is defined by ISO as /1/:

*The phase of life-cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations.*

The procedure of interpretation is further elaborated as /4/:

*To analyse and report results, reach conclusions, explain limitations and provide recommendations for an LCI or an LCIA study.*

A request to analyse, conclude and recommend presumes that there is a question to answer or a problem to solve. Related to waste management the main questions where LCA can help answer are:

- What part of the waste treatment system should be in focus for environmental improvement?
- In case there are several solutions for improvement, how good are the solutions compared to each other in an environmental perspective?
- What are the total environmental impacts associated with different conceptual waste treatment alternatives and how do they perform compared to each other?

The main issues recommended to be included during the interpretation phase of a quantitative LCA are /27/:

- Based on knowledge about the system, identify the methodological choices that significantly affect the performance of the system.
- Define data quality indicators and evaluate data quality. Where possible, estimate uncertainty ranges.
- Completeness check. Determine if missing information, such as data gaps, data quality gaps, information gaps on technical methodological choices, are crucial to the goal and scope of study.
- Sensitivity analysis. Determine if a sensitivity analysis, that is a study of the influence of identified technical and methodological variables, is necessary. If yes, design a factorial scenario calculation plan. Carry out the calculations in a deterministic way, i.e. without considering data uncertainty.
- Uncertainty analysis. Determine whether or not an uncertainty analysis, i.e. replicate calculations of scenario with varying values of selected data elements, is necessary. If yes, make replicate calculations of at least one experiment with selected Y-parameters, representative of identified clusters. Determine if the spread of the replicates is larger than the variance between different scenarios.
- Conclude, from the uncertainty analysis, whether the data quality is sufficient or not. If yes, determine whether or not there are significant differences between the scenarios, and the cause of such differences.

Sensitivity or uncertainty analyses should be performed on the major assumptions and uncertainties. E.g. a sensitivity analysis can reflect assumptions about changes in the market. In a declining market, it is usually not invested in new technology. The old technology will then not be exchanged in a future scenario and the contribution from old technology should be included (if old technology exist within the geographical

boundaries). In an increasing market new technology will be built and therefore BAT scenarios can be applied in a future scenario.

Another example is a study with the goal to compare two alternative solutions for treatment of paper waste (paper recycling and incineration) /27/. Sensitivity analysis and uncertainty analysis were performed. The variables in the sensitivity analysis were:

- Input data (generic or specific)
- Heat production from fuel (oil or biomass)
- Transport distance to paper industry (106 or 300 km)
- Paper composition (100% cardboard, 50% each of cardboard and liquid cardboard, 100% liquid cardboard)

The sensitivity analysis gives the possibility to reach conclusions within some specified presumptions. E.g. it is concluded that material recycling is better the incineration with respect to CO<sub>2</sub> emissions provided that biofuel is used to produce replacement heat from incineration, and that the waste paper contains at least 50% liquid cardboard.

A general important conclusion is that there is no such thing as an unambiguous environmental effect of a change of the waste paper treatment technology. There are reasons to believe that this conclusion is also valid when assessing other waste flows and other waste treatment alternatives.

## **5 OVERVIEW OF LCA STUDIES IN THE WASTE MANAGEMENT SECTOR**

The following chapter gives an overview of the current work on LCA in the waste management sector. It lists groups working on LCA in the waste management sector, provides links to web pages and overview of projects, studies and LCA models being made. Some of the information in the following chapter may become outdated soon after the publication of this report as the projects proceed.

### **5.1 ORWARE – Sweden**

ORWARE is an acronym for Organic Waste Research. It is a model for analysing both environmental and economic aspects of waste management strategies, based on life cycle perspective and developed in cooperation between several Swedish research institutes and institutions. Among treatment methods that can be simulated with the model are incineration, composting, anaerobic digestion, biocell, landfilling, sewage treatment and transport. The model includes production of material, energy and plant nutrients (N and P) by waste treatment, which can substitute virgin raw material in the studied system. There are several ORWARE related projects running at the moment but the main LCA-based project is funded by the Swedish National Energy Administration (STEM) is finished after running for four years. A final report from the project is under editing /38/. Further information about the ORWARE project can be found on the projects web site: <http://www.ima.kth.se/forskning/orware>

### **5.2 ESRG - Sweden**

The Environmental Strategies Research Group (ESRG) has performed a study in order to evaluate different strategies for the treatment of solid waste based on a life cycle perspective. The goal of the study was to identify advantages and disadvantages of different methods for the treatment of solid waste, and to identify critical factors in the systems, including the background systems. The waste fractions considered were the compostable, combustible and recyclable fractions of municipal solid waste. The waste treatment options considered were landfilling, incineration, recycling, digestion and composting. The project was completed in August 2000 and the result is presented in the report “Life Cycle Assessment of Energy from Solid Waste” /9/. The report and further information can be downloaded from the ESRG web site: <http://www.fms.ecology.su.se>

### **5.3 The LCA-LAND model and projects in Denmark**

At the Department of Manufacturing Engineering at the Technical University of Denmark a model for analysing emission from municipal solid waste landfills and waste incineration plants in Denmark, the Netherlands and Germany has been developed. The model was developed as a part of the project LCAGAPS, a EUREKA project, which focuses on developing solutions to remediate identified lacks and shortcomings of existing life cycle assessment methods. The model is product specific, which means that emission from the waste treatment is allocated to the products being landfilled or incinerated. In the model, waste is divided into five

groups: Specific organic compounds (e.g. organic solvents), general organic matter (e.g. paper), inert components (e.g. PVC), metals and inorganic non-metals (e.g. chlorine). Different types of solid waste are a composite of these five groups and the model calculates emission to water and air from products during the first 100 years of the landfill. The model has been made operational in a computer tool called LCA-LAND /40, 41, 42/.

A project is now running by Cowi Consult in Denmark in co-operation with the Department of Manufacturing Engineering at the Technical University of Denmark, concerning how to model landfilling of different types of residuals from incineration and electricity production /43/.

Web site:

Department of Manufacturing Engineering at the Technical University of Denmark: <http://www.ipt.dtu.dk/engelsk/index.html>

#### **5.4 WISARD - EA and Ecobilan (UK)**

In the UK three LCA models for solid waste management have been developed and applied. These are WISARD (developed by Environment Agency and Ecobilan), IWM2 (Procter and Gamble) and the Wasteman model (AEA technology) /44/.

The Environment Agency (EA) of England and Wales initiated in 1994 a life cycle program for waste management. In December 1999, WISARD (Waste-Integrated Systems Assessment for Recovery and Disposal) computer software designed to help waste managers identify more sustainable integrated approaches to waste management was launched. The tool includes the data on waste management operations and processes compiled under the Agency's programme, as well as background data on raw materials, energy and other processes in life cycle from Ecobalance UKs (The Ecobilan Group) proprietary life cycle database, DEAM /45, 46/.

The EA LCA research programme has focused on the development of the WISARD LCA software and numbers of projects are running simultaneously. These projects are:

- Data development and refinement for WISARD e.g. home composting LCA data and the collection of financial data on the waste management.
- The development and enhancement of the WISARD software
- Guidance on the use of Impact Assessment in LCA to local authorities.

A number of LCA studies using the WISARD program have been performed in the UK. These are e.g. assessment of the Scottish Waste Strategy and Area Waste Management Plan by the Scottish Environmental Protection Strategy (SEPA), consultant led studies concerning the development of local authority municipal waste management strategies and applications of WISARD for test/controversial waste planning applications /44/.

Web site:

Environment Agency: <http://www.environment-agency.gov.uk>  
Ecobilan: [http://www.ecobilan.com/uk\\_wisard.php](http://www.ecobilan.com/uk_wisard.php)

## **5.5 IWM2 - Proctor and Gamble (UK)**

Dr. P. White *et al.* /47/ published in 1995 the book “Integrated Solid Waste Management – A Lifecycle Inventory”. Included with the book is a software model (IWM-1) that allows the prediction of the overall environmental burdens and economic costs of municipal waste management. This model has been used by several local authorities in the UK and other EU countries during the development of their integrated waste management /48/. In a second edition of the book, an upgraded version of the model, IWM-2, is provided on a CD /49/. The model has been developed and made more user-friendly for waste managers. IWM-2 is designed to be an “entry level” LCI model for solid waste and appropriate to users starting to apply lifecycle thinking to waste systems. Among sections of waste management that are treated in the model are waste collection, sorting, biological treatment, thermal treatment, landfilling and materials recycling. Proctor and Gamble are currently using the model in countries with developing economies such as Mexico, Brazil, Russia and China /50/.

## **5.6 IWM model for municipalities – Canada**

In Canada, the Environmental and Plastic Industry Council (EPIC) and Corporation Supporting Recycling (CSR) commissioned the development of an environmental analysis model to evaluate the life cycle environmental and energy effects of waste management processes. The object of the project was to provide Canadian municipalities with tools that will enable them to evaluate the environmental and economic performance of the various elements of their existing or proposed waste management systems. The model uses life cycle methodology to quantify the energy consumed and the emissions released from a user specified waste management system. It uses data specific to the user municipality to ensure applicability of the results and accuracy but at the same time default values have been provided to allow the user to undertake a first level screening evaluation.

The model includes the processes: waste collection, waste transfer, sorting of recyclable materials at a material recovery facility, reprocessing of recovered materials into recycled materials, composting, energy recovery and landfilling. Recycled materials, compost and recovered energy are accounted for as avoided burdens i.e. avoided production of virgin materials, conventional soil amendments and energy produced from combustion of fossil fuels. Additional information on the boundaries, data sources, parameters and assumptions used in the development of the model is provided in a Project Report available from the EPIC and CSR.

For further description of the model, its applicability and information about availability of the model, refer to the project web site:

<http://www.iwm-model.uwaterloo.ca>

[http://www.iwm-model.uwaterloo.ca/iswm\\_booklet.pdf](http://www.iwm-model.uwaterloo.ca/iswm_booklet.pdf)

## **5.7 U.S. EPA model**

Through funding by the United States Environmental Protection Agency (U.S. EPA), a municipal solid waste decision support tool (MST-DST) and life-cycle inventory

(LCI) database for North America have been developed. The MST-DST methodology incorporates both full cost accounting and life cycle inventory analysis (LCI) and is now being used in variety of case studies across the United States.

The solid waste management systems analysed may be existing systems, entirely new systems or a combination of both, based on user specific data on municipal solid waste generation, requirements to the system, etc. The processes that can be modelled include collection, transfer, separation, composting, incineration, landfilling and digestion with biogas production. Through an optimisation module the user can identify objectives as minimizing total cost or life cycle parameter such as energy consumption and greenhouse gases. Because much of the data needed for modelling are not readily available to the user, effort has been expended in developing realistic and credible default values for input parameters. To provide a wider accessibility at a lower cost, development of a web-based version of the MST-DST is now being considered /51/.

For further information about availability of the MSW-DST, LCI database and project documentation, refer to the project web site:

<http://www.rti.org/page.cfm?objectid=760BD7F2-7050-4FD3-B0EB101FB48210C8>

## **5.8 International expert group on life cycle assessment for integrated waste management**

Members of the group are experts on life cycle assessment for integrated waste management from ten countries from all over the world.

The objective of the group is to promote more sustainable waste management through the appropriate use of life cycle techniques and the goal is the development and use of life cycle tools for integrated waste management. The group intends to achieve it's goal by e.g. exchanging information on research and development projects, exchanging inventory data, agreement on the way that major technical issues are dealt with, identification of data gaps, research needs and scope for collaboration /44/.

According to the Secretarial of the group the, the groups web page has recently closed but it contained information about members meetings and technical documents /44/.

## **5 FINDINGS OF LCA IN THE WASTE MANAGEMENT SECTOR**

In chapter 3, various aspects of LCA in the waste management sector were outlined and suggestions made for the best practice. Although limited attention has been given to waste treatment in LCA compared to other stages in the products life cycle, a lot of studies have already been performed. In the following chapter the findings of these studies will be discussed. However, the conclusions from the LCA studies cannot be regarded as general in any way as the results of LCA studies are site dependent and depend on assumptions and choices made in each study separately.

### **5.1 LCA as a basis for decision making**

When a municipality decides to carry out an LCA study the intention is usually to compare environmental burdens of future alternatives, in waste treatment, to the current situation or test the current waste management plan or strategy /6, 7, 48, 52, 53/. Many of these studies are also intended to provide the overall economic cost of the system /16, 48, 51/. Finnveden and Ekvall /54/ reviewed several LCA studies concerning recycling of paper packing products and concluded that these studies were unable to decide whether recycling or incineration is better from an environmental perspective. This was mainly because the studies did not take into account all the relevant environmental impacts. The results also depended on a number of key issues which were uncertain (i.e. aspects of the studied system) and the valuation element also includes ideological and ethical aspects, which cannot be finally decided. Besides, since the environmental impact depends on other policy decisions, the question of whether or not to recycle or incinerate waste paper is too narrow a formulation. Other policy areas, such as heat and electricity production, waste management and forestry had to be considered as well. In a paper by McDougall and White /48/ a number of lifecycle inventory (LCI) case studies were reviewed. McDougall and White conclude that LCI could be used as a tool to demonstrate the environmental and economic benefits and the necessity of a certain type of waste management. However, the tool cannot make decisions based solely on the information it provides. The decision making process required to improve waste management strategies, still must come from a dialogue between waste managers, politicians, planners and the public /48/. In LCA studies made for three municipalities in Sweden, using the ORWARE model, no conclusion could be reached regarding whether one waste treatment alternative was better than the other except that landfilling usually was the worst choice /16/. Each of the alternatives (incineration, composting, anaerobic digestion and recycling) had its pros and cons. Utilisation of energy and material from the waste gave credits to the treatment alternative both from environmental and economical perspective. Therefore, the choice of treatment method had effects outside the waste treatment system as regards the production of electricity, heat, plastic, cardboard and fertilisers.

From the results and the discussion above, it can be concluded that even though the LCA method and the LCA studies can be improved, one can usually not draw the conclusion that any product A is environmentally preferable to a given product B from the results of an LCA study. LCA will play a role in providing a better basis for



decision making by identifying key issue aspects, which are of importance when making a decision.

## 5.2 Data gaps

In chapter 3 data quality in an LCA study was addressed. LCAs require the acquisition of significant amounts of data and the quality of that data determines the utility of the final LCA. After studying several case studies and databases Finnveden /55/ concludes that data gaps limit the inclusion of several impact categories or cause them to be less well covered and therefore limits the types of conclusions that can be drawn from these studies. These impact categories were e.g. land use and impact on biodiversity, human and ecotoxicological impact categories, eutrophication of aquatic systems and photo-oxidant formation /55/. Human and ecotoxicological impact categories have severe data gaps due to the large number of possible pollutants that end up in the waste or are produced by waste treatment and lack of knowledge of the behaviour of all these pollutants. In LCA studies of future waste management options in three municipalities in Sweden where the ORWARE model was used, ecotoxicological impacts were not quantified due to data gaps and lack of methods to weight different emissions /16/. In a study by Finnveden *et al.* /9/ treatment of various fractions of municipal solid waste with different alternatives were analysed. Due to data gaps more emphasis was put on the total energy use and emission of greenhouse gases in the study (as these impact categories are better known) than toxicological impact categories. Finnveden *et al.* /9/ conclude in the study that emission with toxicological impacts and impacts from land use need further attention.

Data for the stages of the lifecycle where direct measurements are possible are normally more certain than data from e.g. landfill where data have to be estimated. Long timeperspective makes experiments and field studies on landfills difficult to perform and therefore the uncertainty with landfill models may be large. In the case studies done by Det Norske Veritas for municipalities in Norway, future options in treatment of municipal solid waste and sludge were analysed /6, 7/. Existing process and transport data from the municipalities or neighbour municipalities were used. Data from background processes were from LCA databases. Landfilling of waste was not an alternative in the studies. Instead the impact category “solid waste” was used and the amount of waste produced by the different waste treatment alternatives was reported as “solid waste”. This limits the conclusions that can be drawn from the study as impact of various “solid waste” fractions are not studied, but it simplifies the study. In models such as the ORWARE model, US. EPA model and the IMW2 model, landfill is included. However, these landfill models are based on number of assumptions and predictions about future behaviour of the landfill.

According to the above, data gaps are associated with specific impact categories, mainly concerning toxicological effects, and processes that can not be measured due to long duration. As mentioned in the former subchapter, these data gaps limit the usefulness of LCA as a decision supportive tool because not all impacts are considered to the same extent. Ranking of waste treatment alternatives relative to those environmental impacts as well as weight total impact may also be wrong.

### **5.3 Ranking type of waste treatment**

The waste hierarchy of solid waste i.e. the preference of recycling over incineration over landfilling is often taken as a rule of thumb (difference between incineration, composting and anaerobic digestion is usually small). However, by using life cycle assessment the validity of the waste hierarchy has been tested and proven to be dependent on assumptions and value choices that can be made /9/. Often different choices can lead to more variations in the final result of an LCA study than the differences between the alternatives that are studied. Therefore, the type of waste treatment can not be ranked relative to the environmental impact, without making assumptions and taking choices of value into consideration and different choices are appropriate for different decisions and perspectives. The effect of different choices should be analysed by sensitivity analyses when comparing different waste treatment options.

Choices that affect the comparison of different waste treatment relative to environmental impact are e.g. time aspect of landfilling /e.g. 9/, substitution of new material by recycling /e.g. 57/, energy utilisation from waste /e.g. 7, 9/, choice of allocation principles /61/ and impact categories /55/.

#### **5.3.1 Time perspective**

As noted in chapter 3 emissions from landfills may prevail for a very long time, often thousands of years or longer. The choice of time frame in the LCA of landfilling may therefore clearly affect the results. Choosing a short time perspective i.e. shorter than 100 years, makes the landfill a carbon sink relative to other treatment options e.g. incineration, as e.g. plastic material is not degraded /9/. Likewise, metals have not leached out of the landfill during such a short time /59/. Therefore, short time perspective credits the landfill alternative in the LCI as less emission has occurred.

#### **5.3.2 Recycling of material**

Recycling of material and energy from waste can be done in several ways and recycled material can substitute virgin material in several ways. The choice of substituted virgin material or energy and the quality of the recycled materials affect the ranking of recycling compared to other waste treatment alternatives. The key factors when crediting the recycling of paper are what energy is replaced by energy from incineration of wastepaper, what material is replaced by the recycled fibres, how pulpwood savings are used when recycled fibres replace virgin fibres and external fuel and electricity demand in paper production /54, 57/. If heat from incineration replaces fossil fuel, recycling will lead to increased use of fossil fuels and associated impacts. However, in studies where wood for paper production has been “saved” due to recycling of paper and instead used as fuel, recycling benefits since the use of fossil fuel can be reduced /54/. In a study by Finnveden /9/, quality of recycled material (paper and plastic) was modelled so that one kg of waste material would not replace exactly one kg of virgin material. This was because the losses and sorting out during the process, and in the case of paper and board products the fact that the quality would not be as good and therefore a larger amount of fibre would be necessary in the recycling case. When recycling organic fertiliser products (sewage sludge, reactor compost, and anaerobic digestion sludge) two quality aspects have to be considered, the nutrient availability and the content of polluting compounds from the waste /5, 52, 53/. Metal content of biologically treated waste may limit the use of organic fertiliser

produced. In a study carried out by Björklund *et al.* /52/ on waste management in Stockholm it was concluded that the spreading of organic fertiliser products had to be limited so as not to exceed the regulatory limits of metals (g metal/ha, year). The results of a case study for Uppsala municipality were similar, i.e. metal content of sewage sludge and compost limited their use in agriculture but digester sludge could be used to provide the entire dosage need of phosphorus /53/.

### **5.3.3 Energy recovery**

Energy recovery from waste can be e.g. heat and electricity from incineration and methane gas from landfilling or anaerobic digestion. In a study carried out by Det Norske Veritas /7/ for a municipality in Norway, anaerobic digestion with methane gas production, composting and incineration were compared. The results of the study were mostly dependent on energy recovery possibilities of the treatment methods. Incineration and anaerobic digestion were ranked higher than composting because of heat and biogas production. Ranking of incineration compared to anaerobic digestion was however dependent on the energy efficiency of the incineration plant and which energy source the gas produced substituted. If the methane gas substituted heat production by oil, anaerobic digestion was credited very high. However, if it substituted electricity production, the ranking of anaerobic digestion was not as high because electricity is mainly produced by hydropower in Norway, which is relatively “clean”. In a study carried out by Finnveden *et al.* /9/ substitution of various avoided heat sources was analysed for ranking of landfilling, incineration and recycling. The energy sources were forest residues, natural gas and “saved” forest from paper recycling. As more energy is recovered through incineration than landfilling, the use of non-renewable heat sources (natural gas) lowered landfilling to the least preferred option. In a Swedish study where the ORWARE model was used /60/, the results were the same i.e. composting, which produced the least useable energy from the waste (compared to anaerobic digestion and incineration), became the worst scenario when coal was used instead of biofuel for heat production.

It can be concluded that the effect of various energy source substitutions is site dependent as the energy production at different sites varies. Substitution of non-renewable energy sources credits the system more than substitution of renewable energy sources.

### **5.3.4 Collection and transportation**

Collection and transportation of waste are unit processes, which should be taken into consideration when making a life cycle assessment of waste management. Emission from transport vehicles can represent a large part of the emission from the foreground system /56/. Fuel consumption for waste transport may increase as nutrient recycling and source separation increase. It should however be noted that transportation may also decrease as a result of increased recycling as transport of virgin material is decreased /54/. Several studies have been performed to analyse the importance of transport on LCI results /57/. The conclusion of these studies is that transportation has limited influence on LCI results concerning energy demand and emission of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>, under the assumption that the transportation is reasonably efficient (i.e. no transport of small volumes in cars). Other types of environmental problems, such as cancer and respiratory diseases may however be influenced by transportation. Finnveden *et al.* /9/ studied the effect of different transportation distance by truck to

treatment facility and the effect of transporting waste by passenger car. The study showed that different distance for transportation of waste by truck to treatment facilities did not influence the ranking of treatment options studied. However, transport of waste by passenger cars from household to collection points influenced the results significantly concerning the impact categories photochemical oxidant formation and human and ecotoxicological impacts /9/. In a study by carried out by Det Norske Veritas for Bærum municipality in Norway, different transport distance to three waste incineration plants had effect on ranking of these plants relative to photochemical oxidant formation /7/. In LCA studies performed for the municipalities Uppsala, Stockholm and Älvdalen longer regional transport was of little significance as long as the transport was carried out in an efficient manner /58/.

Choice of collection and transportation may have influence on some impact categories but in general, as long as the transportation is reasonably efficient, it will have no effect on the conclusion of an LCA study.

## 6 REFERENCES

- /1/ ISO 14040: 1997. Environmental Management. Life Cycle Assessment, Principles and Framework.
- /2/ ISO 14041: 1998. Environmental Management. Life Cycle Assessment, Goal and Scope Definition and Inventory Analysis.
- /3/ ISO 14042: 2000. Environmental Management. Life Cycle Assessment, Life cycle impact assessment.
- /4/ ISO 14043: 2000. Environmental Management. Life Cycle Assessment, Life cycle interpretation.
- /5/ Pretlove, B. (2000): Nordisk status for bruk av livsløpsanalyser i avfallssektoren. [NT TECHN REPORT 463](#).
- /6/ Pretlove, B. (2000): Livsløpsanalyse (LCA) av behandlingalternativer for restavfall og avløpslam i Skedsmo kommune. DNV Rapport nr. 2000-3395. Det Norske Veritas.
- /7/ Pretlove, B. (1999): Livsløpsanalyse for behandling av husholdningsavfall. DNV Rapport nr. 99-3126. Det Norske Veritas.
- /8/ Pretlove, B. (1998): Livsløpsanalyse av metoder for slambehandling. DNV Rapport nr. 98-3414. Det Norske Veritas.
- /9/ Finnveden, G., Johansson, J., Lind, P., Moberg, Å. (2000): Life Cycle Assessment of Energy from Solid Waste. Forskningsgruppen för Miljöstrategiska Studier (FMS), report nr. 137, Stockholm.
- /10/ Erichsen, H.L., Hauschild, M.Z. (2000): Technical data for waste incineration – background for modelling of product-specific emissions in a life cycle assessment context. EUREKA project.
- /11/ Lindfors, L-G., Christiansen, K., Hoffmann, L., Virtanen, Y., Juntilla, V., Hanssen, O-J., Rønning, A., Ekvall, T., Finnveden, G. (1995): Nordic Guidelines in Life-Cycle Assessment. Nord 1995:20. Nordic Council of Ministers.
- /12/ European Commission Directive 2000/76/EC on the incineration of waste.
- /13/ Hedstein, A., Bøhler Torsen, T., Grjotheim, K., Karlsen, C. (2001): Avfall. Bellonas mål og virkemidler. Bellona Arbeidsnotat Nr. 2:2001.
- /14/ European Commission Working Document. Biological Treatment of biowaste. 2nd draft.
- /15/ Sandgren, J., Heie, A., Sverud, T. (1996): Utslipp ved håndtering av kommunalt avfall. Statens forurensningstilsyn (SFT). TA-nummer 1366/1996.
- /16/ Sundqvist, J-O., Baky, A., Björklund, A., Carlsson, M., Eriksson, O., Frostell, B., Granath, J., Thyselius, L. (1999): Systemanalys av energiutnyttjande från avfall – utvärdering av energi, miljö och ekonomi. Översiktsrapport. För Statens Energimyndighets forskningsprogram Energi från Avfall.
- /17/ Eriksson, O. (2000): A systems Perspective of Waste and Energy. Strengths and Weaknesses of the ORWARE Model. Royal Institute of Technology, Department of Chemical Engineering and Technology, Section of Industrial Ecology. Stockholm,

Sweden.

- /18/ Braam, J., Tanner, T.M., Askheim, C., Hendriks, N., Maurice, B., Mälkki, H., Vold, M., Wessman, H., de Beaufort, A.S.H. (2001): Energy, Transport and Waste Models. Availability and Quantity of Energy, Transport and Waste Models and Data. *International Journal of LCA* 6 135-139 (2001).
- /19/ Hauschild, M. (1996): Baggrund for miljøvurdering af produkter. UMIP, Udvikling af miljøvenlige industriprodukter.
- /20/ Grant, T., James, K.L., Lundie, S., Sonneveld, K. (2001): Stage 2 Report for Life Cycle Assessment for Paper and Packaging Waste Management Scenarios in Victoria.
- /21/ Heijungs, R., J.B. Guinée, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, H.P. de Goede (1992): Environmental Life Cycle Assessment of products. Guide and background. NOH report 9266. Centre of Environmental Science, Leiden, the Netherlands.
- /22/ The LCA Internet site of Centre of Environmental Science (CML) at Leiden University: <http://www.leidenuniv.nl/interfac/cml/lca2/index.html>.
- /23/ Huijbregts, M.A.J. (1999): Priority Assessment of Toxic Substances in the frame of LCA. Development and application of the multi-media fate, exposure and effect model USES-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Sciences, University of Amsterdam, The Netherlands.
- /24/ de Haes, U. (1996): Towards a Methodology for Life Cycle Impact Assessment. Society of Environmental Toxicology and Chemistry (SETAC) –Europe.
- /25/ Goedkoop, M., Spriensma, R. (1999): The Eco-indicator 99. A damage oriented method for Life Cycle Impact Assessment. Methodology Report. PRé.
- /26/ Steen, B. (1999): A Systematic Approach to Environmental Priority Strategies in Product Development (EPS) Version 2000. CPM report 1999:4 and 1999:5. Chalmers University of Technology, Technical Environmental Planning.
- /27/ Alemark, M., Bjuggren, C., Granath, J., Olsson, J., Røttorp, J., Lindfors, L-G. (2000): Analysis and Development of the Interpretation process in LCA. IVL Svenska Miljöinstitutet AB.
- /28/ Amundsen, C.E., Paulsrud, B., Nedland, K.T., Høgåsen, H., Gjerde, B., Mohn, H. (2001): Miljøgifter og smittestoffer i organisk avfall. Status og veien videre. Jordforsk.
- /29/ Fjærgård, O., Sander, O. (2001): Five years' experience with the Cambi process at HIAS. <http://www.hias.no>.
- /30/ USEPA (2000): Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorobenzo-p-Dioxins (TCDD) and Related Compounds. Part I: Estimating Exposure to Dioxin-Like Compounds. Volume 2: sources of Dioxin-Like Compounds in the United States.
- /31/ The LCA-LAND model lca-land.xls, available at <http://www.ipt.dtu.dk/ap/lceresearch.htm>.
- /32/ ECON Senter for økonomisk analyse (2000): Miljøkostnader ved avfallsbehandling. Rapport 85/00.
- /33/ Hellebrand, H.J. (1998): Emission of Nitrous Oxide and other Trace Gases during Composting of Grass and Green Waste. *J. agric. Engng Res.* (1998) 69, 365-375.

- /34/ South Coast Air Quality Management District (2002): Proposed Rule 1133: Emission Reductions From Composting and Related Operations. USA.
- /35/ Petterson, G. (2001): Livscykelanalys av fyre slamhandteringstekniker. Examensarbetsrapport 2001:4. Chalmers Tekniska Högskola, Göteborg, Sweden.
- /36/ Asdal, Å. (2000): Plantetilgjengelig fosfor i bioavfallskompost og slamkompost. Rapport 14/2000. Planteforsk.
- /37/ Fliedner, A. (1999): Organic Waste Treatment in Biocells. A Computer-based Modelling Approach in the Context of Environmental Systems Analysis. Thesis Report Series 1999:5/1999:6. Royal Institute of Technology, Stockholm, Sweden.
- /38/ Eriksson O. (2002): Personal communication with Ola Eriksson at The Royal Institute of Technology, Division of Industrial Ecology, member of the ORWARE project organisation, via e-mail.
- /39/ Environmental Strategies Research Group (2002): Information from the research group web-page, <http://www.fms.ecology.su.se>, updated 16.10.2001 (accessed January, 2002).
- /40/ Hauschild M. (2000): *Vugge til grav men hvor er graven?*. LCA-nyt nyhedsbrev, Miljøstyrelsen, web-page: <http://www.mst.dk/produkt/02040900.htm#A8> (accessed January 2002).
- /41/ Nielsen P. H., Hauschild M. (1998): *Product Specific Emissions from Municipal Solid Waste Landfills, Part I Landfill model*, International Journal of LCA, Vol. 3, p. 158-168.
- /42/ Nielsen P. H., Exner S., Jörgensen A.-M., Hauschild M. (1998): *Product Specific Emissions from Municipal Solid Waste Landfills, Part II Presentation and Verification of the Computer Tool LCA-Land*, International Journal of LCA, Vol. 3, p. 225-236.
- /43/ Hauschild M. (2002): Personal communication with Michael Hauschild, at The Department of Manufacturing Engineering and Management (IPL), Technical University of Denmark, via e-mail, January 2002.
- /44/ Thomas B. (2002): Personal communication with Bernie Thomas, waste strategy technical adviser at the UK Environmental Agency, Bristol, UK.
- /45/ Industrial Environmental Management (1998): Article in Industrial Environmental Management, February 1998, page 24.
- /46/ Ecobalance UK (2002): Information from the Pricewaterhouse Coopers – Ecobalan web-page, [http://www.ecobalance.com/software/wisard/gb\\_wisardidx.html](http://www.ecobalance.com/software/wisard/gb_wisardidx.html) (accessed January 2002)
- /47/ White P.R., Franke M. and Hindle P. (1995): *Integrated Solid Waste Management – A lifecycle inventory*. Blackie & Son Ltd., London, UK.
- /48/ McDougall F. and White P. R. (1998): *The use of lifecycle inventory to optimise integrated solid waste management systems: a review of case studies*. A paper presented at “Systems engineering models for waste management” International workshop in Göteborg, Sweden, 25-26 February 1998. Web-page: <http://www.entek.chalmers.se/~josu/art-fmc.htm>
- /49/ McDougall F., White P. R., Franke M and Hindle P. (2001): *Integrated Solid Waste Management – A lifecycle inventory, 2. Ed.* Blackwell Science Ltd., London, UK.
- /50/ McDougall F. (2002): Personal communication with Dr. Forbes R. McDougall, Global Technical Policy Dept., Procter & Gamble Technical Centers Ltd., UK.

- /51/ Thorneloe S. A., Weitz K. A., and Nishtala S. R. (2001): *U.S. Case Studies Using Municipal Solid Waste Decision Support Tool*, Sardina 2001, Eighth International Waste Management and Landfill Symposium, Published in Proceedings.
- /52/ Björklund A., Bjuggren C., Dalemo M. and Sonesson U.: *Planning Biodegradable Waste Management in Stockholm*. Journal of Industrial Ecology. Volume 3, Number 4 (2000).
- /53/ Björklund A., Dalemo M. and Sonesson U.: *Evaluating a municipal waste management plan using ORWARE*. Journal of Cleaner Production 7 (1999) 271-280.
- /54/ Finnveden G. and Ekvall T. (1998): *Life-cycle assessment as a decision-support tool – the case of recycling versus incineration of paper*. Resources, Conservation and Recycling, 24: 235-256.
- /55/ Finnveden G. (1998): *On the Possibilities of Life-Cycle Assessment – Development of methodology and review of case studies*. Doctoral thesis in Natural Resources Management, Department of Systems Ecology, Stockholm University.
- /56/ Clift R., Doig A. and Finnveden G. (2000): *The Application of Life Cycle Assessment to Integrated Solid Waste Management – Part 1-Methodology*. Trans IChemE, Vol. 78, Part B, July 2000.
- /57/ Ekvall T. and Finnveden G. (2000): *The application of Life Cycle Assessment to Integrated Solid Waste Management – Part 2-Perspective on Energy and Material Recovery from Paper*. Trans IChemE, Vol. 78, Part B, July 2000.
- /58/ Eriksson O., Frostell B., Björklund A., Assefa G., Sundqvist J.-O., Granath J., Reich M. C., Baky A., Thyselius L. (2001): *Energy Recovery and Material and Nutrient Recycling from a System Perspective*. A paper presented at the international workshop “System Analyses of Integrated Waste Management” in Johannesburg Castle, Sweden, 2-3 April 2001.
- /59/ Finnveden G. (1996): *Solid waste treatment within the framework of Life Cycle Assessment*. Int. Journal of LCA, 1 (2) 74-78.
- /60/ Sonesson U., Björklund A., Carlsson M., Dalemo M. (2000): *Environmental and economic analysis of management systems for biodegradable waste*. Resources, Conservation and Recycling, 28: 29-35.
- /61/ Finnveden G. (1998): *Methodological aspects of life cycle assessment of integrated solid waste management systems*. Resources, Conservation and Recycling, 26: 173-187.
- /62/ Charter, M., Tischner, U. (2001): *Sustainable Solutions. Developing Products and Services for the Future*. The Centre for Sustainable Design, and Econcept, Germany.



Nordtest project nr. 1537-01

**Guidelines for the use of LCA in the  
waste management sector**

**APPENDIX 1**

Icelandic comparative case study –  
landfill, biocell, compost

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Waste management in Iceland has been developing fast during the last 20 years from open fires and dumps to controlled landfills and modern technology incineration plants. Due to sparsely inhabited areas and cold climate, and low cost of landfilling, landfilling is the most preferred waste treatment. However, because of the European Council Directive on the landfill of waste, biodegradable waste going to landfills has to be reduced to 35% of the total amount landfilled in 1995 by the year 2016. Therefore, FENÚR (The Icelandic Association of Waste Management) is interested in assessing environmental effects of biocell and composting compared to landfill, under Icelandic conditions, where electricity is mainly produced by hydropower and space heating is provided with geothermal water. Due to limited time and resources the study is only an LCA-screening study, i.e. it is not an iterative study. Sensitivity analysis will be used to assess the sensitivity of the results related to change in choices of value and inventory data.

This study is a comparative study where the current waste management situation in Reykjavik and its neighbour municipalities, landfilling with gas collection, is compared to future options, biocell and composting. Inhabitants in Reykjavik and its neighbouring municipalities (Kópavogur, Garðabær, Hafnarfjörður, Seltjarnarnes, Mosfellsbær and Bessastaðahreppur) were approximately 175.000 in the year 2000, which is approximately 62% of Iceland's total population. These municipalities have formed the municipal waste disposal company SORPA. Today, the household waste from these municipalities is baled in Reykjavik and then transported to a landfill in Álfsnes, 20 km away from the baling station.

## 1 Goal and scope of the study

### 1.1 Specification of the goal

The goal of the study was:

*To use life cycle assessment to assess the environmental impact of the household waste management system in Reykjavik and its neighbour municipalities and compare it with impact of future options, biocell or composting.*

The study was made for FENUR as an example of Icelandic LCA study on waste management systems. Real life data from the waste management in Reykjavik and its neighbour municipalities were used in the study to make it useable as a decision-supporting tool for future waste treatment options in Reykjavik and its neighbouring municipalities.

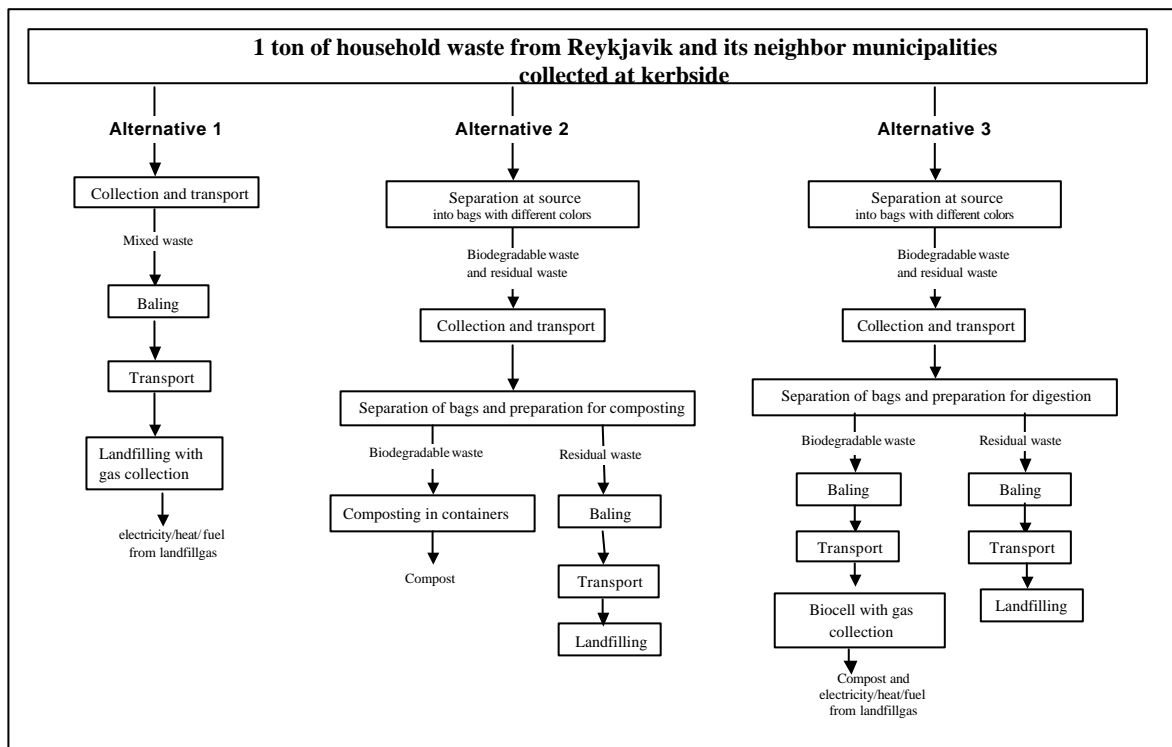
Three alternatives were compared. Alternative one is the current waste management in Reykjavik and its neighbouring municipalities and alternatives two and three are future options.

- **Alternative 1:** Current situation. Household waste is collected by the municipality or a contractor (kerbside collection) and transported to a baling station. After being baled the waste is transported to a landfill where it is landfilled. Landfill gas is collected and is used as energy source.
- **Alternative 2:** Biodegradable and residual waste are separated at the source into bags with different colours. The waste is then collected the same way as in alternative 1 and transported to the baling station. At the baling station the degradable and residual waste is separated with optical sensors. The residual

waste is baled and landfilled. The degradable waste is composted in containers after mincing, mixing and screening for plastic and metals. Compost produced is used as topsoil in the residual waste landfill.

- **Alternative 3:** Waste is separated into degradable and residual waste and collected the same way as in alternative 2. The residual waste is baled and landfilled like in alternative 2. The degradable fraction is baled after mincing, mixing and screening for plastic and metals and then treated in a biocell. Landfill gas is collected and used as an energy source but the compost produced is used as topsoil in the residual waste landfill and the new biocells.

Figure 1 shows a flow diagram of these alternatives.



**Figure 1: Alternatives compared in the LCA study on waste management in Reykjavik and its neighbour municipalities.**

## 1.2 Functional unit

The goal of the study is to compare different waste management options. Therefore, a common basis for comparison of the three alternatives is needed. A specific amount of household waste of a specific composition is a preferable option in this case. In Reykjavik and its neighbouring municipalities writing papers, paper liquid packs, plastic bottles and glass bottles can be disposed of at high-density material banks (close to home drop-off). Material banks for e.g. metals, timber, garden waste, corrugated cardboard, hazardous waste and textiles are also offered but at lower density. The functional unit was therefore chosen to be:

*One ton of household waste from Reykjavik and its neighbouring municipalities, collected at kerbside, with the composition as it is today.*

In July 1999 and September 2000, SORPA did research on composition of the waste described in the functional unit. The waste has the average composition listed in table 1 /9/.

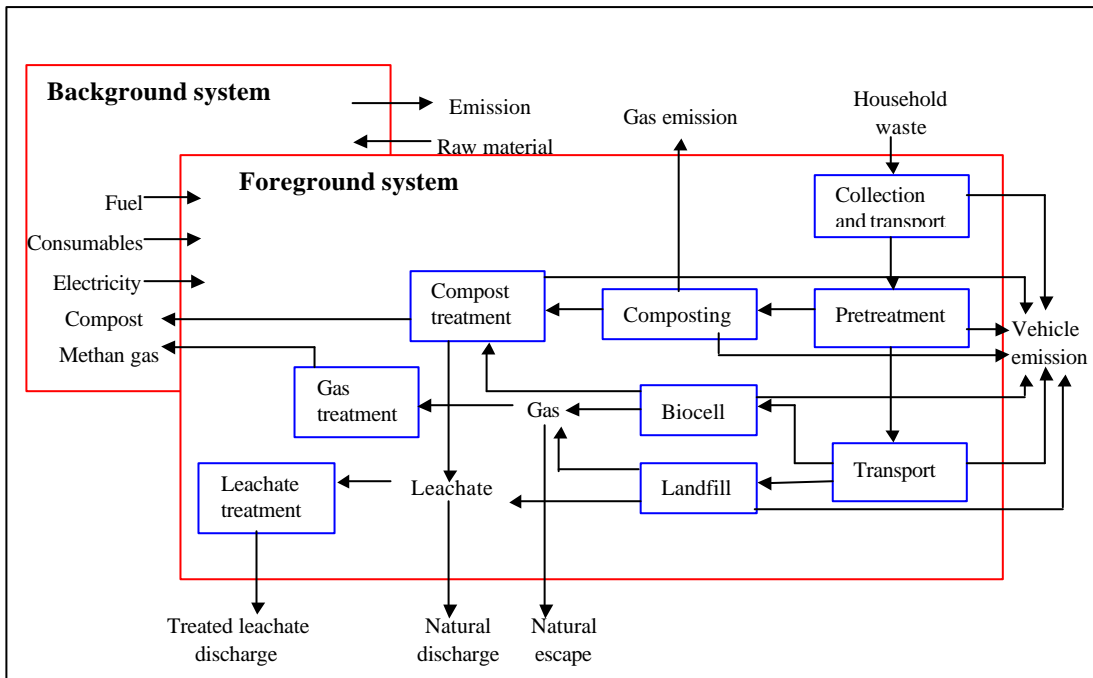
**Table 1: Average composition of household waste in the functional unit**

Type of waste	%	Type of waste	%
Mixed cardboard	10,1	Wood	0,6
Newspaper	13,5	Paper packing	3,0
Plastics	13,3	Garden waste	2,1
Glass	3,5	Diapers	4,5
Textiles	3,8	Food waste	30,5
Aluminium cans	0,4	Hazardous waste	1,0
Metals	3,0	Others	10,7

### 1.3 System boundaries

It is assumed that the waste formation (i.e. amount and composition) at the household is identical in all three alternatives and can therefore be disregarded. Therefore, the input to the system is solid waste collected at kerbside. The degree of separation of recyclable material may however increase when separation at source into biodegradable and residual waste is implemented. It is also assumed that collection of waste from the household and transport to a baling and reloading centre is the same in all alternatives and that separation at source will not increase the use of plastic bags despite use of special coloured bags. It is, however, of interest to know the relative environmental impact of the waste collection. Therefore the collection process unit is included in the system.

The system itself can be divided into foreground and background system. The foreground system comprises the waste management activities themselves. The background system includes the activities, which exchange materials and energy with the foreground system (e.g. fuel, consumables and electricity). Figure 2 shows the system in the study.



**Figure 2: The system in the study**

In alternative 2 and 3 compost is produced. It is however not easy to determine how the compost will be used and the quality of the compost is not well known. It is doubtful that farmers would accept these products as fertilisers but they might be used for land recovery. The use of the products is still more or less in the speculative stage as no full-scale trial has been conducted to investigate the application of degraded organic waste. Therefore it is assumed that the compost will only be used as topsoil on residual waste landfills, the old landfill in Ålfsnes and new biocells. Alternatives 2 and 3 are credited with avoided transport of virgin topsoil.

In alternatives 1 and 3 landfill gas is produced. Alternatives 1 and 3 are therefore credited with avoided use of petroleum on passenger cars, heating oil in industry and production of electricity.

System boundaries related to time are divided into surveyable time (ST) and remaining time (RT). In case of landfills, ST is approximately 100 years, which corresponds to the time until a pseudo steady state is reached in the landfill, i.e. until the major part of the methane production has ceased. RT corresponds to complete spreading of all landfilled material, from now until infinity. For the biocell ST is the time that takes to treat the waste in the biocell plus aeration of the cell, approximately 5 years /13/. RT is the same for biocells as for landfills. In case of composting ST is the time that takes to treat the waste in containers and stabilise it in windrows afterwards, approximately 10 weeks in total. Degradation of compost after the composting treatment, i.e. during RT, is not a part of the study as the composition of the compost after ST is not known. It is therefore not possible to compare the composting alternative to the landfill or biocell alternatives for RT.

In the study, distinction is made between biotic (from renewable sources) and non-biotic carbon (from fossil sources). It is a common practice to disregard biotic carbon dioxide (CO<sub>2</sub>-b) emission for composting treatment in a LCA. Finnveden /11/ argues that landfill acting as a carbon trap can be an issue when not easily degradable materials are considered and biotic CO<sub>2</sub>-emission are not considered. I.e. due to slow

degradation, not all carbon is emitted to the atmosphere like when the waste is incinerated and the trapped CO<sub>2</sub> should be subtracted from the landfilling inventory. The composting and the biocell act as carbon traps just like the landfill, i.e. carbon is trapped as humus in the compost formed during ST but the amount of carbon trapped is different between these three processes. To solve this problem there are two solutions /11/. One is to include modelling of the processes where there is a CO<sub>2</sub>-uptake and then there is no need to make differentiation between biotic and non-biotic CO<sub>2</sub>. Another simpler solution is to continue the differentiation between biotic and non-biotic CO<sub>2</sub>, but simply attribute a negative CO<sub>2</sub>-emission to the trapped carbon. Due to limited resources, expansion of the system was not an option in this study. Biotic carbon emission during the composting treatment (alternative 2) was not known and therefore not possible to subtract the carbon trapped in the compost from the CO<sub>2</sub>-emission. In the study biotic CO<sub>2</sub> emission was disregarded but the carbon trapped in the compost or landfill after ST was not subtracted from the total CO<sub>2</sub>-emission. This may have caused some error in the results, i.e. the comparison of the alternatives for ST. A better description of the “carbon sink” concept can be seen in section 3.4.4.2 in the guidelines.

Capital equipment is in general not included in the study and so is materials needed for maintenance of equipment (e.g. compactor or garbage trucks).

#### **1.4 Data quality**

LCA is an iterative process. However, this study is only a screening LCA, i.e. the results of the study have not been iterated. Some of the data are however from other LCA studies which have been iterated several times. To see the effect of some of the assumptions made in the inventory, sensitivity studies with different assumptions were made.

Time perspective of the study is several decades. Access to relevant data for such long time-periods is not possible. Therefore data for the current situation are mainly used. Data from the waste management by SORPA were used as far as possible but when data was missing the gaps were filled up with data from other Nordic life cycle assessments and data from the databases in the Sima Pro program. Following are discussions on models and data used in the inventory and possible uncertainties in the inventory. The uncertainty is not given in Figures but only discussed and the possible effect of them.

For waste composition, data from waste analysis done by SORPA were used. Information about composition of various waste fractions are however from Swedish and Norwegian LCA studies /1, 8, 11/. Some of the waste fractions in the study by SORPA had to be combined to fit with the fractions of the Swedish and Norwegian studies (i.e. corrugated cardboard and mixed cardboard and aluminium cans and metals).

Waste had to be sorted into biodegradable and residual waste in both the composting and biocell alternative. Efficiency of sorting the waste at source and composition of the biodegradable waste and residual waste had to be estimated. No full scale trial or long time experience exist for sorting waste into biodegradable and residual waste in Iceland. Many factors e.g. mentality, the closeness of the authorities to the public and advertising can affect the sorting efficiency. Therefore sensitivity of the results relative to sorting efficiency was estimated by varying the sorting efficiency.

For collection and transport of waste, the data for diesel consumption are from contractors collecting waste in the area served by SORPA and also from SORPA itself. The uncertainties of these data should therefore be low.

The landfills (both mixed and inorganic waste landfills) were modelled with a model made for average Swedish landfill /2/. The waste landfilled in Álfsnes has to be baled. That is not the average way in Sweden and climate conditions might also be different in Sweden compared to Iceland. The effect of this deviation is hard to predict. Data for landfill leachate treatment efficiency are uncertain. Measurements on treatment efficiency have not been performed in Álfsnes (only measurements on emission after treatment) and literature data for the treatment system cannot be found. The data used in this study were based on the measurements from Álfsnes and emission from landfills in Europe /12/. Sensitivity study, where lower treatment efficiency was used, was performed to assess the effect of the assumptions made on treatment efficiency.

Data for pre-treatment before composting are quite certain, based on information from the vendor of the pre-treatment technique (Optibag, 2002). Data for energy use (fuel and electricity) in the composting process are also from vendor of the technique (composting in containers) but no data were available for emission from degradation of the waste. Emission data for similar composting technique were used /14/.

Emission due to degradation of waste in the biocell was modelled with a model described by Flidner /3/. SORPA is interested in putting up a biocell provided by SWECO VBB VIAK in Sweden. The biocell provided by SWECO is highly controlled and therefore the biocell was modelled with extreme values for landfill gas emission and leachate control in the model provided by Flidner. The leachate was assumed to be circulated in the biocell and therefore no leachate released during ST. Data for energy use at the biocell were from Halldórsson /13/ based on information from SWECO. Data for leachate treatment by recirculation in the biocell were hard to find in the literature. The exact figures for leachate treatment were based on figures from Flidner /3/, Reinhart /10/ and educated guess and are therefore uncertain.

No full-scale trial has been conducted to investigate the application of degraded organic waste in Iceland. Use of the compost from the composting alternative and the biocell alternative are therefore more or less speculations. In the study it is assumed that all compost is used as topsoil on landfills or biocells. How the compost is exploited can affect the outcome of the LCA, as avoided use of fuel and electricity is important. Therefore a sensitivity study was done where the compost was used as fertiliser and the avoided energy due to less production of artificial fertiliser credited the system. However, transport, distribution and soil pollution due to use of the compost were not considered in the sensitivity study.

Landfill gas was exploited for electricity production, fuel on passenger cars and in industry. The data for emission from these three processes were from Hekla Ltd. /16/ and from LCA studies done by Björklund /2/, Sandgren *et al.* /8/.

### **1.5 The Sima Pro program**

In this study the Sima Pro 5 program was used. Sima Pro is a product-related software based on LCA-methodology. Sima Pro includes several inventory databases



and impact assessment methods. Inventory data from the several databases in Sima Pro were used for the background processes in the study, e.g. production of fuel, energy and iron strapping (in the baling process). Two of the life cycle impact assessment methods included in Sima Pro were used in this study. The Danish EDIP method was used as the main assessment method to compare the alternatives. The Eco-indicator 99 method was used in addition to check the ranking of the different treatment alternatives relative to different weighting method. A more thorough description of the program can be found in /23/.

## 1.6 Impact categories and methodology

The EDIP method (Environmental Design of Industrial Products, in Danish UMIP) was developed by the Institute for Product Development at the Technical University of Denmark. It includes characterization, normalization and weighting. As weighting steps are based on value-choices and are not based on natural science it was of interest to see how much weight results of the study would change if another weighting method was used. Therefore, the three alternatives were also compared by using the Eco-indicator 99 method, also provided in the Sima Pro.

The impact categories included in the EDIP method and also in this study are as described in table 3. Further description of the characterisation and weighting method of the EDIP method can be found in Hauschild and Wenzel /17, 18/. In Sima Pro high NO<sub>x</sub> values (> 10 ppbv) are used as default for photochemical smog formation. According to Hauschild and Wenzel /18/, the lower NO<sub>x</sub> value (< 10 ppbv) should be used for Scandinavian conditions. The NO<sub>x</sub> value in Sima Pro was therefore changed to the lower value.

**Table 3: Impact categories in the EDIP method in Sima Pro.**

Impact category
Resource use
Global warming
Ozone depletion
Acidification
Eutrophication
Photochemical smog
Ecotoxicity water chronic
Ecotoxicity water acute
Ecotoxicity soil chronic
Human toxicity air
Human toxicity water
Human toxicity soil
Bulk waste
Hazardous waste
Slags/ashes

In the Eco-indicator 99 method normalisation and weighting are performed at damage category level (endpoint level in ISO terminology). Three types of environmental damages (endpoints) are weighted. The damage categories and the impact category indicators linked to them are listed in table 4. To tackle model uncertainties a system referred to as Cultural Theory has been used to separate three versions of the damage model. The default version, corresponding to a “Hierarchist” perspective, was used in this study. Further description of the Eco-indicator 99 method can be found in Goedkoop and Spriensma /19/.

**Table 4: Damage and impact categories in the Eco-indicator method in Sima Pro.**

Damage category	Impact category
Human health	Carcinogenic effects
	Respiratory effects
	Climate change
	Ionising radiation
	Ozone layer depletion
Ecosystem quality	Ecotoxicity
	Acidification and eutrophication
	Land use
Resources	Minerals
	Fossil fuels

## 2 Life cycle inventory analysis

### 2.1 Waste composition and separation

#### 2.1.1 Household waste composition

The household waste composition used in this life cycle assessment is based on household waste composition analyses made by SORPA. The analyses were made in July 1999 and October 2000 /9/. The composition in table 5 is the average composition from these two analyses. Table 1 and 5 are the same except that some of the waste groups in table 1 have been combined in table 5 as described below.

**Table 5: Composition of household waste /9/**

Type of waste	%	Type of waste	%
Mixed cardboard	13,1	Wood	0,6
Newspaper	13,5	Garden waste	2,1
Plastics	13,3	Diapers	4,5
Glass	3,5	Food waste	30,5
Textiles	3,8	Hazardous waste	1,0
Metals	3,4	Others	10,7

The composition of the “hazardous waste” and “others” fractions were not known and are therefore not covered in this study.

#### 2.1.2 Composition of waste fractions

Compositions of the waste fractions of the household waste studied are from Finnveden *et al.* /11/, Sandgren *et al.* /8/, Sundqvist *et al.* /1/ and Björklund /2/. Table 6 lists the composition of food waste, newspaper, mixed cardboard and plastic, glass, diapers, textiles, metals, wood and garden waste. Explanations for the abbreviations used for description of compositions are listed in table 7.

**Table 6: Composition of waste fractions studied (kg/kg waste)**

	Food waste <sup>1</sup>	Newspaper <sup>1</sup>	Mix. cardb. <sup>1</sup>	PE <sup>1</sup>	PP <sup>1</sup>	PS <sup>1</sup>	PET <sup>1</sup>	PVC <sup>1</sup>	Glass <sup>2</sup>	Diapers <sup>3</sup>	Textiles <sup>2,4</sup>	Iron <sup>2</sup>	Aluminium <sup>2</sup>	Other metals <sup>2</sup>	Wood <sup>2,4</sup>	Garden waste <sup>2</sup>
TS	0,3	0,88	0,79	0,95	0,95	0,95	0,95	0,95	1,00	0,28	0,90	1,00	1,00	1,00	0,80	0,25
C-fossil	-	0,008	0,17	0,856	0,855	0,889	0,64	0,401	0,005	0,38	0,5	0,045	-	-	-	-
C-tot bio	0,434	0,44	0,4	-	-	-	-	-	-	0,21	-	-	-	-	0,396	0,1
-lignin	0,029	0,14	0,059	-	-	-	-	-	-	-	-	-	-	-	0,118	0,025
-cellulose	0,107	0,3	0,34	-	-	-	-	-	-	0,21	-	-	-	-	0,277	0,04
-starch and sugar	0,097	0,002	-	-	-	-	-	-	0,005	-	-	-	-	-	-	0,035
-fat	0,135	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-protein	0,066	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H	0,058	0,05	0,069	0,142	0,143	0,083	0,021	0,051	-	0,079	-	-	-	-	-	-
O	0,287	0,38	-	0,003	0,0019	0,0016	0,34	0,0065	-	-	-	-	-	-	-	-
VOC	2,00E-06	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CHX	1,00E-08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PAH	5,00E-07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Phenols	2,75E-05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PCB	4,35E-08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Dioxin	9,00E-14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cl	3,90E-03	6,00E-06	1,70E-03	-	-	-	-	-	2,00E-03	-	1,50E-03	-	-	-	1,00E-03	-
N-tot	0,02	-	2,60E-03	-	-	-	-	-	-	1,30E-02	0,04	-	-	-	1,60E-03	7,50E-03
P-tot	3,80E-03	-	4,70E-04	-	-	-	-	-	-	9,90E-04	-	-	-	-	-	1,40E-03
S-tot	2,40E-03	-	1,20E-03	-	-	-	-	-	-	-	1,40E-03	-	-	-	6,00E-04	7,50E-04
Al	-	0,015	-	-	-	-	-	-	-	-	-	-	-	-	-	-
K	9,30E-03	-	1,20E-03	-	-	-	-	-	-	3,30E-03	-	-	-	-	-	-
Ca	0,028	0,006	1,40E-02	-	-	-	-	-	-	9,10E-04	-	-	-	-	-	-
Pb	1,00E-05	3,50E-06	4,00E-06	1,90E-04	1,90E-04	1,90E-04	1,90E-04	1,90E-04	3,00E-04	5,00E-06	1,00E-05	1,00E-03	1,50E-03	4,00E-04	1,00E-05	-
Cd	1,30E-07	5,00E-08	3,80E-08	1,20E-07	1,20E-07	1,20E-07	1,20E-07	1,20E-07	1,00E-06	3,00E-07	9,00E-07	6,00E-07	1,00E-07	-	5,00E-07	-
Hg	2,80E-08	1,10E-08	1,80E-08	7,10E-08	7,10E-08	7,10E-08	7,10E-08	7,10E-08	2,00E-07	5,00E-08	5,00E-08	2,00E-07	1,00E-07	1,00E-06	3,00E-09	-
Cu	3,40E-05	3,50E-05	2,70E-05	1,80E-04	1,80E-04	1,80E-04	1,80E-04	1,80E-04	-	5,00E-06	2,70E-05	9,00E-04	5,00E-04	3,00E-01	8,00E-06	2,00E-06
Cr	1,00E-05	5,90E-06	1,40E-05	1,30E-05	1,30E-05	1,30E-05	1,30E-05	1,30E-05	1,00E-04	5,00E-06	1,80E-04	3,00E-04	1,00E-04	5,00E-04	5,00E-06	-
Ni	7,00E-06	6,20E-06	8,20E-06	7,70E-06	7,70E-06	7,70E-06	7,70E-06	7,70E-06	-	2,00E-06	-	-	-	-	-	-
Zn	8,00E-05	4,20E-05	4,50E-05	1,90E-04	1,90E-04	1,90E-04	1,90E-04	1,90E-04	-	4,70E-05	2,80E-04	5,00E-04	2,50E-04	5,00E-02	1,60E-05	5,00E-06
As	-	-	-	-	-	-	-	-	3,00E-04	-	5,00E-06	1,00E-06	5,00E-07	1,00E-03	1,00E-06	-

1. Finnveden et al. /11/
2. Sandgren et al. /8/, appendix A
3. Sundqvist et al. /1/, appendix 1
4. Björklund /2/

**Table 7: Explanations for the abbreviations used for description of compositions**

Abbreviation	Explanation
TS	Total solids. Weight after evaporation of moisture.
C-fossil	Carbon of fossil origin, e.g. carbon in plastics.
C-tot bio	Carbon of biological origin.
-lignin	Carbon in stable carbohydrates, e.g. lignin.
-cellulose	Carbon in semi-stable carbohydrates, e.g. cellulose.
-starch and sugar	Carbon in degradable carbohydrates, e.g. starch and sugars.
-fat	Carbon in fat.
-protein	Carbon in proteins.
TOC	Total organic carbon.
H	Hydrogen (except hydrogen in water).
O	Oxygen (except oxygen in water).
VOC	Volatile organic compounds, including methane.
CHX	Volatile halogenated hydrocarbons.
PAH	Polyaromatic hydrocarbons.
Phenols	
PCB	Polychlorinated biphenyls, existing in organic waste
Dioxin	TCDD equivalents, measured according to Eadon.
Cl	Total chlorine.
N-tot	Total nitrogen.
P-tot	Total phosphorus.
S-tot	Total sulphur.
Al	Aluminium.
K	Potassium.
Ca	Calcium.
Pb	Lead.
Cd	Cadmium.
Hg	Mercury.
Cu	Copper.
Cr	Chromium.
Ni	Nickel.
Zn	Zinc.
As	Arsenic.
Clay	China clay, $Al_2(OH)_4Si_2O_5$ , used in magazine paper.
DEHP	Diethylhexylftalat, exemplifies the total of plasticisers in PVC.
DOM	Dioktyltinmalat, exemplifies the total of stabilisers in PVC.

### *Food waste*

The food waste makes up about 30 % of the household waste and is the largest waste fraction in the study. The composition of the food waste is from Finnveden *et al.* /11/.

### *Newspaper*

Newspaper is also a large part of the household waste. About 48% of the newspaper discarded in the area served by SORPA ends up in the household waste and makes up the 13% in table 5. The rest (52%) is recycled. The composition of the newspaper fraction in table 6 assumes 70% newspaper and 30% magazine paper /11/.

### *Mixed cardboard*

In the household waste composition analysis done by SORPA /9/ corrugated cardboard is not a separate fraction but milk and other liquid product packages are. I.e. the fractions are mixed cardboard (containing corrugated cardboard) and paper packaging (see table 1). In Finnveden *et al.* /11/ the mixed cardboard fraction contains paper packaging but corrugated cardboard is a separate fraction. According to Finnveden *et al.* /11/ corrugated cardboard in the household waste is comparatively small as much of this waste fraction is formed in industry and business. Therefore, in this study, the mixed cardboard and paper packaging fractions in table 1 have been combined into one fraction, mixed cardboard (table 5). The mixed cardboard fraction

in table 5 is assumed to have the same composition as in Finnveden *et al.* /11/. Corrugated cardboard is assumed to be insignificant in the household waste.

#### *Plastics*

The composition of the plastic fraction (plastic packages and other plastics) is divided between polymers according to the following distribution: 74% PE, 10% PP, 8% PS, 4% PET and 3% PVC /11/.

#### *Glass*

In the household waste composition analysis done by SORPA /9/, glass is separated into glass with and without return fee. In table 5 these fractions have been combined. The composition of the glass fraction is from Sandgren *et al.* /8/.

#### *Diapers*

The composition of diapers is from Sundqvist *et al.* /1/.

#### *Textiles*

The composition of textiles is from Sandgren *et al.* /8/, and stands for cotton, wool and synthesised textile. According to Björklund /2/ the carbon in textiles is either cellulosic or polymeric.

#### *Metals*

According to Sandgren *et al.* /8/ the composition of the metal fraction in household waste is approximately 56% iron, 33 % aluminium and 11% other metals. In the household waste composition analysis done by SORPA, aluminium cans are a separate fraction and metals a separate fraction. The percentage off these two fractions have been combined in table 5 and the composition of the metal fraction in table 5 is assumed to be the same as in Sandgren *et al.* /8/.

#### *Wood*

For the wood fraction in table 5 the composition given in Sandgren *et al.* /8/ is used. The carbon content of wood is mainly lignin and cellulose. The carbon in wood is assumed to be 70% cellulose and hemicellulose and 30% lignin.

#### *Garden waste*

The composition of garden waste is given in Sandgren *et al.* /8/ and contains flowers, soil, plants and other garden waste.

#### *Hazardous and other waste*

Hazardous waste and other waste make up about 12% (1,0% and 10,7% respectively) of the household waste. Due to limited information about the composition of these fractions, they are not considered in this study.

### **2.1.3 Pre-sorting**

In alternative 2 and 3, waste has to be separated into biodegradable and residual waste fractions before treatment in a composting plant or biocell. In both alternatives the waste is separated at source into degradable and residual fraction. The waste fractions are sorted at source into plastic bags with two different colours and an optical sensor is used to separate the bags at a reloading station. The sorting efficiency of the optical bag separator is approximately 95%. Plastic bags are separated from the

biodegradable waste and approximately 5% of the organic waste will separate with the plastic bags. The sorting efficiency at source depends on the information campaign and motivation of the citizens to follow the system. Together with SORPA the composition of the biodegradable fraction and the rest fraction was estimated. According to the separation assumed, the biodegradable waste fraction is 32 % of the weight of waste in the functional unit and the rest fraction is 56 %. Hazardous waste and the “other waste” are 12% of the weight. Table 8 shows the composition of the biodegradable and residual waste:

**Table 8: Composition of biodegradable and rest waste**

Waste fraction	% of bio-degradable waste	% of rest waste
Food waste	66,0	16,4
Mixed cardboard	8,1	18,7
Newspaper	8,3	19,3
Plastics	1,6	22,8
Glass	0,4	6,0
Diapers	9,7	2,4
Textile	0,5	6,5
Metals	0,4	5,8
Wood	0,4	0,9
Garden waste	4,5	1,1

## 2.2 Description of processes and major assumptions

In the following sections, the foreground and background processes in the system analysed are described. The processes are:

- Collection and transport of the waste.
- Landfilling with gas collection.
- Composting in containers and compost used as topsoil.
- Biocell with gas collection and compost used as topsoil.
- Background processes.

### 2.2.1 Collection and transport of waste

In Reykjavik and its neighbour municipalities (i.e. the area served by SORPA), household waste is collected at the household by garbage trucks, transported to a central baling station in Gufunes, Reykjavik, and then the bales are transported to a landfill in Álfsnes, approximately 20 km from the baling station. Contractors do the waste collection and transport in all the municipalities except Reykjavik where the City does the collection. Inventory data on diesel consumption due to collection and transport of each ton of household waste are from the contractors and Reykjavik City. The average diesel consumption is 3,54 L diesel/ton waste. Diesel consumption data for transport of baled waste from the baling station to the landfill are from SORPA. The diesel consumption is 0,87 L diesel/ton waste. For transportation of baled biodegradable waste in alternative 3 (the biocell) the diesel consumption is higher per ton waste because bulking material have been added to the waste. It is assumed that the ratio of bulking material versus biodegradable waste will be 40:60. The bulking material is mainly newspaper, cardboard and wood to control the moisture content and structure of the waste. These waste fractions are transported to the central baling station in Gufunes, independent of whether they will be used as bulking material or

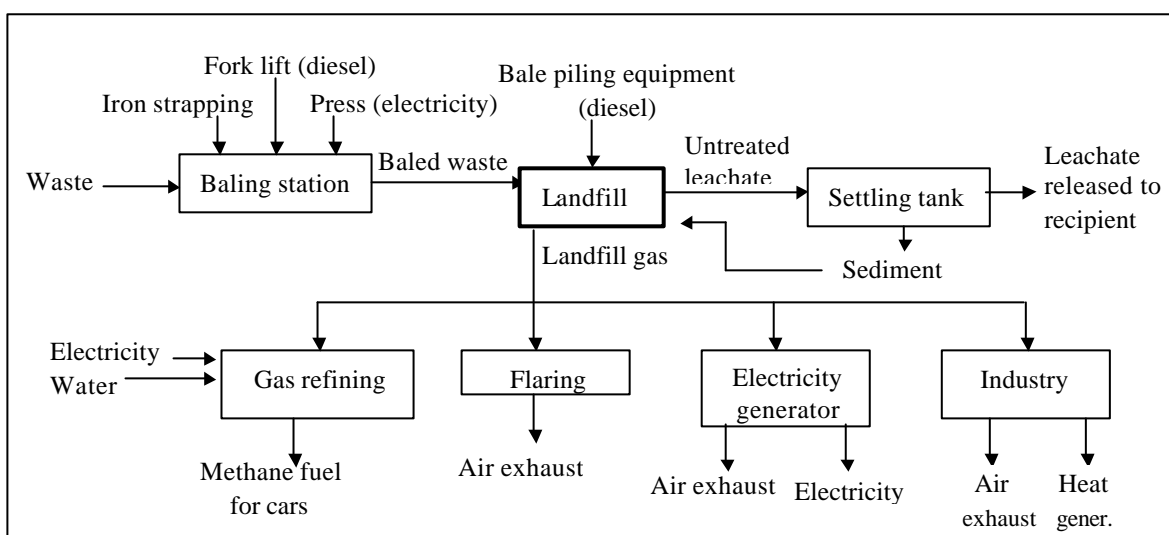
not. Transportation of the bulking material to the station in Gufunes is therefore not included in the inventory of this study.

In alternative 2 and 3, the household waste is separated into biodegradable and residual waste fractions. Despite of that, it is assumed that there will be no increase in transport or collection. The waste will be separated into bags with different colours and then discarded into a single bin. The diesel use due to collection and transport of the waste to the reloading and pre-treatment station in Gufunes will therefore be the same as in alternative 1.

The database BUWAL 132 in Sima Pro was used to calculate emission from garbage trucks due to diesel combustion.

### 2.2.2 Alternative 1, landfill with gas collection

Figure 3 shows process flow diagram of the landfill alternative.



**Figure 3: Process flow diagram for landfilling with gas collection, alternative 1.**

#### 2.2.2.1 Waste baling

All waste landfilled in Álfsnes has to be baled before it is landfilled. Each ton of household waste is baled with 1,67 kg iron strapping which is approximately 9% of the iron that is landfilled. The iron strapping are added to the composition of the metal fraction of household waste described in section 2.1.1 but has insignificant effect on total composition of the household waste as metals are only 3,4 % of the waste. The baling press is driven by electricity and a forklift is used to load baled waste on a truck for transportation to Álfsnes. Data for electricity use and fuel use at the baling station, for each ton of household waste, are from SORPA. The electricity use of the baling press is 26 kJ/ton waste and the forklift uses 0,277 L diesel/ton waste. Some liquid is squeezed out of the waste during baling. The amount of the liquid is dependent on the type of waste being baled. Paper, cardboard and textile will absorb some of the liquid. Analyses have been done on the concentration of various pollutants in the liquid from the press but the amount squeezed from each ton is not known. The amount looks insignificant compared to the amount of waste being baled in each bale. Due to the data gap on amount of liquid squeezed out of the waste, it is ignored in this study. This may credit the baling process.

Data for steel processing from the Sima Pro database were used to analyse the impact of iron strapping production for the baling process. Transport of the iron strapping to Iceland were however not included in the study and is probably insignificant compared to production of the strapping. Description of the steel production data used is given in subsection 2.2.5.

#### 2.2.2.2 Landfilling

Emission from landfills has been difficult to model as they occur over extended period of time and field data for modelling purposes therefore not available. The landfill model therefore must rely on several estimated values and assumptions. In this study, the landfill model used is based on a model described by Björklund /2/. The model describes an average Swedish municipal landfill and was the best available model for this study. Emissions from the landfill are separated into landfill gas and leachate, and emission occurring during surveyable time period (ST) and emission that occur during remaining time period (RT). As noted in section 1.3, the surveyable time period corresponds to the time until a pseudo steady state is reached in the landfill, i.e. until the major part of the methane production is ceased, which is approximately 100 years. The remaining time corresponds to complete spreading of all landfilled material.

Degradation of household waste is modelled as completely anaerobic during ST. Biological carbon will degrade during ST except lignin and 30% of cellulose and hemi-cellulose, which degrades during RT. All material left after ST will be completely degraded or emitted during the RT. At the beginning of RT, the landfill is anaerobic but oxygen will slowly diffuse into the landfill and it will become aerobic. Half of the cellulose and hemi-cellulose left after ST will degrade anaerobically before air intrusion is completed. Plastic, lignin, and half of the remaining cellulose and hemi-cellulose will degrade aerobically during RT. Major part of nitrogen will leach out as ammonium during ST and so will chlorine, potassium and calcium content of the household waste. Only 2% of phosphorus and 0,1-0,3% of metals are emitted during ST but completely emitted to the recipient during RT. The leaching of metals is very important for RT. It is assumed that all the metals will leach out during RT but it will occur over time period of hundred thousands of years. This may cause overestimate of ecotoxicity impact in the impact assessment and interpretation of the results. A more thorough description of emission partitioning coefficients with reference to primary sources is available in Björklund /2/.

Measurements on leachate from Álfnsnes show that the leachate contains less COD and BOD compared to landfills of similar age in Europe /13/. Several factors may cause this difference e.g. higher compaction due to baling, different climate conditions, construction of the landfill, composition of the waste etc. Due to this difference, variation has been made from the Björklund /2/ model described above and 0,7% of the carbon in waste assumed to end up in leachate instead of 1%.

Compaction of waste in Álfnsnes is high due to baling of the waste and no incineration ash is landfilled in Álfnsnes, which reduces the potential for landfill fires. Landfill fires have occurred twice during the 10 years the landfill at Álfnsnes has been in use /13/. The landfill will be in use another 12 years, until 2014. The frequency of landfill fires in Sweden is approximately 0,5 – 1 fire per year and landfill /1/. I.e.



landfill fires are much less frequent in Álfsnes than Swedish landfills. Landfill fires as a degradation process and emission from landfill fires are therefore not considered in this study.

### 2.2.2.3 Gas collection, refining and use

It is assumed that 50% of the landfill gas produced during ST is collected. The rest will pass through the topsoil where 15% of the methane formed in the landfill will oxidise to carbon dioxide /2/. Electricity consumption of the landfill gas pumps in Álfsnes is 37,5 Wh/Nm<sup>3</sup> /13/.

Due to use of the landfill gas formed, the landfill alternative is credited by avoided petroleum use on passenger cars, avoided electricity production and avoided use of heating oil in industry. Today, 17% of the gas collected at Álfsnes is combusted in an electricity generator and 2% is refined and used as fuel on passenger cars. These percentages are however increasing and within few years it is assumed that all landfill gas collected will be utilised. In this study it is assumed that 30% of the gas will be refined and used as fuel on passenger cars, 40% combusted in an electricity generator and 30% of the collected landfill gas will replace heating oil in industry. Reykjavik Energy owns the electricity generator in Álfsnes and all the electricity produced is now added to its electricity grid and therefore replaces electricity produced by hydropower. The energy content of methane in the collected gas is 50,1 MJ/kg CH<sub>4</sub>. It is assumed that the energy efficiency of the electricity generator is 30% /11/ and that each kg of methane will replace 1,57 L of petroleum. Unrefined landfill gas used in industry is assumed to replace oil as heat producer. The heating oil has lower heating value 41,4 MJ/kg /11/.

Data for emission from combustion of landfill gas in the generator are from Dalemo /7/. Data used to describe the emission from use of landfill gas as heat source in industry is approximated with data for flaring landfill gas /8/ and data for emission from combustion of methane gas on passenger cars are from Hekla Ltd. /16/. Hekla Ltd. is the dealer for Volkswagen in Iceland and Volkswagen methane gas cars are already in use by SORPA, Reykjavik City and others in Iceland, using methane gas from Álfsnes.

A scrubber is used to refine the landfill gas from Álfsnes, used on passenger cars. Water-soluble compounds in the landfill gas dissolve in the scrubber and are led with the leachate from the landfill to a seawater recipient. The main compound in the wastewater from the scrubber is carbonic acid but hydrogen sulphide and ammonia will also dissolve in the scrubber. Concentration and environmental impact of the carbonic acid in the recipient is very little and therefore ignored. The hydrogen sulphide and ammonium are insignificant (<2%) compared to the concentration in the leachate from the landfill and therefore ignored in the study. Electricity consumption of the scrubber in Álfsnes is 228,6 kWh/Nm<sup>3</sup> landfill gas /13/. Today, 1590 Nm<sup>3</sup> of methane gas are transported in each trip to the methane filling station for cars and to the industry but the electricity generator is placed in Álfsnes. Compared to the amount of gas transported in each trip and avoided use of diesel due to use of the gas, the diesel consumption and emission due to the transport is insignificant. Because limited information is available about future transportation of the methane gas (e.g. whether pipeline or truck will be used) and the environmental impact of the transport

is probably insignificant, the diesel consumption due to transportation of the methane gas is not considered in the study.

#### 2.2.2.4 Leachate collection and treatment

It is assumed that 80% of the leachate produced is collected and the remaining 20% will leak to aquatic recipients /20/. In Álfsnes, leachate from the landfill is lead through a settling tank before it is released to a seawater recipient. The retention time in the tank is approximately 24 hours. The leachate flows by gravity and therefore no resource use or emission is connected to the transport of the leachate. From measurements on leachate composition in Álfsnes /9/ and comparison with other landfills in Europe /12/ and Iceland, the following treatment efficiency is assumed:

**Table 9: Reduction factors for leachate treatment at Álfsnes**

Substance	Reduction factor (%)	Substance	Reduction factor (%)
COD	30	Pb	60
BOD	30	Cd	35
NH3	10	Hg	50
S	20	Cu	40
P	20	Cr	40
Cl	0	Ni	30
K	0	Zn	60
Ca	0	As	60

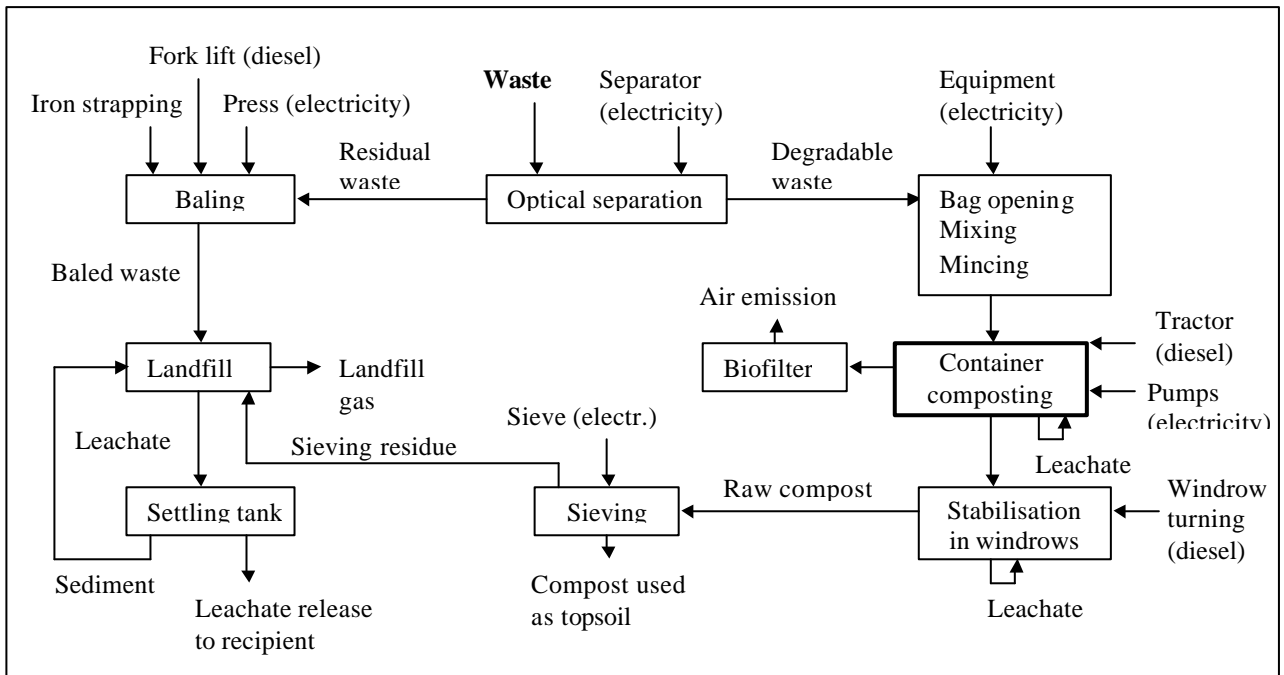
Diesel use for cleaning and maintenance of the settling tank is from SORPA. Sediment from the settling tank is landfilled. Carbon addition to the landfill due to landfilling of the sediment is insignificant as only 0,7% of the total landfilled carbon is assumed to end up in leachate in the landfill model.

#### 2.2.2.5 Fuel use at the landfill

All the household waste landfilled in Álfsnes is baled and therefore no compactor is used. Consumption of diesel to pile up the baled waste and other use of diesel at the landfill is provided by Halldórsson /13/. Total use of diesel at the landfill side is 0,75 L diesel/ton waste.

### 2.2.3 Alternative 2, compost

Figure 4 shows process flow diagram of the compost alternative.



**Figure 4: Process flow diagram for composting, alternative 2.**

#### 2.2.3.1 Separation of waste and pre-treatment

As discussed in section 2.1.3 (pre-sorting) waste is separated into biodegradable waste and residual waste. The biodegradable waste is composted in containers and the residual waste is landfilled. It is assumed that the waste will be separated at source in to bags with different colours and then discarded into a single bin. The bags are then separated at a reloading and pre-treatment station. The optical separation system assumed to be used is provided by OptiBag Systems AB (OptiBag, 2002). The system is suitable for 40.000 tons of waste, which is approximately the household waste production in Reykjavik and its neighbour municipalities today. The energy consumption of such a separation system is 100 kW and it would need 2000 hours of sorting per year.

Before the biodegradable waste is put into the containers, the bags have to be opened, the waste screened for plastic and metals, then shredded and mixed and bulking material added. The bulking material is as described in section 2.2.1. The energy consumption data used in this study are for a system called Enviflex, provided by OptiBag Systems AB (Optibag, 2002). The system works parallel with the sorting-plant and consumes 34 kW to treat 40.000 tons of waste in 2000 hours. The metals and plastic (including plastic waste bags) sieved from the biodegradable waste are landfilled with the residual waste. However, due to limited information about amount and composition of the sieving residuals, the composition of the biodegradable waste and residual waste in table 8 is unchanged.

According to the permits to treat waste in Álfsnes, all waste has to be baled. It is therefore assumed that all residual waste will be baled before landfilling. The same baling press as used in alternative 1, will be used to bale the residual waste.

### 2.2.3.2 Composting

The biodegradable waste will be composted in containers. The inventory is based on information from SORPA /13/ and Stinnes Enerco /4/. The composting in the containers will take approximately 10 days. During that time, 1 ton of biodegradable waste will produce approximately 500 kg of compost. The compost is then stabilised in windrows under a roof for approximately 8 weeks.

The leachate, which drains from the containers and other points of the process flows through a closed piping system to a leachate-receiving tank. Leachate from this tank is re-injected into the containers to control moisture level and to manage leachate production. It is therefore assumed that no net leachate is produced.

The containers are equipped with a sealed lid. All air emission from the containers is led through a biological filter consisting of compost. Exact data for air emission due to degradation of the waste were not available for this specific composting technique. Instead data from an LCA study done by Edelmann and Schleiss /14/, were used. Edelmann and Schleiss did an LCA study for degradation of biodegradable waste in a closed (i.e. no uncontrolled air emission) and fully automatic composting plant. The composting technique was not exactly the same as in this study, but both the techniques are closed and highly controlled. Edelmann and Schleiss measured the CH<sub>4</sub> emission ( $1,1 \cdot 10^{-5}$  kg CH<sub>4</sub>/kg waste) but emissions of NH<sub>3</sub> ( $2,64 \cdot 10^{-5}$  kg NH<sub>3</sub>/kg waste), N<sub>2</sub>O ( $1,52 \cdot 10^{-4}$  kg N<sub>2</sub>O/kg waste) and H<sub>2</sub>S ( $2,85 \cdot 10^{-4}$  kg H<sub>2</sub>S/kg waste) were estimated. The waste in Edelmanns and Schleiss study was similar as in this study but not exactly the same (60% municipal waste, high in food waste and 40% garden waste and waste for official places (high in lignin).

For a treatment plant with annual capacity of 20.000 tons of waste plus bulking material (in the ration 40:60), the consumption of electricity is 96 MJ/ton waste and diesel consumption for a tractor is 1,04 L/ton waste /13/.

The composting plant will be placed at the reloading and pre-treatment station in Gufunes but the compost will be stabilised in windrows at the old landfill in Álfnes. It is assumed that a 40 ton truck (40 ton total weight, including full load) will be used to transport the compost. Diesel consumption of the truck is 13,04 MJ/km (assuming 70% of full load due to low density of compost) and 10,08 MJ/km empty /5/. Low heating value of the diesel is 42,95 MJ/kg /5/ and density 0,84 kg/litre.

### 2.2.3.3 Compost treatment and use

No full-scale trial has been conducted to investigate the application of degraded organic waste in Iceland. Soil erosion is a large problem in Iceland so there might be interest for using the compost as soil improvement product. The use of compost as fertiliser instead of artificial fertiliser is, according to SORPA /13/, expected to be of low interest. Topsoil will be needed in the old landfill area in Álfnes and for the residual waste landfill. Therefore, due to limited information about interest for using the compost outside the landfill area, in this study it is assumed that all the compost produced by the composting process will be used as topsoil on the landfill for residual waste and spread on the old landfill area in Álfnes. A sensitivity study was done where the compost was used as fertiliser. Data from a study performed by DNV in

Norway for the Bærum Municipality were used /15/. In the sensitivity study, it is assumed that the soil limits the amount of compost with respect to N. Transport and spreading of the compost and artificial fertiliser were not considered. Effect of compost on soil quality was also not considered. It was assumed that one ton of compost will replace 14 kg of artificial fertiliser and the avoided energy use due to less production of artificial fertiliser is 0,045 MW/ton compost. Environmental impacts of pollutants in the compost are not considered. The database for N-fertiliser production, which is used, is described in subsection 2.2.5.

Transportation of topsoil from outside the landfill area will therefore not be needed and the compost alternative is credited by avoided transport of topsoil. It is assumed that the same type of truck will be used to transport the topsoil as the compost. The truck will be fully loaded when transporting the soil. Diesel consumption of the truck is 14,31 MJ/km with full load /5/. Approximately 25 tons of topsoil is transported per trip. The topsoil will be mined within 15 km radius from the landfill area. It is assumed that 1 ton of compost will replace 1 ton of topsoil and that each ton of biodegradable waste forms 0,5 ton of compost. The topsoil will be excavated for house foundations in Reykjavik or its neighbour municipalities and is therefore excavated independent of whether it will be used at the landfill or not. Impact of an excavator due to excavation of the topsoil is therefore not included in the inventory.

Even though the compost will only be used as topsoil on landfills it has to be sieved. The sieve uses 0,085 L diesel to sieve 1 ton of raw compost. It is expected that 500 kg of raw compost will be produced from each ton of waste i.e. 50% weight loss. Transport to and from the sieve is taken care of by a wheel loader. Diesel consumption of wheel loader (type CAT 914G, with 1,3 m<sup>3</sup> bucket, assuming medium load factor) is 0,057 L diesel/ton biodegradable waste /6/.

The residues sieved from the compost are landfilled with the residual waste. The impact of the sieving residues is not included in this study because limited information exists about composition and amount of the residues.

#### 2.2.3.4 Residual waste

The residual waste will be landfilled. The waste has to be baled before it is landfilled. SORPA expects to use the same baling station as in alternative 1, 20 km from the landfill in Álfsnes. The baling process, use of iron strapping and energy per kg waste, is expected to be the same as in alternative 1 (landfilling with gas collection).

According to Sundqvist *et al.* /1/ there is a lack of relevant field data for emission from residual waste landfills and there is also a lack of characterisation of the waste that make it difficult to derive a mathematical model for the residual waste landfill. Sundqvist *et al.* /1/ argue that aerobic oxygen and nitrate reducing stage in a municipal solid waste landfill may to some extent be representative for the conditions in the residual waste landfill: a slightly positive redox potential and a slightly acidic pH. Sundqvist *et al.* /1/ consequently calculate different emission factors for residual waste landfills than municipal solid waste landfills. According to Sundqvist *et al.* /1/ the residual waste is defined as the residue when hazardous materials, recyclable materials, combustible wastes and biodegradable wastes have been separated. In a model by Flidner /3/, the model used in alternative 1 is used to calculate emission due to degradation of organic impurities in the residual waste, but different emission

factors are calculated for other waste fractions. In Fliedners /3/ model, plastic and metals are dominant components of the residual waste.

In this study, it is assumed that separation of recyclable paper and cardboard is the same whether the municipal waste is separated into biodegradable waste and residual waste or not. The content of food waste is also much higher in the residual waste fraction in this study compared to the composition reported in Sundqvist *et al.* /1/. It is therefore assumed that the degradation of waste in the residual waste landfill is the same as in municipal solid waste landfill and the model used in alternative 1 is used for the residual waste.

Landfill gas is not collected in the residual waste landfill. The formed landfill gas will pass through the cover and 15% of the methane will be oxidised in the topsoil like in alternative 1.

Leachate collection and treatment is the same as in alternative 1. It is assumed that 80% of the leachate produced will be collected and treated in a settling tank with reduction factors described in table 9.

### 2.2.4 Alternative 3, biocell

Figure 5 shows process flow diagram of the biocell alternative.

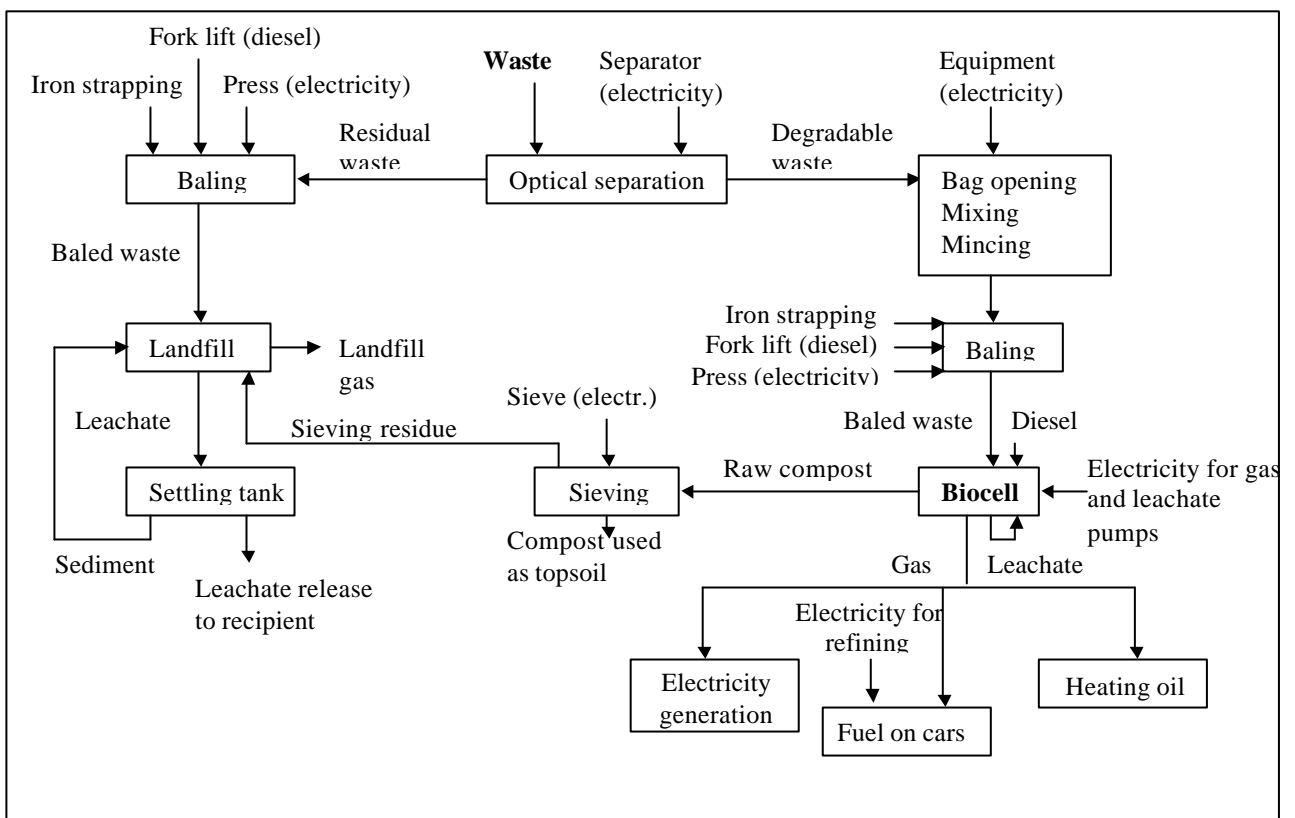


Figure 5: Process flow diagram for biocell, alternative 3

#### 2.2.4.1 Separation of waste and pre-treatment

Separation and pre-treatment of the waste is the same as in alternative 2 (composting in containers). The biodegradable waste is treated in the biocell and the residual waste is landfilled. It is assumed that the waste will be separated at source in bags with different colours and then discarded into a single bin. The bags are then separated at a reloading and pre-treatment station, with the same type and size of equipment as described in alternative 2. Before the biodegradable waste is put into the biocell, the bags have to be opened, the waste screened for plastic and metals, then shredded and mixed and bulking material added.

It is assumed that the biocell will be placed on top of the old landfill in Álfnes (alternative 1). According to the permits to treat waste in Álfnes, all waste has to be baled. It is therefore assumed that biodegradable waste will be baled before treatment in biocell and residual waste will be baled before it is landfilled.

#### 2.2.4.2 Biocell

The model for degradation of waste in the biocell and emission of gas and leachate is described in Flidner /3/. It is based on the landfill model used in alternative 1 with few variations. Like for the landfill model the time period is divided into surveyable time period (ST) and remaining time period (RT). The surveyable time period is the time that takes to treat the waste in the biocell and the remaining time corresponds to complete degradation of all the waste material. According to Flidner /3/, treatment time of 5 to 20 years in biocell have been reported. SORPA is interested in setting up a biocell developed by SWECO VBB VIAK in Sweden /13/. Heat from flaring landfill gas is used to heat up the biocell and leachate will be recycled, which accelerates the degradation. It is therefore assumed that the surveyable time is 5 years. It is assumed that no landfill fires will occur in the biocell as it was for the landfill.

Degradation of the biodegradable waste in the biocell is modelled as completely anaerobic during ST. Degradation of carbon containing compounds is the same as in the landfill model (alternative 1) but it is assumed that the  $\text{CH}_4:\text{CO}_2$  ratio is 55:45 instead of 50:50. It is assumed that 99% of the emitted carbon content will be emitted as gas and 1% in leachate. The same degradation is assumed for inorganic waste in the biocell model as in the landfill model. After the surveyable time the biocell is aerated for 2-3 months and then excavated. Degradation during the remaining time is therefore assumed to be aerobic. Variation had to be made from Flidner's /3/ model, which originally was based on the model made by Björklund /2/ (alternative 1). All cellulose degrading during RT is assumed to degrade aerobically and 70% of nitrogen emission to air is assumed to be in the form of  $\text{NO}_x$ . The rest, 30% forms  $\text{NH}_3$  (in Flidner's model  $\text{NO}_x:\text{NH}_3$  is 50:50).

Due to additional activity of machines, required to load the waste into the biocell and construct all additional installations such as gas extractions system and leachate control system, it is assumed that oil consumption is 20% higher in the biocell model than in the landfill model /3/.

#### 2.2.4.3 Leachate collection and treatment

Regarding leachate, the biocell is assumed to be a closed system, i.e. all leachate leaching from the biocell is pumped back into the cell to increase moisture and treat the leachate. It is assumed that 8% of the energy content of the methane gas collected from the biocell is used to drive the biocell (i.e. gas collection, leachate circulation, heating the cell and aerate after treatment) /13/. Due to circulation of the leachate, metals and other nondegradable compounds will not leach out of the biocell during ST. Leachate emission of nondegradable compounds, degradation products and elements during ST is therefore added to the emission during RT.

According to Flidner /3/, 90% removal of BOD can be attained by recirculation of leachate. In this study it is assumed that 90% of the BOD is degraded during ST. Ammonia (NH<sub>3</sub>) is however hardly removed by leachate recirculation /3/ and sulphide will precipitate as metal sulphide /10/. According to Reinhart /10/ conversion of organic pollutants like halogenated compounds is enhanced by recirculation due to reduced oxidation-reduction potential and stimulated methanogenesis. Exact figure for degradation of halogenated organic compounds were not found in the literature but 20% degradation is assumed in this study (educated guess). Removal potential for halogenated organic compounds in a municipal wastewater treatment plant is approximately 40% /3/. Metals and other inorganic compounds will not degrade and will be released during RT. The leaching of metals is very important for RT. It is assumed that all the metals will leach out during RT but it will occur over time period of hundred thousands of years. This may cause overestimate of ecotoxicity impact in the impact assessment and interpretation of the results.

#### 2.2.4.4 Gas collection, refining and use

It is assumed that 75% of the gas produced during ST is collected and 15% of the methane formed in the biocell will oxidise in the top layer to carbon dioxide. Therefore the total release of methane from the biocell is 10% /3/. As noted above, energy consumption of the process, including gas pumps, is approximately 8% of the energy content of the methane gas collected from the biocell.

It is assumed that the 92% of the collected landfill gas will be utilised outside the biocell process. I.e. 28% of the gas collected will be used as fuel on passenger cars, 36% combusted in an electricity generator and 28% used in industry, replacing heating oil. The landfill gas refining process is the same as in alternative 1 (section 2.2.2.3). The efficiency of the generator is the same as in alternative 1 and so is the energy content of the methane gas, petroleum and heating oil. Because limited information is available about future transportation of the methane gas (e.g. whether pipeline or truck will be used) the diesel consumption due to transportation of the methane gas is not considered in the study.

#### 2.2.4.5 Compost treatment and use

Treatment and use of the compost produced will be the same as in alternative 2. Besides using the compost on the old landfill in Álfnes and the residual landfill, it will be used as topsoil on new biocells.



#### 2.2.4.6 Residual waste

Treatment of the residual waste is the same as in alternative 2 (section 2.2.3.4).

### 2.2.5 Background processes

Process data records for background processes in this study are from the Sima Pro database. The processes are production of fuel, electricity, iron ribbons (for baling) and nitrogen fertiliser.

For heating oil production and use in industry and production of steel for iron ribbons in the baling process data from the BUWAL 250 database were used. The database BUWAL 250 focuses on packaging materials (plastic, carton, paper, glass, tin plated steel, aluminium), energy, transport and waste treatments. It was assumed that the steel is produced in Germany, 50% from scrap steel and 50% from virgin material. For diesel production and emission from use of diesel data from the BUWAL 132 database were used.

Approximately 95% of the electricity used in Reykjavik is produced by hydropower and approximately 5% is produced by geothermal energy. As no inventory data are available for electricity production by geothermal energy, it is assumed that all the electricity used by SORPA is produced by hydropower (except electricity used in the biocell process which is produced from landfill gas). For production of hydro power the database ETH Energy Version 2 (1994) was used. The database provides detailed data on electricity production from hydropower in Europe, including capital goods, exploration of energy sources and transport. Power distribution system is not included.

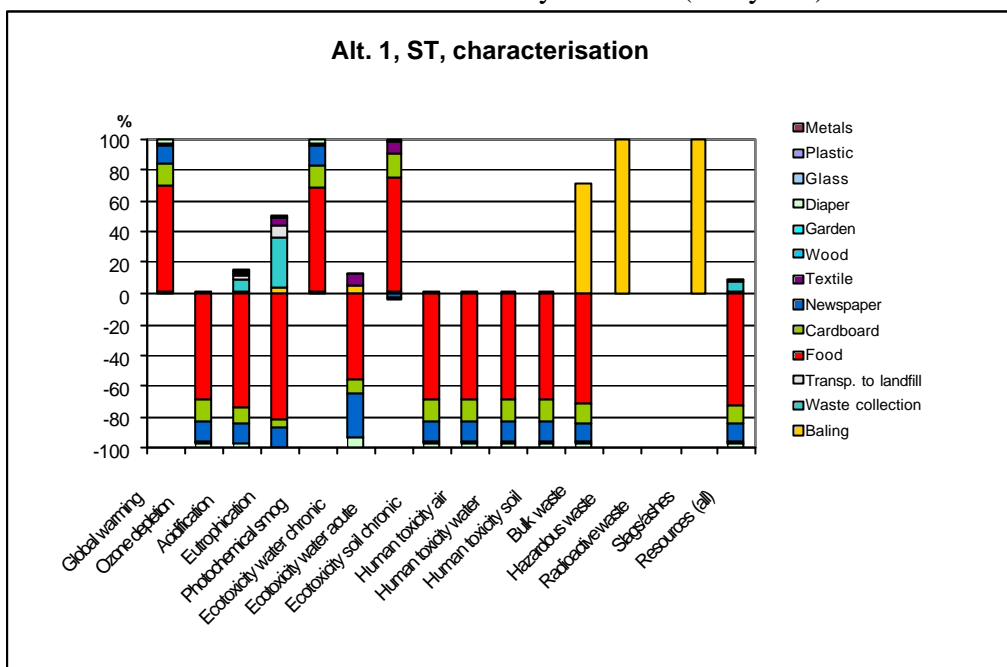
For nitrogen fertiliser production, data from the database SPIN N-fertiliser (1995) were used. The database contains LCA data for production of N-fertiliser from eight producers in the Netherlands (average over 1993).

## 3 Life cycle impact assessment

In this section, the results of the characterisation and weighting in the life cycle impact assessment are presented and discussed. The results are all presented in column graphs. Tables with the life cycle impact assessment results are presented at the end of the appendix. Each of the alternatives will be presented and discussed separately and then compared. The results in subsections 3.1 – 3.4 are calculated with the EDIP method but the results in subsection 3.5 are calculated with the Eco-indicator 99 method.

### 3.1 Alternative 1, landfill with gas collection

Alternative 1 is the present waste management system by SORPA, where the waste is collected, transported to a central baling station, baled and then transported to a landfill outside the city. Landfill gas is collected. Figure 6 shows the results of characterisation in alternative 1 for surveyable time (100 years).



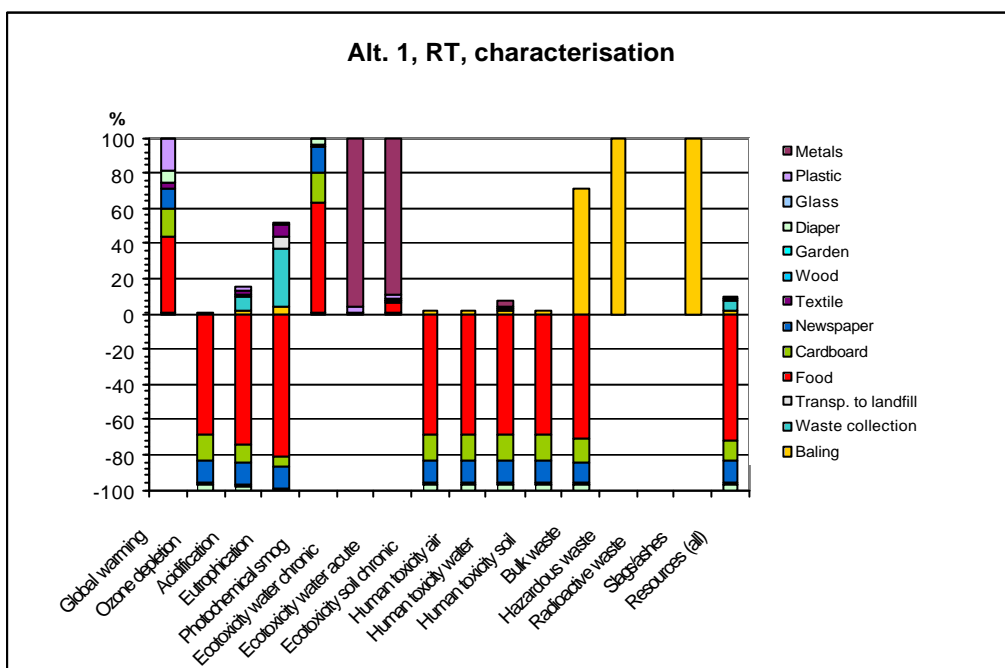
**Figure 6: Characterised LCIA results of landfill with gas collection (alternative 1) for surveyable time (100 years).**

In Figure 6 the impact categories are shown on the x-axis and the waste processes on the y-axis. The waste processes are waste collection, baling, transport to landfill and landfilling which is shown as impacts of each waste fraction e.g. food, cardboard, newspaper, textile, wood, garden, diaper, glass, plastic and metal. The impact of each waste processes and each waste fractions at landfilling are shown as relative impacts of total impacts for the category in question.

Some of the impact categories in Figure 6 have both positive and negative (avoided) impact. For those impact categories the higher sum of impact, positive or negative, is taken as 100%. E.g. for eutrophication in Figure 6 the sum of positive impact is 0,297 but the sum of negative impact  $-0,591$ . The sum of negative impact is therefore taken as 100% and the sum of positive impacts is  $0,297/0,591 \times 100 = 50\%$  of the total avoided eutrophication impact. The eutrophication caused by e.g. just the waste collection is  $0,186/0,591 \times 100 = 31\%$  of the total avoided eutrophication impact. The impact of the waste fractions in landfilling is mainly due to emission from degradation of the waste in the landfill but also landfill related processes such as gas collection, piling of bales and leachate treatment. According to Figure 6, the degradation of waste in the landfill is either giving the largest impact in the various impact categories or the most avoided impact. Avoided impact due to use of landfill gas is allocated to each waste fraction relative to gas production from degradation of the specific waste fraction.

Degradation of food waste gives the highest contribution to most of the impact categories and degradation of newspaper and cardboard also give high contribution. The results for different waste fractions are dependent on their respective share of the whole system. A part of the high contribution of food waste, cardboard and newspaper can therefore be related to high percentage of these waste fractions in the household waste. Relatively high impact of the food waste, newspaper and cardboard can also be related to how easily these fractions degrade during the surveyable time (first 100 years) compared to e.g. plastic and timber. Baling is the only process giving contribution to hazardous waste and slags/ashes. This is due to production of iron strapping for the baling process. The contribution of baling to bulk waste is also due to production of iron strapping. Waste collection and transport gives very low contribution to nearly all of the impact categories compared to the degradation of waste and baling. The only impact categories where collection and transport of waste has visible effect is in acidification, eutrophication and resource use. The waste management system causes net negative effect in ten out of sixteen impact categories due to collection and use of landfill gas.

In Figure 7, the characterised results of alternative 1 for remaining time are presented.

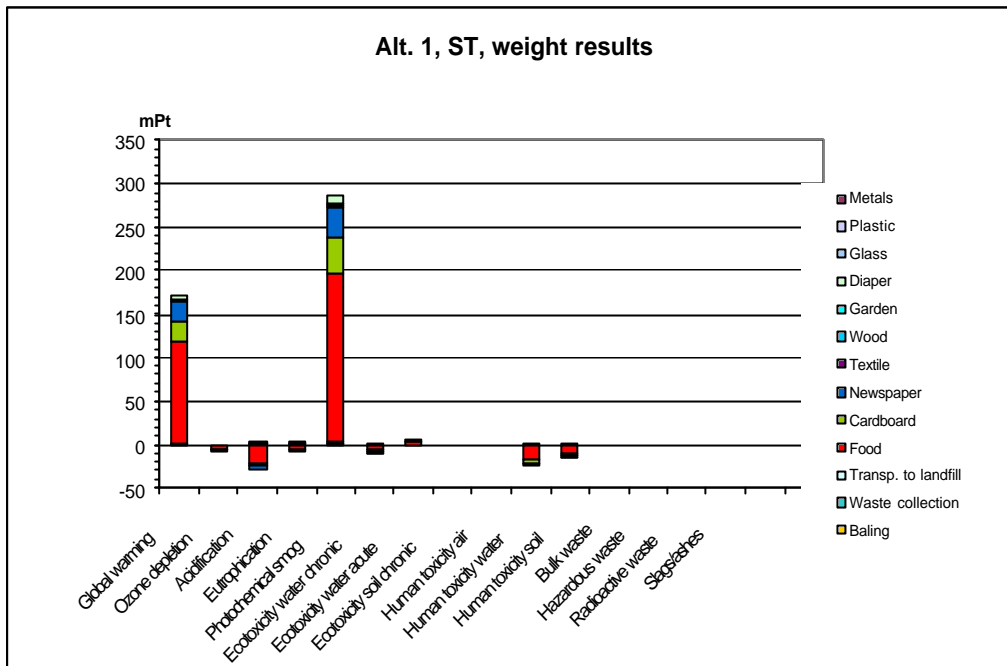


**Figure 7: Characterised LCIA results of landfill with gas collection (alternative 1) for remaining time (infinite time)**

According to Figure 7, metals and plastic are now also contributing to the global warming and the metal is contributing to the impact category ecotoxicity to water. This is expected because metals leach out of the landfill and the plastic degrades in the remaining time.

Figure 8 shows weight results of alternative 1 for surveyable time. I.e. the seriousness of the results for the various environmental impact categories presented in Figure 6 has been assessed to make them comparable. The unit “Pt” on the y-axis is the percentage of the person-equivalent, which can be expected if political targets for reduction are achieved /17/. The politically set target emissions are Danish for the

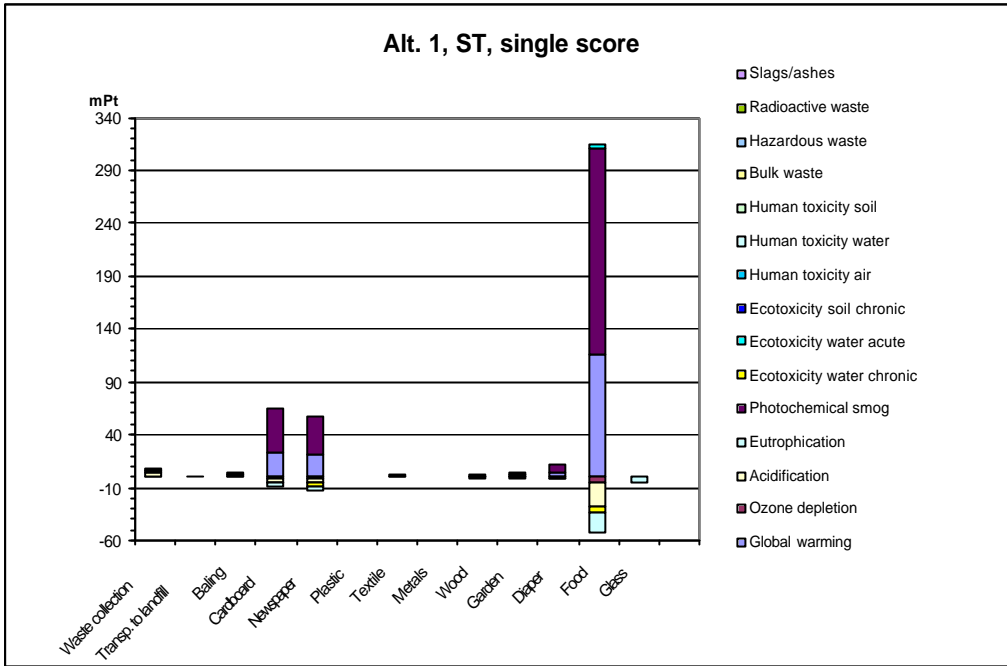
regional and the local impact categories but the weighting of global impact categories is based on the accepted global contribution.



**Figure 8: Weight results of landfill with gas collection (alternative 1) for surveyable time (100 years).**

According to Figure 8, global warming and photochemical smog cause the most serious environmental impacts in alternative 1, for surveyable time. Photochemical smog formation means here the contribution to photochemical ozone (O<sub>3</sub>) formation. The classification step in the EDIP method defines substances with potential to contribute to photochemical smog formation as volatile organic compounds VOC (e.g. methane), carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>). Like the global warming impact, the high photochemical smog impact is therefore caused by methane release from the landfill due to degradation of biodegradable waste. Some of the impact categories give net negative impact, e.g. ozone depletion, acidification, and human and ecotoxic effects. This is due to collection and use of the landfill gas. Because there is used a different method of weighting in the EDIP method (based on reserves rather than political targets) for the impact category resources use, it cannot be compared with the other impact categories. Therefore, the weighting factor is set to zero in Sima Pro and the resource use is not displayed in Figure 8.

Figure 9 shows the weight results as a function of processes (collection, transport, baling) and degradation of waste fractions in the landfilling process.



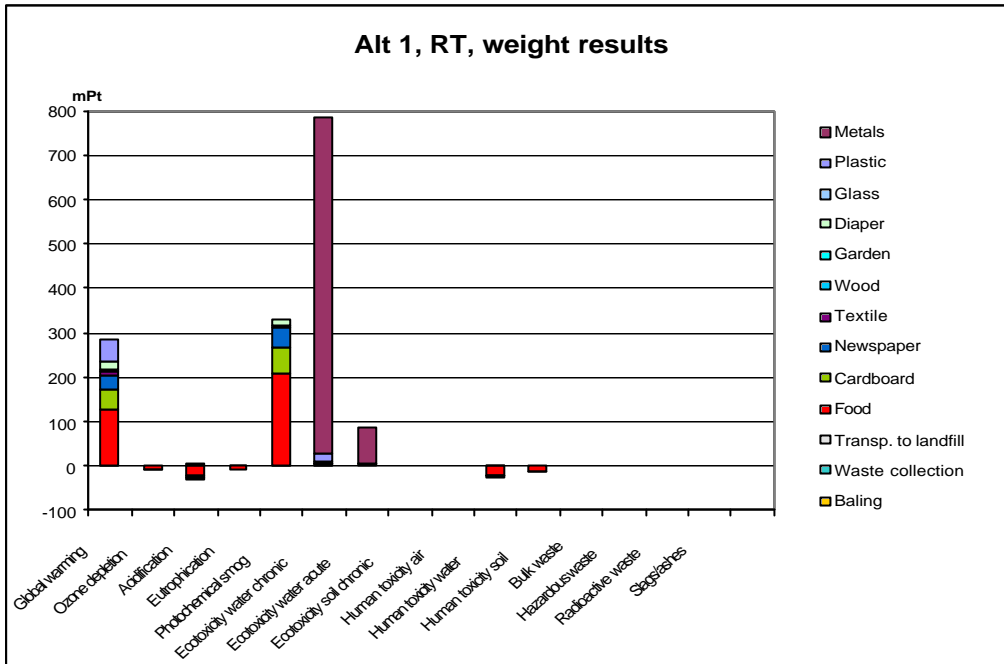
**Figure 9: Landfill with gas collection (alternative 1) for surveyable time (100 years) presented as single score<sup>1</sup> results.**

According to Figure 9 the waste collection, transport and baling are causing insignificant environmental impact compared to the landfilling process. It can also be seen that the food waste, cardboard and newspaper in the landfilling process give the highest contribution to the environmental impacts of the waste management system and plastic and metals are causing insignificant impact in that process during surveyable time.

During remaining time, metals will leach out of the landfill and plastic will degrade. Figure 10 shows weight results of alternative 1 for remaining time.

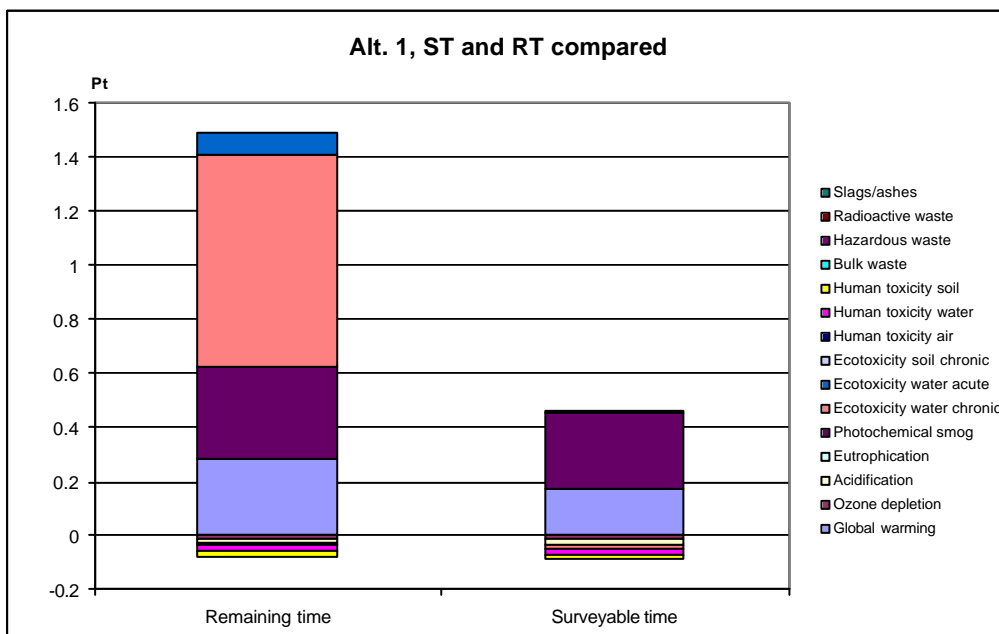
The main change of weighted results from the surveyable (100 years) to the remaining time (total infinitive time) is the appearance of chronic water ecotoxicity which is now the most serious environmental impact, giving more than twice the effect of photochemical smog which is the second highest. This is due to leaching of metals from the landfill. The increase in other impact categories is not as high. Acute water ecotoxicity becomes positive due to leaching of metals but was negative after surveyable time. Global warming increase approximately 120 mPt or 70% compared to surveyable time, due to degradation of plastic, textile and lignin in cardboard, newspaper and food waste.

<sup>11</sup> Single score means adding the impacts of various impact categories, caused by specific process, into a single impact score (in Pt) for the process



**Figure 10: Weight results of landfill with gas collection (alternative 1) for remaining time (infinite time).**

In Figure 11 the environmental impact of the waste management system in alternative 1 is compared for surveyable time and remaining time. The figure shows that environmental impact of the waste management system in alternative 1 triples during RT compared to ST, due to increased global warming and acute and chronic ecotoxicity effects. The most serious impact of the waste management system is chronic water ecotoxicity but it is nearly all caused after the surveyable time. Global warming and photochemical smog are also high and those impacts are caused to a large extent during surveyable time.

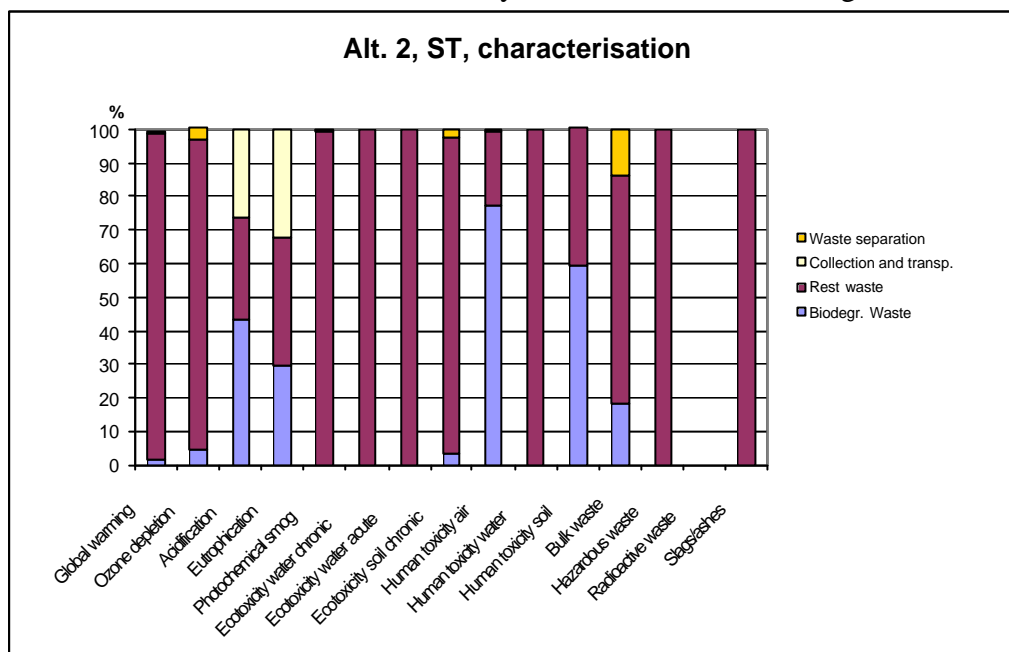


**Figure 11: Comparison of weight results for remaining time (infinite time) and surveyable time (100 years) for landfill with gas collection (alternative 1).**

### 3.2 Alternative 2, composting in containers

Composting biodegradable waste in containers is a future option, which possibly could be implemented by SORPA, when organic waste may not be landfilled. As noted in section 1.4 (data quality), limited information was available on emission due to degradation of the organic waste in the containers and also on the emission from maturing and stabilisation of the compost. The composting process benefits from this lack of data compared to the other alternatives and compared to the impact of waste collection, transportation and degradation of the rest waste.

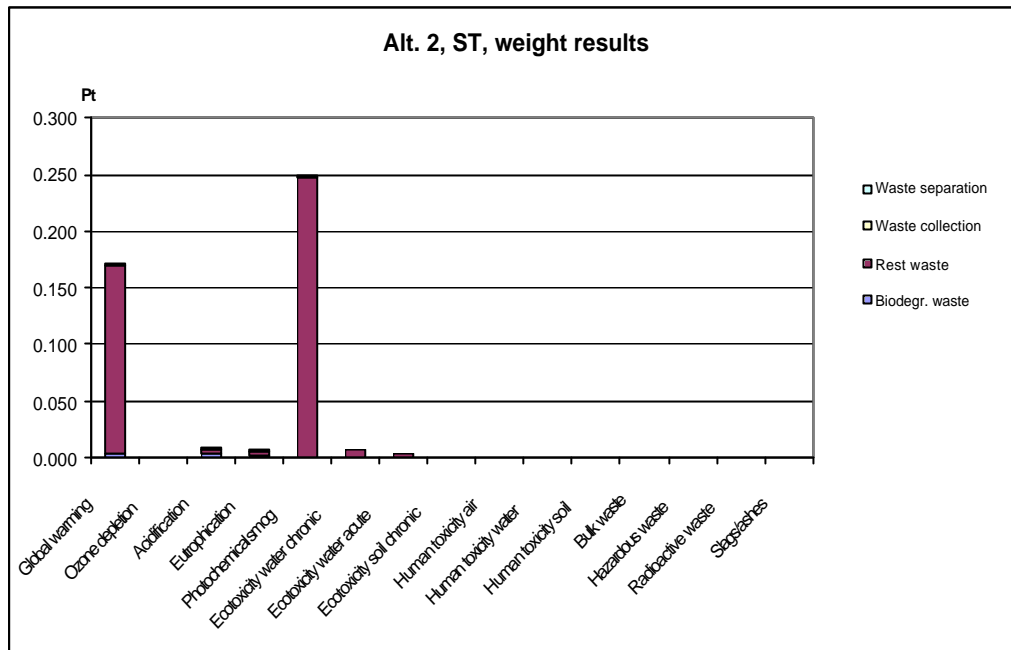
The results of characterisation for surveyable time are shown in Figure 12.



**Figure 12: Characterised LCIA results of alternative 2, composting in containers, for surveyable time (100 years).**

In Figure 12, all the different waste fractions have been combined into just two fractions, biodegradable and rest waste. The biodegradable waste fraction represents the composting process. The residual waste fraction represents baling and landfilling of that fraction which is not composted. Figure 12 shows that the residual waste causes nearly all the environmental impact in nine of the 15 impact categories that were considered. Global warming is nearly all caused by the rest waste as it degrades in the landfill (no landfill gas is collected) and also the ozone depletion, photochemical smog and the toxic impacts. Degradation of the biodegradable waste however causes largest part of the air and soil toxicity to humans. Collection and transport of the waste cause the largest part of resource use (fuel) and contribute also to the acidification and eutrophication due to combustion of diesel. Waste separation seems to cause very little effect compared to other processes, mainly causing formation of bulk waste.

When looking at the weight results for the surveyable time, it can be seen that the landfilling of rest waste causes nearly all of the most serious environmental impacts. Figure 13 shows the weight results of alternative 2 during surveyable time.



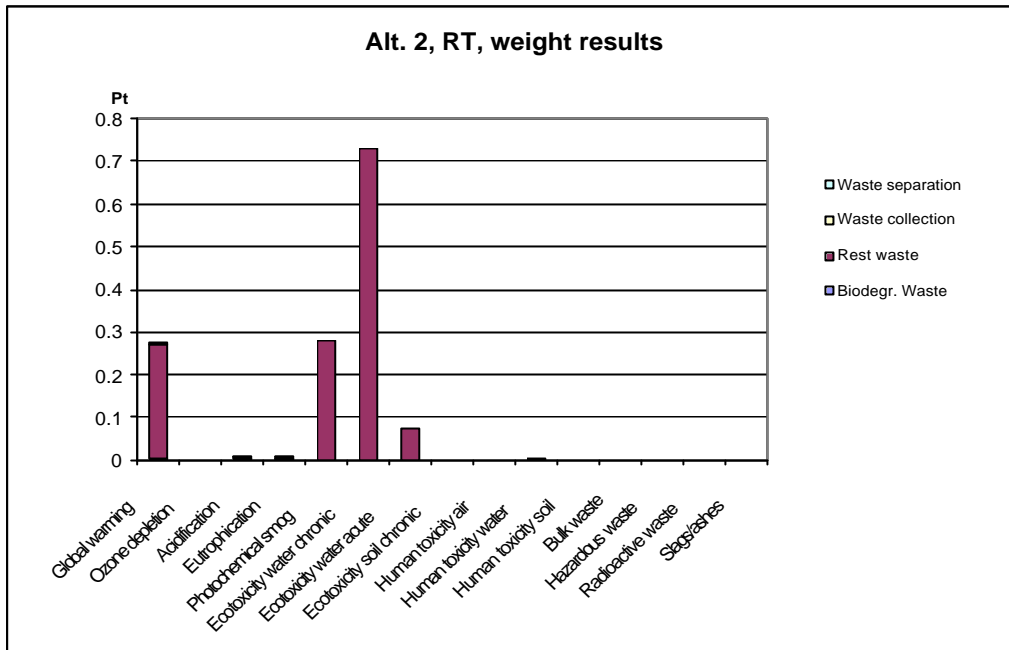
**Figure 13: Weight results of alternative 2, composting in containers, for surveyable time (100 years).**

From Figure 13 it can be seen that the major environmental impacts caused by alternative 2 during surveyable time are global warming and photochemical smog. The landfill gas that is emitted when biodegradable fraction in the rest waste is degraded causes these effects. With a better separation of the biodegradable waste fraction from the rest waste fraction these impacts could be decreased. The acidification and the eutrophication impacts, which are caused to some extent by collection and transport of the waste and the composting process, are however much less serious.

Due to large impact of the rest waste landfill compared to the compost treatment the insufficient quality of emission data for degradation of biodegradable waste in the compost treatment probably does not affect the total results much.

During remaining time the weight results change in the same way as in alternative 1. I.e. the strong impacts of landfilling the rest waste are dominating. Figure 14 shows the weight results of alternative 2 for remaining time.

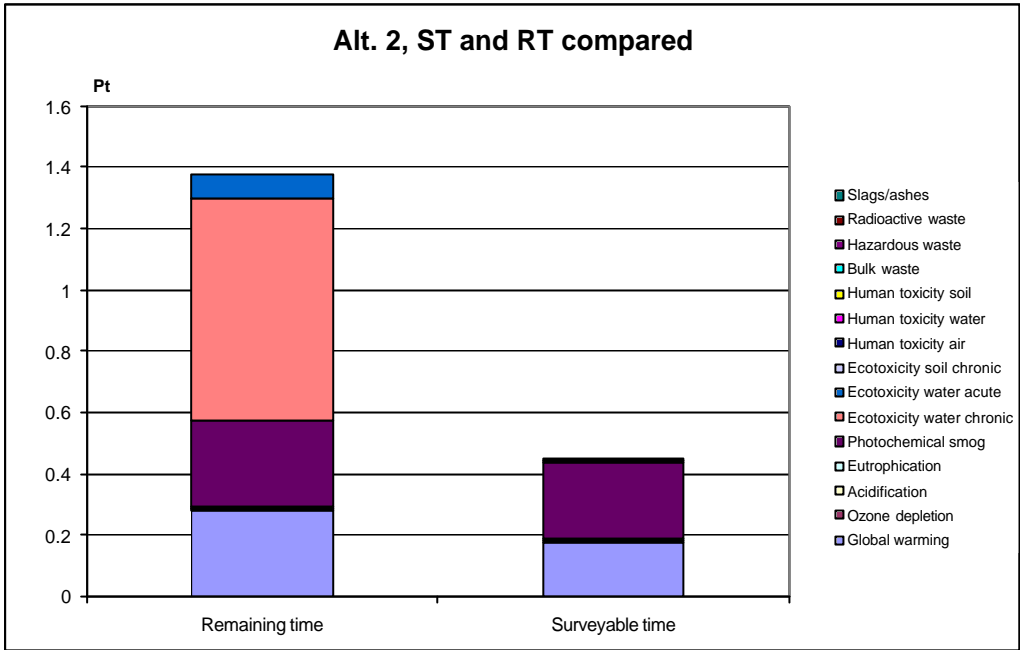




**Figure 14: Weight results of alternative 2, composting in containers, for remaining time (infinite time)**

Like in alternative 1, the impact category chronic water toxicity is the most serious environmental impact during RT caused by leaching of metals. Acute water toxicity also increases and so does the global warming due to degradation of lignin, textile and plastic.

In Figure 15 the weight environmental impact of alternative 2 during surveyable time and remaining time are compared. The environmental impact caused by the compost during remaining time, i.e. leaching of pollutants from the compost is however not included in this study. The total impact during remaining time may therefore be larger than shown in Figure 15.

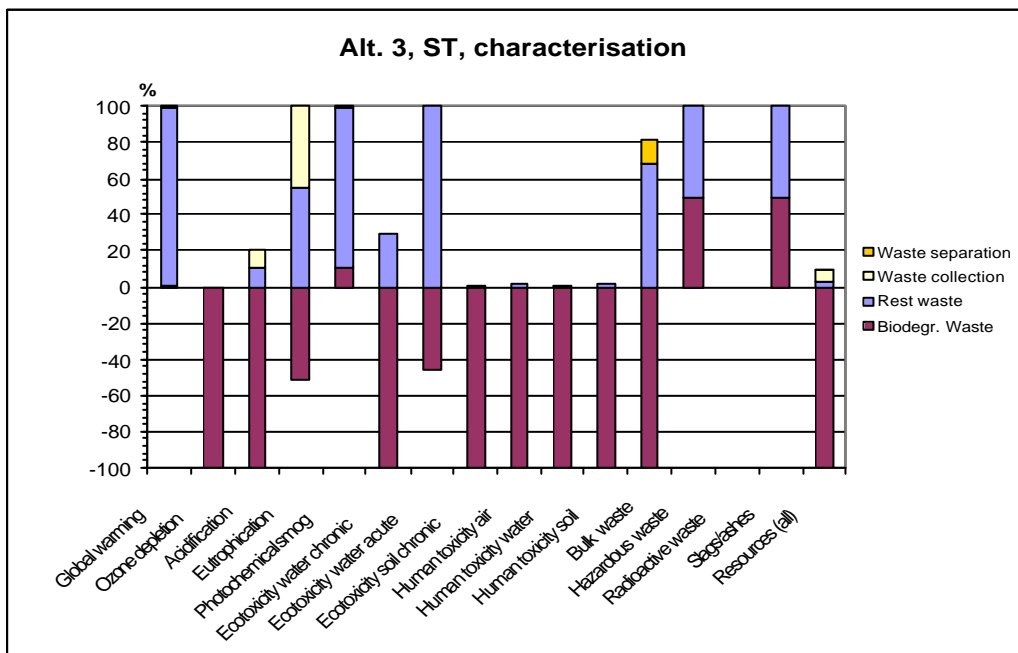


**Figure 15: Alternative 2, composting in containers, compared for surveyable time (100 years) and remaining time (infinite).**

### 3.3 Alternative 3, biocell

Alternative 3, the biocell, is also a future option, which could be implemented by SORPA, when organic waste may not be landfilled. Data for emission from degradation of biodegradable waste is of better quality in this alternative compared to alternative 2.

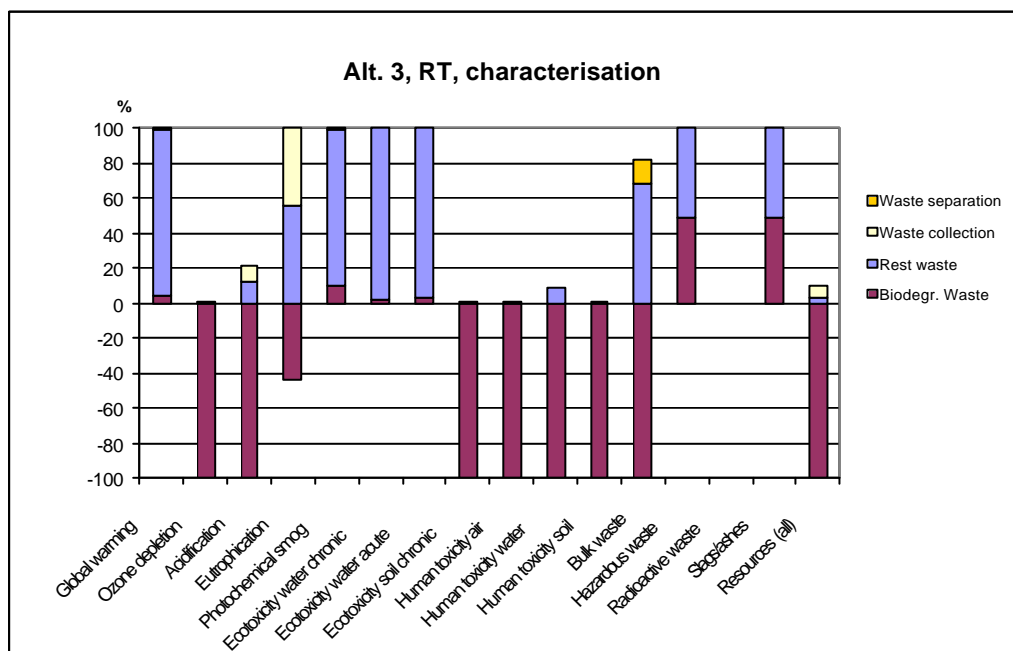
The results of characterisation for surveyable time are shown in Figure 16.



**Figure 16: Results of characterisation for alternative 3, biocell, for surveyable time (100 years).**

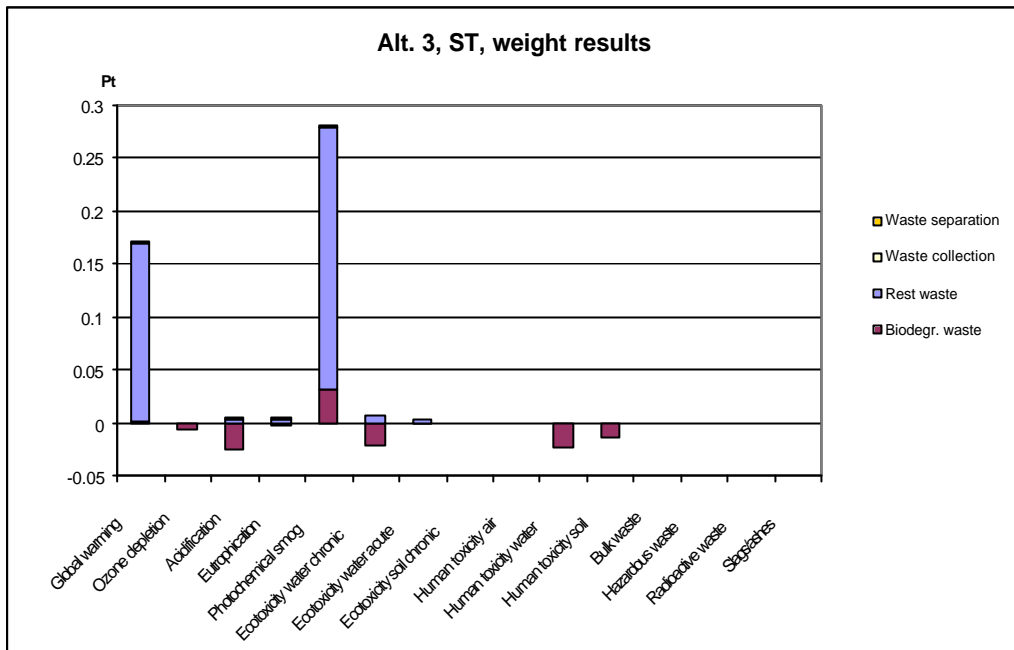
In Figure 16, the waste fractions have been combined into biodegradable and residual waste. The biodegradable waste fraction represents baling of the biodegradable waste and degradation of it in the biocell process. The residual waste fraction represents baling and landfilling of that fraction. From Figure 16 can be seen that more than half of the impact categories have net negative environmental effect due to utilisation of the landfill gas collected. Waste collection and separation causes little of the environmental impact except in the eutrophication category where waste collection causes nearly half of the eutrophication in the waste management system and for acidification. Very little global warming is caused by the biodegradable waste as avoided emission due to use of fossil fuel make up for the global warming caused by emission of landfill gas, which is not collected. The global warming is therefore 98% caused by the rest waste landfill. Avoided resource use (i.e. the bar for resource use bar under the x-axis in figure 16), is very high compared to resource use (mainly fuel) caused by collection of the waste. The use is only 10% of the avoided use.

Figure 17 shows the characterised impact assessment results for remaining time. For the remaining time the results do not change much. From Figure 17 can be seen that only chronic and acute waste toxicity change significantly during remaining time compared to surveyable time. The change is related to leaching of metals from the inorganic waste landfill during remaining time. In the inventory the digested waste produced was assumed to be used as topsoil and degrade like in landfill but aerobically. Leaching of metals, which causes acute and chronic water ecotoxicity, is insignificant for the biodegradable waste compared to the residual waste. The result is probably the same in alternative 2.



**Figure 17: Results of characterisation for alternative 3, biocell, for remaining time (infinite).**

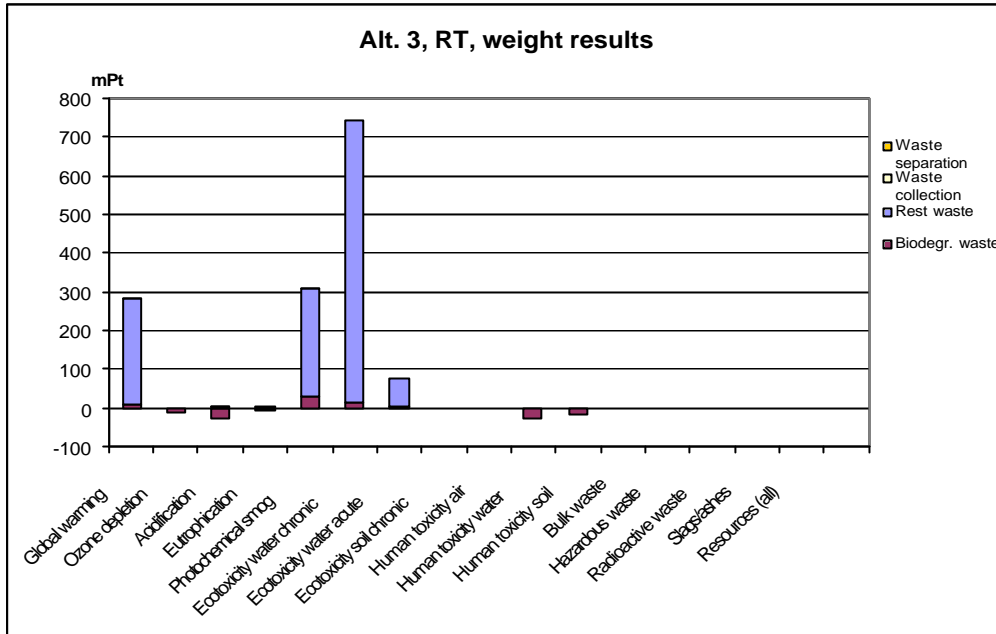
Figure 18 shows the weight results of alternative 3, biocell, for surveyable time (100 years).



**Figure 18: Weight results of alternative 3, biocell, for surveyable time (100 years).**

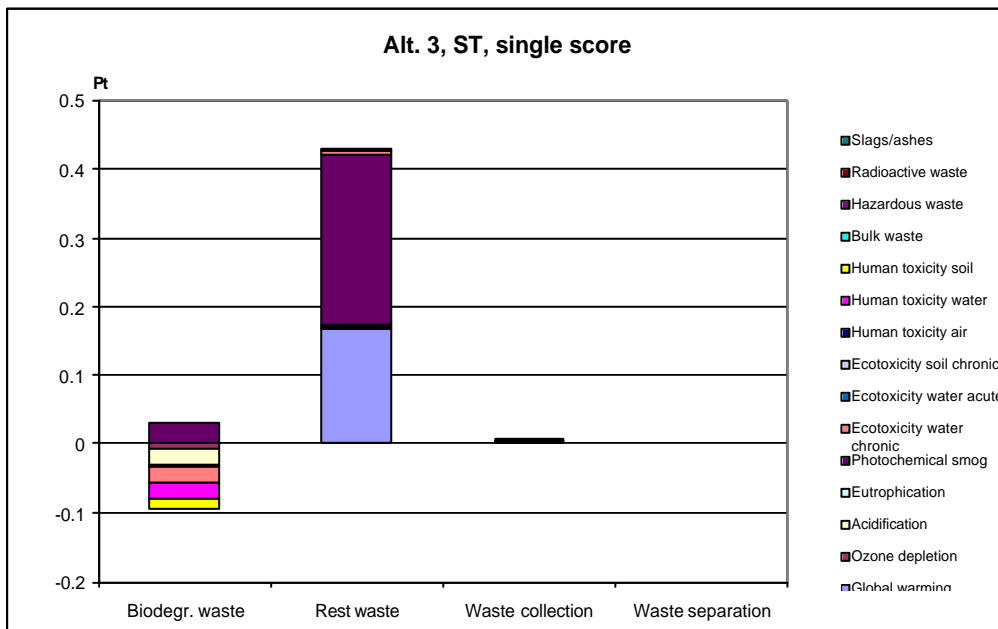
According to Figure 18, the seriousness of the impact categories global warming and photochemical smog are much higher relative to other impact categories. Landfilling of rest waste mainly causes both these impact categories. This is due to emission of landfill gas from the rest waste landfill. By better separation of the biodegradable waste from the rest waste fraction these impacts could be decreased. Waste collection and separation seems to have insignificant impact compared to degradation of the waste. According to Figure 18 the biodegradable waste has net negative environmental impact.

Figure 19 shows the weight impact of alternative 3 during remaining time. The tendency is the same, i.e. metal leaching from the residual waste landfill cause ecotoxic effect, which by weighting causes much larger impacts than other impact categories. The global warming and photochemical smog also increases due to degradation of lignin, plastic and textiles.



**Figure 19: Weight results of alternative 3,biocell, for remaining time (infinite).**

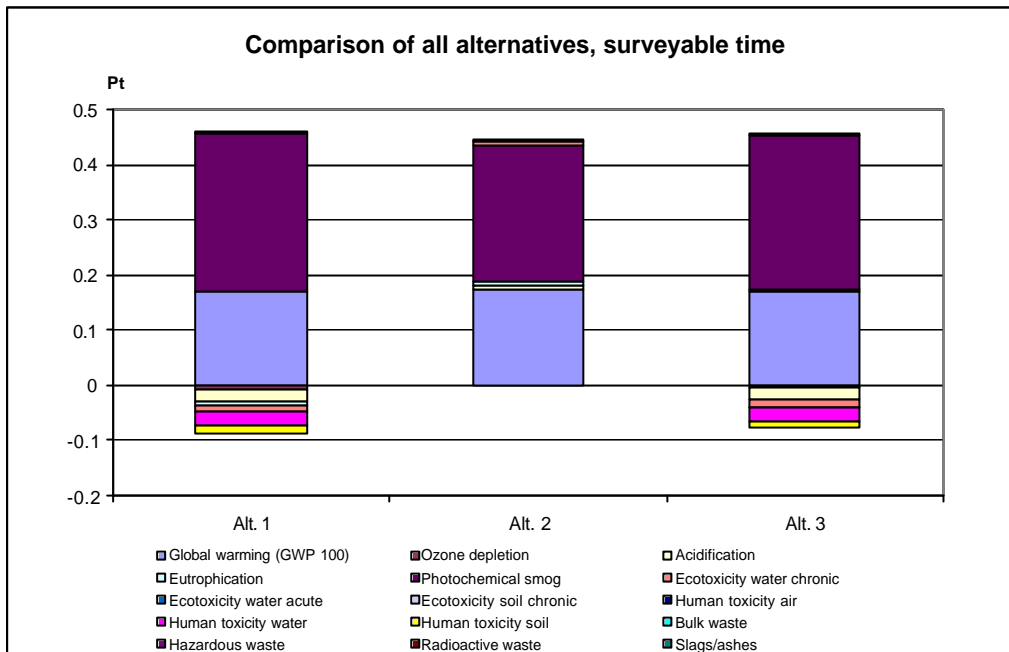
To get a better sight on the different impact of each unit processes in alternative 3, a single score graph for surveyable time has been set up in Figure 20. The figure shows that major part of the environmental impact caused by the environmental waste management system in alternative 3 is due to landfilling of the rest waste. The largest impact during surveyable time is due to global warming and photochemical smog. The biocell however has net negative environmental impact, approximately three times larger than the positive impact caused by the biocell.



**Figure 20: Alternative 3, biocell, for surveyable time (100 years) presented as single score results.**

### 3.4 Comparison of the three alternatives.

The weight results of the impact assessment for all the alternatives during surveyable time are shown in Figure 21.



**Figure 21: Comparison of all alternatives for surveyable time (100 years).**

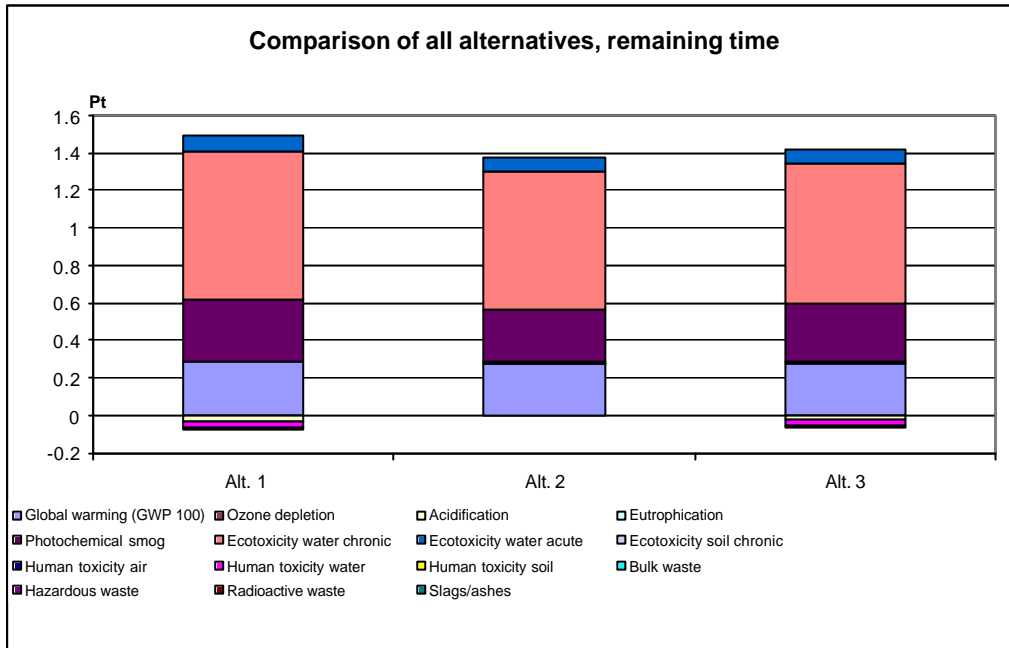
According to Figure 21 the environmental impact of all the alternatives is very similar but alternative 1 and 3 also have avoided impact, which credits these alternatives. The impact is mainly global warming and photochemical smog. As noted before alternative 2 may have higher impact than shown in Figure 21 as limited data were available about emission from the composting process and emission from compost during remaining time is not included.

According to subsections 3.2 and 3.3, the global warming and photochemical smog impacts in alternative 2 and 3 are mainly caused by the residual waste landfill due to release of landfill gas. These alternatives could therefore give better results if the sorting efficiency of the biodegradable and rest waste fractions were better.

For all the alternatives the transportation and pre-treatment of the waste cause insignificant environmental impact compared to emission from degradation of the waste.

The avoided environmental impact in alternative 1 is a little higher than in alternative 3 even though the efficiency of landfill gas collection in alternative 3 is 75% compared to 50% in alternative 1. This is due to the environmental impact of the rest waste landfill, which is not equipped with gas collection system but receives biodegradable waste to some extent due to insufficient sorting.

The weight results of the environmental impact assessment for all the alternatives during remaining time are shown in Figure 22.



**Figure 22: Comparison of all alternatives, remaining time (infinite time).**

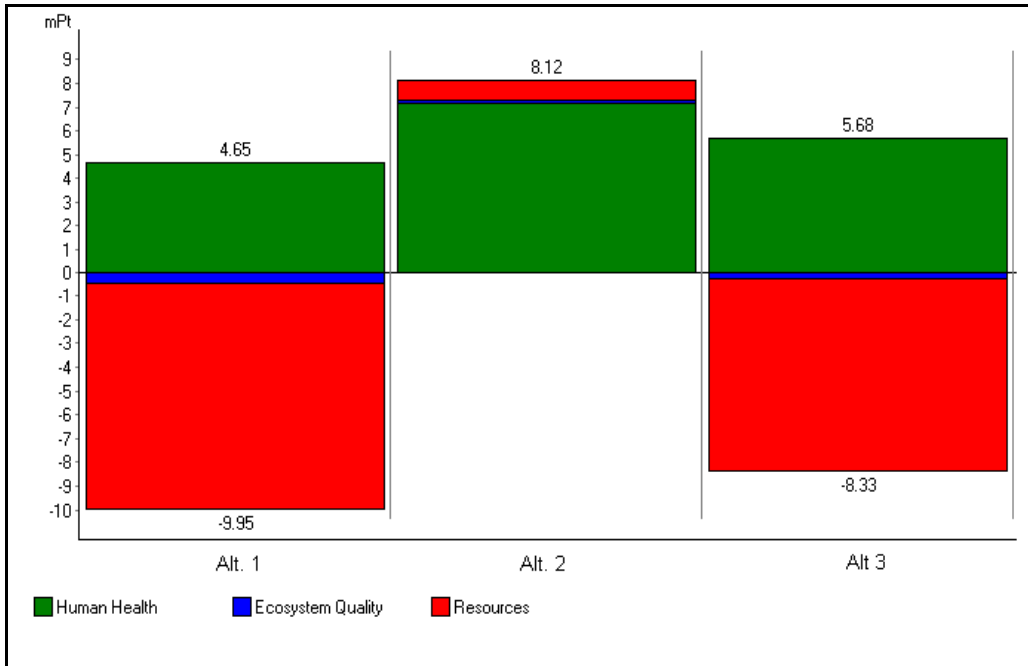
As noted in the previous subsections chronic water ecotoxicity has the largest impact in all the alternatives due to leaching of metals from the landfill or rest waste landfill during remaining time. Acute water ecotoxicity also increases and so do the global warming impact due to degradation of plastic, textile and lignin.

According to Figure 22 the environmental impact of all the three alternatives is very similar but alternative 1 and 3 have avoided impact in some impact categories.

As noted before alternative 2 benefits from not including emission from compost during remaining time.

### 3.5 Impact assessment – Eco-indicator 99

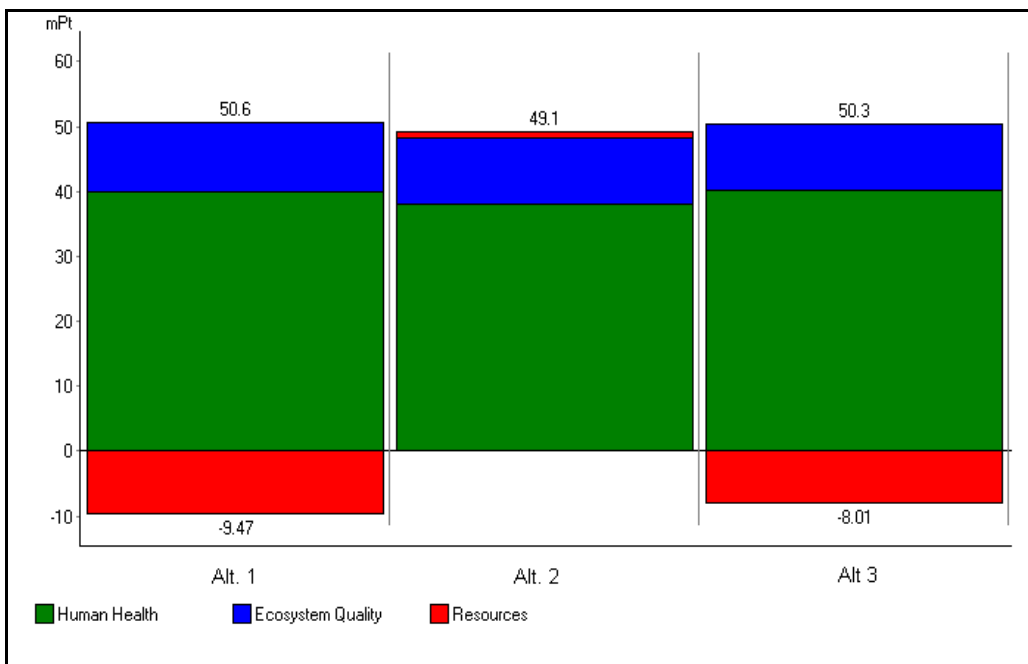
To check the ranking of the different treatment alternatives relative to different weighting method the Eco-indicator 99, described in subsection 1.6, was used. Figure 23 shows comparison of total weight results of all the three alternatives for surveyable time using the Eco-indicator 99 method.



**Figure 23: Comparison of total weight results of all the three alternatives, surveyable time.**

The composting alternative (alt. 2) causes the highest impact (8,12 mPt) and has no avoided resource use. Alternative 1 has the highest avoided impact and also the lowest impact but the difference between alternative 1 and 3 is not much. By using the EDIP method, alternative 1 also had the highest avoided impact and a slightly lower impact.

Figure 24 shows comparison of total weight results of all three alternatives for remaining time.



**Figure 24: Comparison of total weight results of all the three alternatives, remaining time.**



Like by using the EDIP method the toxic effects increase considerably during remaining time due to leaching of metals from the landfilled waste. Alternative 2 (composting) now causes the lowest impact. However, the impact of metals and other pollutants in the compost and degradation of the humus material formed in the composting treatment is not considered in the study. The impact of the composting technique is therefore, in reality, higher than shown in Figure 24, compared to the other alternatives. The difference between impact of alternative 1 and 3 is still very little but alternative 3 has slightly less avoided impact as when the EDIP method was used.

Even though the weighting methods are quite different, based on different principles and methods, the results of the Eco-indicator method look similar to the results of the EDIP method in Figure 21 and 22. However, it can be noted that they do give different results concerning identification of most important interventions, i.e. Eco-indicator-99 gives more weight on human health than the EDIP method and less on ecosystem quality.

## 4 Sensitivity studies

Sensitivity analyses were done to assess the sensitivity of the results related to change in choices of value and inventory data. In the following subsections the changes made and the results of the life cycle impact assessment are presented and discussed. All the impact assessments in the sensitivity study were made using the EDIP method in Sima Pro.

Considering the importance of global warming and photochemical ozone formation, it would be important for assessing the validity of the results to alter the collection efficiency of landfill gas. Due to limited resources that sensitivity study was not carried out.

If there will ever be a continuation of this study, then it would also be very interesting to alter the leaching fraction of metals during RT because it is a very important precondition.

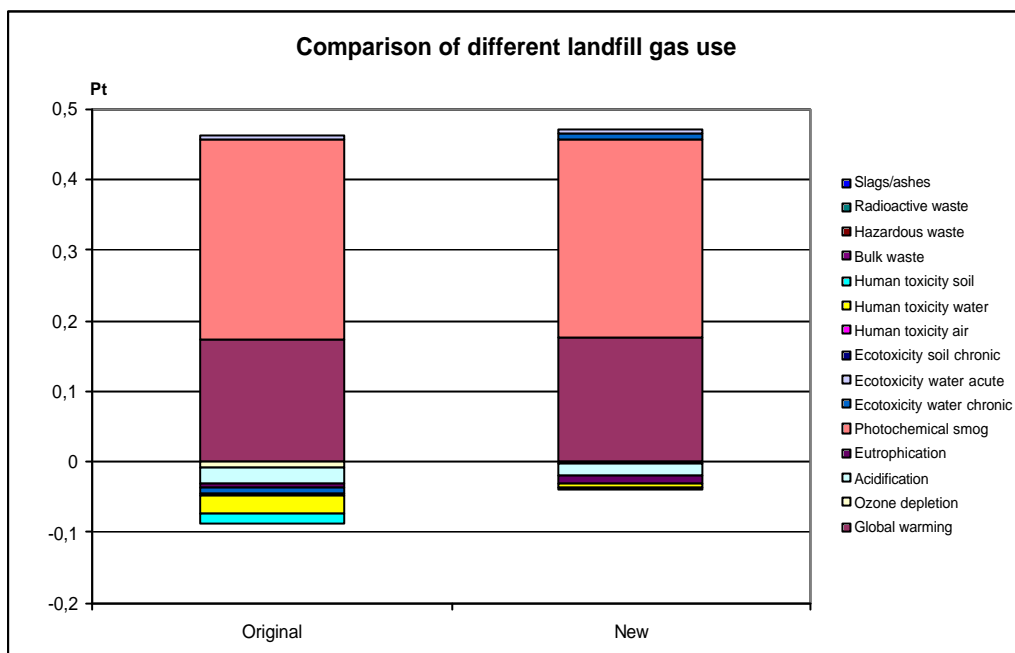
### 4.1 Different use of landfill gas in alternative 1

Only a small part of the landfill gas collected by SORPA is utilised today. Future use of the landfill gas, which is collected in alternative 1 and alternative 3, is uncertain. The environmental impact of electricity production by hydropower and fuel production and refining are unlike. It is therefore of interest to see how the environmental impact might change if the landfill gas is used in a different way. The following table shows how the utilisation of the landfill gas was changed in a sensitivity study for alternative 1 (the landfill with gas collection):

**Table 10: Use of gas in the study for alternative 1 vs. sensitivity study for alternative 1**

Gas used on:	% In study	% In sensitivity study
As fuel on cars	30	60
In industry as heating oil	30	10

Figure 25 shows comparison of the weight results of the life cycle impact assessment



before and after the changes.

**Figure 25: Comparison of different landfill gas use in alternative 1, during surveyable time (100 years).**

According to this the avoided environmental impact decreases considerably. This can be related to less avoided use of heating oil, which contains higher concentration of polluting substances such as sulphur and heavy metals. By combustion of more heating oil the impact of e.g. acidification and toxic effects are therefore higher. However, the decrease in avoided impact can to some extent be related to the database for emission from combustion of heating oil and diesel. The database for emission from combustion of heating oil is more extensive (i.e. contains more data) and therefore the avoided use of heating oil is more important than the avoided use of diesel.

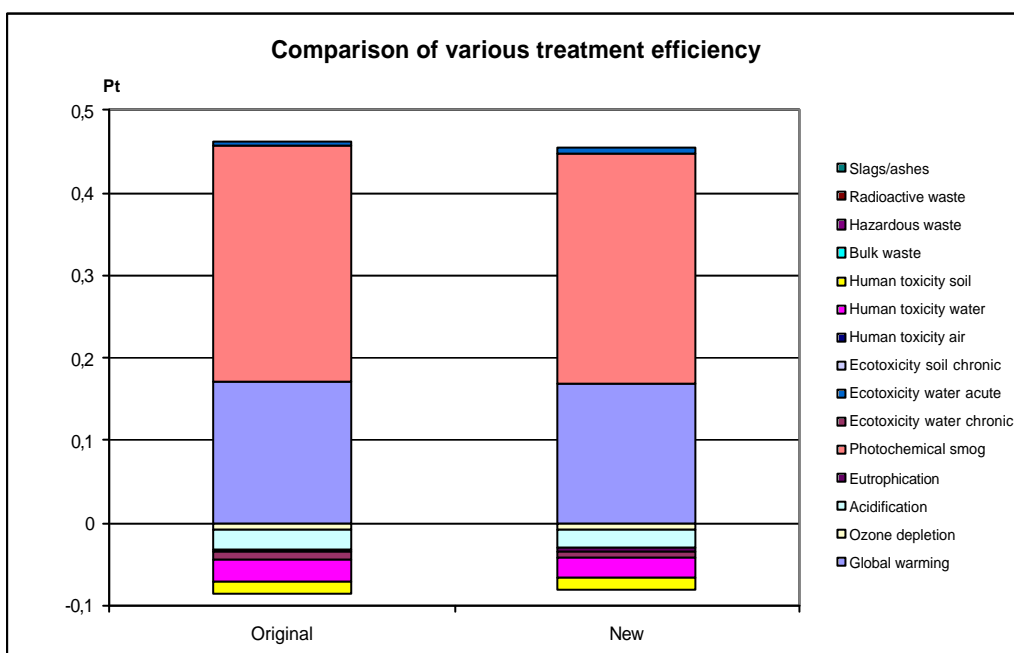
#### 4.2 Different treatment efficiency of leachate from the landfill in alternative 1

The treatment efficiency of the leachate treatment in alternative 1 was uncertain, as no measurements have been done on the leachate composition before treatment in Álfnes. It was therefore of interest to see how the results of the study would change if lower treatment efficiency would be used. The treatment efficiency used in the study (see also table 9) and the new treatment efficiency are described in table 10. The treatment efficiency was lowered by 20%. To limit the data that had to be changed in Sima Pro, treatment of metals in the leachate was not considered, as leaching of metals is very low during the surveyable time.

**Table 11: Reduction factors for leachate treatment in Álfsnes in the study and in the sensitivity study.**

Substance	Original reduction factors (%)	New reduction factors (%)
COD	30	10
BOD	30	10
NH3	10	0
S	20	0
P	20	0

Figure 26 shows the total weight impact using the original and new reduction factors.



**Figure 26: Comparison of various treatment efficiency in alternative 1.**

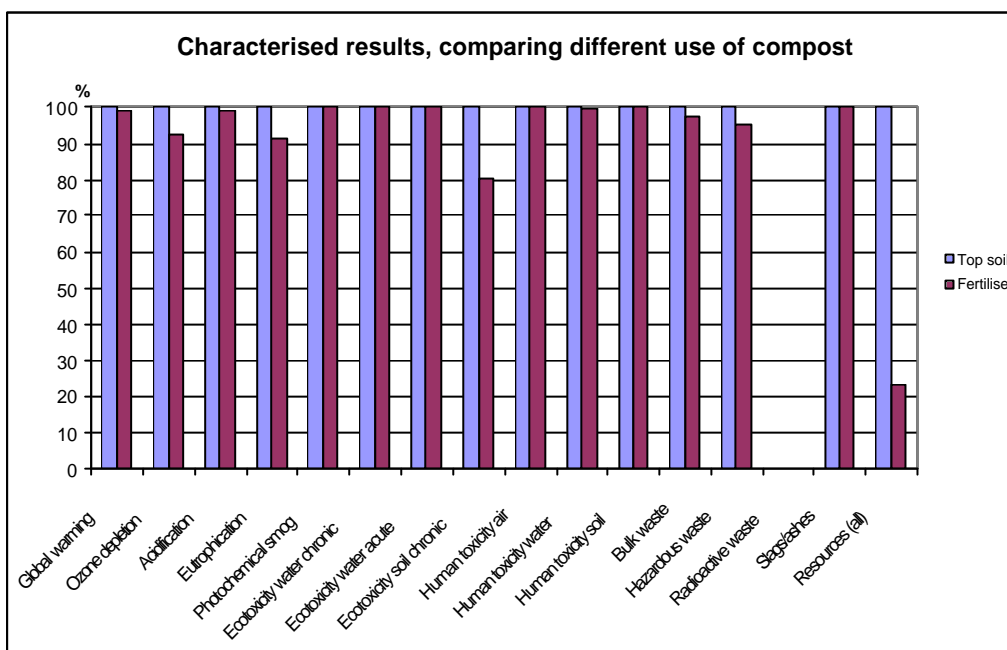
According to Figure 26 the difference is very little if the treatment efficiency of the leachate is 20% lower. I.e. the leachate is not causing a large part of the environmental impact of the waste management system being studied and the effect of low quality of the data for treatment efficiency does not have effect on the weight results of the study.

### 4.3 Compost used as fertiliser instead of topsoil

As was discussed in the inventory for alternative 2, no full-scale trial has been conducted to investigate the application of degraded organic waste in Iceland and the use of the compost is therefore uncertain. In the study it was assumed that the compost produced by degradation of the biodegradable waste would be used as topsoil on landfills and biocells. The system was credited by less transportation of topsoil to the landfill and biocells. It was of interest to see the effect of using the compost as fertiliser instead of topsoil. Due to limited resources and time the use of

the compost as fertiliser was only analysed in a limited way. The system was credited by avoided production of artificial fertiliser. Transportation and spreading of artificial fertiliser and compost was not considered. Environmental impact of metals and other pollutants leaching from the compost after spreading were not included. Data from a Norwegian study /15/ were used. It is assumed that nitrogen in the compost limits the amount of compost that can be spread on the farmland. It is assumed that 1 ton of compost will replace 14 kg of artificial fertiliser. Data from Sima Pro for production of nitrogen fertiliser were used (see Spin N-fertiliser (1995) in section 2.2.5). The data are from 8 producers in the Netherlands, averaged over 1993.

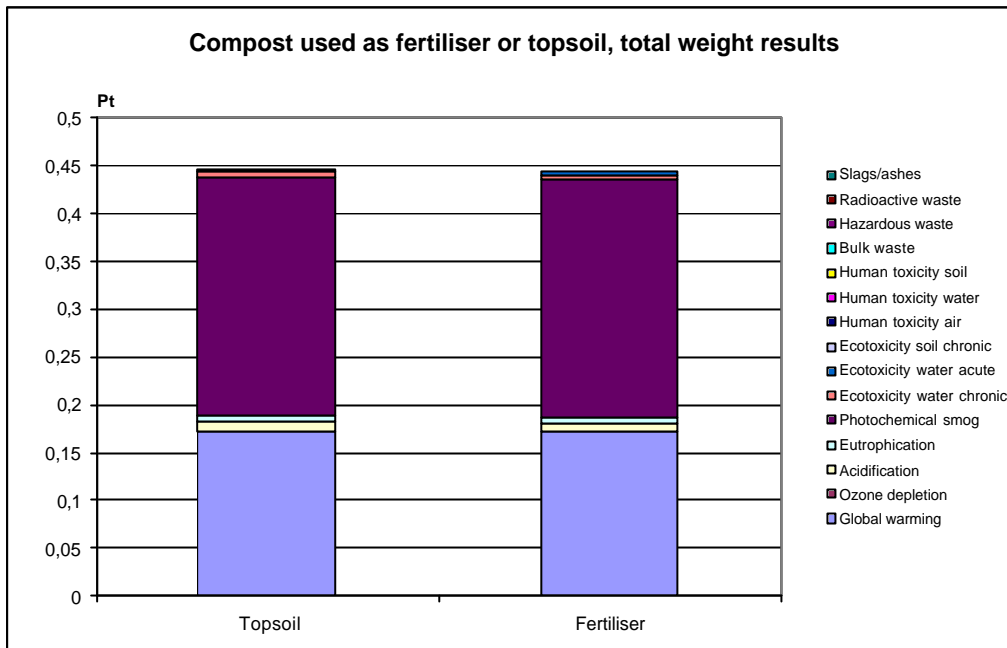
Figure 27 shows the characterised results of the impact assessment.



**Figure 27: Results of characterisation, comparing different use of compost in alternative 2, composting in containers.**

From Figure 27 can be seen that impact of some of the impact categories decreases. The decrease in resource use is largest, 77%, but other categories decrease less than 20%, e.g. ozone depletion, eutrophication and chronic soil ecotoxicity. However, spreading of compost costs more fuel than spreading of artificial fertiliser due to less nutrient content in each kg of product. The acidification, eutrophication and resource use impacts would therefore increase more in the fertiliser alternative compared to topsoil if spreading of the fertilisers would be included. Ecotoxicity would also probably increase more in the fertiliser alternative compared to topsoil if leaching of pollutants from the compost would be included.

When the results of the various impact categories are weight the difference between using the compost as top soil or fertiliser is very little. Figure 28 shows weight result of using the compost as fertiliser or top soil.



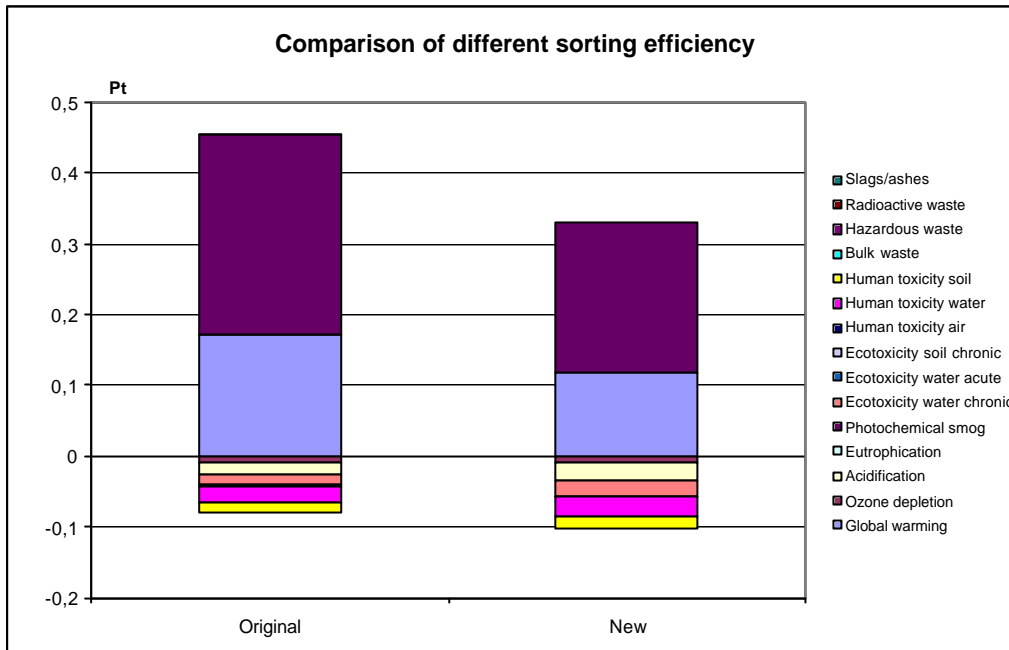
**Figure 28: Compost used as fertiliser or topsoil, weight results.**

According to Figure 28, difference in eutrophication and ozone depletion do not seem to affect the total weight results (n.b. as noted on page 28 resource use cannot be compared to other impact categories and is therefore not included in Figure 28). According to figure 28, with the limitations of the sensitivity study noted above, the compost process does not benefit from using the compost as fertiliser instead of topsoil.

#### **4.4 Sorting efficiency**

The sorting efficiency in alternative of household waste in alternative 2 and 3 (composting and biocell) seems to have a large effect on the results of the study. I.e. biodegradable waste that ends up in the rest waste fraction due to low sorting efficiency causes high global warming and photochemical smog impact. It was therefore of interest to see how changes in sorting efficiency would effect the results of alternative 2 and 3. The sorting efficiency was increased from 70% to 85%. The biodegradable waste fraction was 40,6% of the weight of waste in the functional unit and the rest waste fraction 47,7%. Originally it was 32% biodegradable waste and 56% rest waste.

Figure 29 shows total weight results of the original and the new sorting efficiency during surveyable time for alternative 3, the biocell.



**Figure 29: Comparison of different sorting efficiency, weight results, surveyable time.**

The weighted impact of alternative 3 decreases considerably by increasing the sorting efficiency (40% decrease). I.e. the sorting efficiency is very important for the results of the biocell alternative and probably also the composting alternative. The photochemical smog and the global warming which are caused by release of landfill gas from the rest waste landfill and have the highest environmental impact decrease considerably by increasing the sorting efficiency of organic waste.

## 5 Interpretation

A lot of factors affect the results of this study but some are more critical than others. The results are affected by assumptions made in the inventory such as assumptions about the sorting efficiency of waste, quality of the inventory data available and use of products formed by the waste treatment. In this section the results of the study will be summarised and also the factors that affect them the most. The results will be compared to the goal and scope of the study and recommendations made. The results of the study have not been iterated, i.e. this is only a screening study.

The most important impact category in all the weight results were photochemical smog and global warming during surveyable time and chronic water ecotoxicity during remaining time.

The photochemical smog formation depends on local conditions. The classification step in the EDIP method defines substances with potential to contribute to photochemical smog formation as volatile organic compounds VOC (e.g. methane), carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>). The contribution of NO<sub>x</sub> to the photochemical smog cannot be calculated with the same method as VOC and therefore two sets of values are used, “low NO<sub>x</sub>” and “high NO<sub>x</sub>” depending on areas. For Scandinavia low NO<sub>x</sub> values are recommended /18/ and the lower values were

used in this study. Low NO<sub>x</sub> value mean concentration of NO<sub>x</sub> over rural areas < 10 ppbv. At a measuring station in Keldnaholt, which is located in the suburb of Reykjavik (approximately 10 km from Álfarnes) the average annual NO<sub>x</sub> concentration in the year 2000 was 1,8 ppbv /22/. The characterisation for photochemical smog is therefore realistic for the area. Ozone, formed by the photochemical smog reactions in the troposphere, is the air pollutant that most often crosses the guideline values in Reykjavik due to high background concentrations like in the other Scandinavian countries /21/. The political targets for reduction of the photochemical smog, which are used in weighting the characterisation results in the EDIP method, should therefore be similar in the Reykjavik area.

Global warming is mainly caused by methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) emission due to degradation of biodegradable waste. Global warming is a global phenomenon but the political targets for reduction, used in the EDIP method are European. The weighting of global warming relative to other impact categories is therefore not overestimated.

Leaching of metals from the landfill or compost cause the high chronic water ecotoxicity during remaining time (infinite time).

The landfill alternative (alt. 1) and the biocell alternative (alt. 3) give similar total weight results during surveyable time. Both of the alternatives have avoided impacts due to utilisation of landfill gas formed and the impacts are similar. One might expect the biocell alternative to give better results than the landfill because the landfill gas collection is more efficient and all leachate is circulated. However, due to low sorting efficiency of biodegradable waste, landfill gas emission from the rest waste landfill lowers the ranking of the biocell alternative. The data quality of the landfill alternative and the biocell alternative are similar. To rank the biocell alternative higher the sorting efficiency has to be higher.

The composting alternative (alt. 2) has the lowest impact during surveyable time but no avoided impact and therefore the ranking of the composting alternative relative to total weight impact during surveyable time is lower than alternative 1 and 3. The data for emission from degradation of biodegradable waste during composting were limited. By using emission data from similar composting treatment (but not identical) the impact of emission from the composting treatment has insignificant effect on the weight results because of relatively large impact of the rest waste landfill. Lower emission from the composting treatment would therefore not rank the composting alternative higher. To rank the composting alternative higher, sorting of household waste has to be more efficient.

The biocell alternative will probably always be ranked higher than the composting alternative for surveyable time as it produces fuel and the sorting efficiency in the composting alternative is the same as in the biocell alternative. The composting alternative might be ranked higher than the landfill alternative if sorting efficiency is increased but with the sorting efficiency in this study it does not. Using the compost produced as fertiliser instead of topsoil does not rank the composting alternative higher even though it lowers the impact in some impact categories.

For remaining time the three alternatives have similar total weight results, i.e. 1,36, 1,38 and 1,42 Pt. Comparison of the compost alternative to the other alternatives for the remaining time is though not realistic because further degradation of the humus in the compost and leaching of pollutants from the compost are not included in this study. The biocell alternative would be ranked higher than the landfill alternative for remaining time if sorting efficiency would be higher as for the surveyable time.

Using another weighting method, i.e. Eco-indicator instead of EDIP, did not change the ranking of the alternatives significantly. The total weight impact of the landfill alternative and the biocell alternative are still similar for both surveyable and remaining time. The compost alternative has however higher total weight impact for surveyable time compared to the other alternatives than in the EDIP method.

A sensitivity study shows that different use of the landfill gas produced in the landfill and biocell alternatives affects the total weight results due to different avoided impact from fuel production and electricity production and different emission from combustion of different fuel. Increasing the use of landfill gas on cars and lowering the use in industry increases the total weight impact and lowers the avoided impact.

The treatment efficiency of leachate from the landfills in the study was uncertain. However, the weight results and a sensitivity study showed that leachate from the landfill was of minor importance during the surveyable time and therefore also the treatment efficiency. Leachate is not treated after the surveyable time.

The collection and transport of waste causes the highest resource use impact due to use of fuel. As resources use a different method of weighting in the EDIP method compared to other impact categories, the weight resource impact cannot be compared to the other impact categories. Other impacts caused by the collection and transport of waste processes seems to have little effect on the total weight results for all the alternatives. Increasing the transport distances or using another type of transport vehicle would therefore not change the total weight results much (the resource use would however increase considerably). The pre-treatment also seems to have little effect on the weight results in all the three alternatives compared to effect of degradation of the waste.

In the study the household waste fractions in the analysis performed by SORPA had to be adjusted to the fractions which composition data were available for. The composition of the metal fractions derives from a Norwegian study /8/ and composition of the newspaper, cardboard and plastic from a Swedish study /11/. The composition of the waste fractions in Iceland may be different from Norway or Sweden but how much it differs and the effect of the differences is hard to predict. A sensitivity study would give a view of how important these assumptions are but due to limited resources it was not possible to perform sensitivity studies for the composition of the waste and waste fractions.

## **5.1 Conclusions and recommendations**

The goal of this study was to use life cycle assessment to assess the environmental impact of the household waste management system in Reykjavik and its neighbouring municipalities and compare it with impact of future options, biocell or aerobic composting. The functional unit of the study was one ton of household waste from



Reykjavik and its neighbouring municipalities, collected at kerbside. As noted in the previous section photochemical smog, global warming are the most critical impacts during the surveyable time and ecotoxicity during remaining time. The critical impacts are caused by degradation of the waste but not by the collection, transport and pre-treatment. In table 12 the impacts of various process for the three alternatives are listed:

**Table 12: Summarised results**

Alternative	Process	Impact	Cause of impact	Remarks
Landfill with gas collection	Landfilling	High impact, mainly global warming and photochemical smog the first 100 years but then also chronic water ecotoxicity	Biodegradable waste, mainly food waste, newspaper and cardboard. Metals in leachate.	
	Composting	Low impact compared to the rest waste landfill		Low quality of data
Composting	Rest waste landfill	High impact, the same impacts as for landfilling.	Degradation of biodegradable waste and no gas collection at the landfill. Metals in leachate.	
	Anaerobic digestion	Low impact compared to the rest waste landfill		High gas collection efficiency of low importance due to emission from rest waste landfill
Biocell	Rest waste landfill	High impact, the same impacts as for landfilling.	Degradation of biodegradable waste and no gas collection at the landfill. Metals in leachate	
	Waste collection Pre-treatment Transport of waste	Impact of emission from these processes is low compared to degradation of waste. Main impacts are acidification, eutrophication and resource use.	Energy use, both electricity and diesel.	Weight results of resource use are not comparable to other impact categories

From the summarised results in table 12 and the discussion above the following recommendations are made:

- Focus should be put on decreasing the impact of the rest waste landfill, as it is much more than the impact of the digestion in the biocell or the composting treatment.
- High sorting efficiency is important for the composting and biocell alternatives and therefore much weight should be put on strategies to increase sorting efficiency if either of these treatment alternatives will be implemented.
- Waste collection, pre-treatment and transport causes much lower impact than degradation of waste. Increasing the waste collection or transport to increase the sorting efficiency would therefore decrease total impact of the system if waste is to be sorted.
- More landfill gas should be used in industry to lower the use of heating oil, as it contains higher concentration of polluting substances such as sulphur and heavy metals than fuel used on cars.

- Leachate from the landfill is of low importance during the first 100 years compared to impact of the landfill gas. More focus should therefore be put on collection efficiency of the landfill gas than leachate treatment.

The most critical factor in ranking of the treatment alternatives is the separation efficiency of household waste into biodegradable and rest waste fraction. If the sorting efficiency is good, biocell will be the best alternative and composting might get higher ranked than landfilling.

## 6 References

- /1/ Sundqvist J-O., Björklund A., Carlsson M., Eriksson O., Frostell B., Granath J. and Thyselius L. (1999): *Systemanalys av energiutnyttjande från avfall – utvärdering av energi, miljö och ekonomi, Fallstudie – Stockholm*. Statens Energimyndighets forskningsprogram Energi från Avfall. Projektnr: P10544-1. Stockholm, Sweden.
- /2/ Björklund A. (1998): *Environmental System Analysis of Waste Management*. Licentiate Thesis, Department of Chemical Engineering and Technology/Industrial Ecology, Royal Institute of Technology, Stockholm Sweden.
- /3/ Fliedner A. (1999): *Organic Waste Treatment in Biocells. A Computer-based Modelling Approach In the Context of Environmental System Analysis*. Master of Science Degree Thesis. Royal Institute of Technology, Stockholm.
- /4/ Stinnes (2001): Stinnes Enerco web page:  
<http://www.stinnesenerco.com/System251/Odour/default-odour.htm>
- /5/ Frees, N. and B.P. Weideman (1998): *Life Cycle Assessment of Packaging systems for Beer and Soft Drinks – Energy and Transport scenarios*, Technical report No 406, Ministry of Environment and Energy, Danish Environmental Protection Agency.
- /6/ Caterpillar (2001): *Caterpillar Performance Handbook*, 32 Edition. CAT publication by Caterpillar Inc., Peoria, Illinois, USA.
- /7/ Dalemo, M. (1997): *The ORWARE Simulation Model - Anaerobic Digestion and Sewage Plant Sub-models*. Licentiate thesis. Swedish University of Agricultural Sciences, SLU, Uppsala.
- /8/ Sandgren, Jonas; Heie, Aage; Sverud, Terje (2000): *Utslipp ved håndtering av kommunalt avfall, SFT-rapport TA-1366*. Statens Forureningstilsyn, Oslo, Norway.
- /9/ SORPA (2001): *Annual report 2000*. Sorpeyðing Höfuðborgarsvæðisins bs., Reykjavík, Iceland.
- /10/ Reinhart, D.R. (1989): *Active Municipal Waste Landfill Operation: A Biochemical Reactor*. National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.
- /11/ Finnveden, G., Johansson, J., Lind, P., Moberg, Å. (2000): *Life Cycle Assessment of Energy from Solid Waste*. Forskningsgruppen för Miljöstrategiska Studier (FMS), report nr. 137, Stockholm.
- /12/ Hjelmar, O., Johannessen, L.M., Knox, K., Ehrig, H.-J., Flyvbjerg, J., Winther, P. and Christensen, T.H. (1994): *Management and Composition of Leachate from Landfills. Final Report for the Commission of the European Communities, DGXI A.4. Waste 92*. Prepared by Water Quality Institute and Carl Bro Environmental a/s in co-operation with Knox Associates, University of Wuppertal and Technical University of Denmark. VKI, Hørsholm, Denmark. Commission of the European Communities DGXI A.4. Waste 92 (1994) Management and composition of Leachate from landfills, Contract No. B4-3040/013665/92 Final report.
- /13/ Halldórsson, B.H. (2002): Personal communication with Björn Halldórsson, chief engineer at SORPA.

- /14/ Edelmann, W. and Schleiss, K. (1999): *Ökologischer, energetischer und konomischer Vergleich von Vergärung, Kompostierung und Verbrennung fester biogener Abfallstoffe*. Elaborated by The Arbeitsgemeinschaft Bioenergie, arbi, Baar and Umwelt- und Kompostberatung Schleiss, Baar, Switzerland.
- /15/ Pretlove, B. (1999): *Livsløpsanalyse for behandling av husholdningsavfall*. DNV Rapport nr. 99-3126. Det Norske Veritas, Norway.
- /16/ Hekla Ltd. (2002): Personal communication with Finnbogí Eyjólfsson by Hekla, the dealer for Volkswagen in Iceland.
- /17/ Hauschild, M. and Wenzel, H. (1997): *Environmental Assessment of Products, Volume 1 – methodology, tools and case studies in product development*. Chapman & Hall, London.
- /18/ Hauschild, M. and Wenzel, H. (1998): *Environmental Assessment of Products, Volume 2 – Scientific background*. Chapman & Hall, London.
- /19/ Goedkoop, M. and Spriensma, R. (2000): *The Eco-indicator 99. A damage oriented method for Life Cycle Impact Assessment. Methodology Report – second edition*. PRÉ Consultants B.V., Amsterfort.
- /20/ Nielsen, P.H. and Hauschild M. (1998): *Product Specific Emission from Municipal Solid Waste Landfills*. International Journal of LCA. 3 (3) 158-168.
- /21/ Hollustuvernd (1999): *Loftmengunarmælingar, staða í árslok 1999*. The Icelandic Environment and Food Agency.
- /22/ Hollustuvernd (2000): *Loftgæðamælingar á vegum Hollustuverndar ríkisins – niðurstöður 2000*. The Icelandic Environment and Food Agency.
- /23/ PRÉ (2002): Web-page of PRÉ Consultants by: [www.pre.nl](http://www.pre.nl)

## 7 Results of impact assessment

### Case 1, alt. 1 - results of characterisation using EDIP, ST

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:06:48 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Impact indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Waste collection	Transp. to landfill	Bailing	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron
Global warming (GWP 100)	g CO2	1.14E3	9.56	2.36	4.49	159	144	0.199	0.0264	0.0163	0.00813	0.0223	0.0772	0.0406
Ozone depletion	g CFC11	-6.72E-5	x	x	2.65E-7	-9.24E-6	-8.69E-6	x	x	x	x	x	x	x
Acidification	g SO2	-1.24	0.117	0.0288	0.0212	-0.159	-0.181	0.0165	0.00218	0.00134	0.000671	0.00185	0.024	0.00336
Eutrophication	g NO3	-0.295	0.186	0.0458	0.0228	-0.0272	-0.0757	0.00387	0.000513	0.000316	0.000158	0.000434	0.0339	0.000789
Photochemical smog	g ethene	0.363	0.0022	0.000541	0.00102	0.0504	0.0458	4.57E-5	6.06E-6	3.73E-6	1.86E-6	5.13E-6	1.77E-5	9.32E-6
Ecotoxicity water chronic	g/m3	-197	x	x	12.2	-21	-64.1	0.0168	0.00223	0.00137	0.000686	0.00189	15.9	0.0158
Ecotoxicity water acute	g/m3	112	x	x	0.948	19	-4	0.00168	0.000223	0.000137	6.86E-5	0.000189	7.84	0.00158
Ecotoxicity soil chronic	g/m3	-0.727	x	x	0.0107	-0.101	-0.0951	2.95E-9	3.91E-10	2.41E-10	1.2E-10	3.31E-10	8.06E-10	1.7E-9
Human toxicity air	g/m3	-2.74E6	71.8	17.7	4.26E4	-3.81E5	-3.59E5	1.5	0.199	0.122	0.0612	0.168	444	0.307
Human toxicity water	g/m3	-604	0	0	9.32	-84.1	-79.1	0.000248	3.29E-5	2.03E-5	1.01E-5	2.79E-5	0.000128	0.000275
Human toxicity soil	g/m3	-1.82	0	0	0.0271	-0.254	-0.239	4.51E-8	5.98E-9	3.68E-9	1.84E-9	5.06E-9	0.000105	2.59E-8
Bulk waste	kg	-0.000512	x	x	0.00121	-0.000225	-0.000207	x	x	x	x	x	x	x
Hazardous waste	kg	1.6E-5	x	x	1.6E-5	x	x	x	x	x	x	x	x	x
Radioactive waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	kg	0.000361	x	x	0.000361	x	x	x	x	x	x	x	x	x
Resources (all)	kg	-1.72E-6	1.04E-7	2.55E-8	3.56E-8	-2.21E-7	-2.31E-7	2.16E-9	2.86E-10	1.76E-10	8.8E-11	2.42E-10	8.36E-10	4.4E-10

### Case 1, alt. 1 - results of characterisation using EDIP, RT

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:01:39 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Impact indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Waste collection	Transp. to landfill	Bailing	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron
Global warming (GWP 100)	g CO2	1.94E3	9.56	2.36	4.49	315	204	305	42	1.47	0.736	16	69	3.3
Ozone depletion	g CFC11	-6.72E-5	x	x	2.65E-7	-9.24E-6	-8.69E-6	x	x	x	x	x	x	x
Acidification	g SO2	-1.23	0.117	0.0288	0.0212	-0.159	-0.181	0.0165	0.00218	0.00154	0.000769	0.00185	0.0259	0.00336
Eutrophication	g NO3	-0.274	0.186	0.0458	0.0228	-0.0264	-0.0757	0.00387	0.000513	0.000694	0.000347	0.000434	0.0375	0.000789
Photochemical smog	g ethene	0.422	0.0022	0.000541	0.00102	0.0715	0.0617	4.57E-5	6.06E-6	0.000411	0.000206	5.13E-6	1.77E-5	9.32E-6
Ecotoxicity water chronic	g/m3	1.65E4	x	x	12.2	34.5	5.86	288	38.2	4.56	2.28	32.3	49.7	38.9
Ecotoxicity water acute	g/m3	1.78E3	x	x	0.948	24.5	3	28.8	3.82	0.456	0.228	3.23	11.2	3.9
Ecotoxicity soil chronic	g/m3	-0.727	x	x	0.0107	-0.101	-0.0951	3.69E-5	4.9E-6	1.19E-6	5.94E-7	4.14E-6	1.01E-5	2.12E-5
Human toxicity air	g/m3	-2.74E6	71.8	17.7	4.26E4	-3.81E5	-3.59E5	48.2	6.39	1.62	0.812	5.41	456	27.1
Human toxicity water	g/m3	-562	0	0	9.32	-83.6	-78.7	5.96	0.791	0.0549	0.0274	0.669	0.552	0.614
Human toxicity soil	g/m3	-1.82	0	0	0.0271	-0.253	-0.239	0.000564	7.48E-5	1.82E-5	9.08E-6	6.33E-5	0.000259	0.000324
Bulk waste	kg	-0.000512	x	x	0.00121	-0.000225	-0.000207	x	x	x	x	x	x	x
Hazardous waste	kg	1.6E-5	x	x	1.6E-5	x	x	x	x	x	x	x	x	x
Radioactive waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	kg	0.000361	x	x	0.000361	x	x	x	x	x	x	x	x	x
Resources (all)	kg	-1.72E-6	1.04E-7	2.55E-8	3.56E-8	-2.21E-7	-2.31E-7	2.16E-9	2.86E-10	1.76E-10	8.8E-11	2.42E-10	8.36E-10	4.4E-10

**Case 1, alt. 1 - results of weighting using EDIP, ST**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:07:17 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Waste collection	Transp. to landfill	Bailing	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron
Total	Pt	0.374	0.00775	0.00191	0.00348	0.0529	0.0432	0.000446	5.92E-5	3.64E-5	1.82E-5	5.01E-5	0.00206	9.18E-5
Global warming (GWP 100)	Pt	0.171	0.00143	0.000352	0.000671	0.0238	0.0215	2.98E-5	3.95E-6	2.43E-6	1.21E-6	3.34E-6	1.15E-5	6.07E-6
Ozone depletion	Pt	-0.00765	x	x	3.01E-5	-0.00105	-0.00099	x	x	x	x	x	x	x
Acidification	Pt	-0.0252	0.00237	0.000585	0.00043	-0.00323	-0.00368	0.000334	4.43E-5	2.72E-5	1.36E-5	3.74E-5	0.000488	6.81E-5
Eutrophication	Pt	-0.00353	0.00222	0.000548	0.000273	-0.000326	-0.000906	4.63E-5	6.14E-6	3.78E-6	1.89E-6	5.2E-6	0.000405	9.45E-6
Photochemical smog	Pt	0.285	0.00172	0.000424	0.000801	0.0395	0.0359	3.59E-5	4.76E-6	2.93E-6	1.46E-6	4.02E-6	1.39E-5	7.32E-6
Ecotoxicity water chronic	Pt	-0.00941	x	x	0.000584	-0.001	-0.00307	8.04E-7	1.07E-7	6.57E-8	3.28E-8	9.03E-8	0.000762	7.58E-7
Ecotoxicity water acute	Pt	0.00534	x	x	4.53E-5	0.000907	-0.000191	8.04E-8	1.07E-8	6.57E-9	3.28E-9	9.03E-9	0.000375	7.58E-8
Ecotoxicity soil chronic	Pt	-3.48E-5	x	x	5.14E-7	-4.84E-6	-4.55E-6	1.41E-13	1.87E-14	1.15E-14	5.76E-15	1.58E-14	3.85E-14	8.11E-14
Human toxicity air	Pt	-0.000835	2.19E-8	5.4E-9	1.3E-5	-0.000116	-0.00011	4.58E-10	6.07E-11	3.74E-11	1.87E-11	5.14E-11	1.35E-7	9.38E-11
Human toxicity water	Pt	-0.0255	0	0	0.000394	-0.00355	-0.00334	1.05E-8	1.39E-9	8.56E-10	4.28E-10	1.18E-9	5.4E-9	1.16E-8
Human toxicity soil	Pt	-0.0147	0	0	0.000219	-0.00205	-0.00193	3.64E-10	4.83E-11	2.97E-11	1.49E-11	4.09E-11	8.46E-7	2.09E-10
Bulk waste	Pt	-1.26E-6	x	x	2.99E-6	-5.56E-7	-5.12E-7	x	x	x	x	x	x	x
Hazardous waste	Pt	3.99E-7	x	x	3.99E-7	x	x	x	x	x	x	x	x	x
Radioactive waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	Pt	1.22E-5	x	x	1.22E-5	x	x	x	x	x	x	x	x	x
Resources (all)	Pt	0	0	0	0	0	0	0	0	0	0	0	0	0

**Case 1, alt. 1 - results of weighting using EDIP, RT**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:02:00 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Waste collection	Transp. to landfill	Bailing	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron
Total	Pt	1.42	0.00775	0.00191	0.00348	0.0958	0.0685	0.0614	0.00839	0.000825	0.000412	0.00417	0.0143	0.00266
Global warming (GWP 100)	Pt	0.289	0.00143	0.000352	0.000671	0.0472	0.0306	0.0456	0.00629	0.00022	0.00011	0.0024	0.0103	0.000493
Ozone depletion	Pt	-0.00765	x	x	3.01E-5	-0.00105	-0.00099	x	x	x	x	x	x	x
Acidification	Pt	-0.025	0.00237	0.000585	0.00043	-0.00322	-0.00368	0.000334	4.43E-5	3.12E-5	1.56E-5	3.74E-5	0.000525	6.81E-5
Eutrophication	Pt	-0.00328	0.00222	0.000548	0.000273	-0.000316	-0.000906	4.63E-5	6.14E-6	8.31E-6	4.15E-6	5.2E-6	0.000448	9.45E-6
Photochemical smog	Pt	0.331	0.00172	0.000424	0.000801	0.0561	0.0484	3.59E-5	4.76E-6	0.000323	0.000161	4.02E-6	1.39E-5	7.32E-6
Ecotoxicity water chronic	Pt	0.79	x	x	0.000584	0.00165	0.00028	0.0138	0.00183	0.000218	0.000109	0.00155	0.00238	0.00186
Ecotoxicity water acute	Pt	0.0853	x	x	4.53E-5	0.00117	0.000143	0.00138	0.000183	2.18E-5	1.09E-5	0.000155	0.000537	0.000187
Ecotoxicity soil chronic	Pt	-3.48E-5	x	x	5.14E-7	-4.84E-6	-4.55E-6	1.77E-9	2.34E-10	5.69E-11	2.84E-11	1.98E-10	4.82E-10	1.02E-9
Human toxicity air	Pt	-0.000835	2.19E-8	5.4E-9	1.3E-5	-0.000116	-0.00011	1.47E-8	1.95E-9	4.96E-10	2.48E-10	1.65E-9	1.39E-7	8.28E-9
Human toxicity water	Pt	-0.0238	0	0	0.000394	-0.00353	-0.00332	0.000252	3.34E-5	2.32E-6	1.16E-6	2.83E-5	2.33E-5	2.59E-5
Human toxicity soil	Pt	-0.0147	0	0	0.000219	-0.00205	-0.00193	4.56E-6	6.04E-7	1.47E-7	7.33E-8	5.11E-7	2.09E-6	2.62E-6
Bulk waste	Pt	-1.26E-6	x	x	2.99E-6	-5.56E-7	-5.12E-7	x	x	x	x	x	x	x
Hazardous waste	Pt	3.99E-7	x	x	3.99E-7	x	x	x	x	x	x	x	x	x
Radioactive waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	Pt	1.22E-5	x	x	1.22E-5	x	x	x	x	x	x	x	x	x
Resources (all)	Pt	0	0	0	0	0	0	0	0	0	0	0	0	0

**Case 1, alt. 2 - results of characterisation using EDIP, ST**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:21:01 PM

Title:  
Method: EDIP/UMIP 96 (low) / EDIP World/China  
Value: Impact indicator  
Per impact category: Yes  
Skip unused: Never  
Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Global warming (GWP 100)	g CO2	1.15E3	17.4	1.12E3	9.56	0.02842
Ozone depletion	g CFC11	1.6E-7	6.93E-9	1.48E-7	x	5.36E-09
Acidification	g SO2	0.445	0.193	0.135	0.117	0.0001474
Eutrophication	g NO3	0.577	0.169	0.222	0.186	0.0001406
Photochemical smog	g ethene	0.317	0.000372	0.314	0.0022	1.595E-06
Ecotoxicity water chronic	g/m3	130	0.0137	130	x	0.0106
Ecotoxicity water acute	g/m3	60.4	0.00132	60.4	x	0.001024
Ecotoxicity soil chronic	g/m3	0.00637	0.000203	0.00601	x	0.0001568
Human toxicity air	g/m3	1.32E5	1.02E5	2.97E4	71.8	5.03
Human toxicity water	g/m3	5.24	0.000259	5.24	0	0.0001421
Human toxicity soil	g/m3	0.0406	0.0241	0.0166	0	1.077E-06
Bulk waste	kg	0.000999	0.000181	0.000678	x	0.0001394
Hazardous waste	kg	8.94E-6	x	8.94E-6	x	x
Radioactive waste	kg	x	x	x	x	x
Slags/ashes	kg	0.000202	x	0.000202	x	x
Resources (all)	kg	1.69E-7	1.77E-8	4.65E-8	1.04E-7	1.111E-09

**Case 1, alt. 2 - results of characterisation using EDIP, RT**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:17:41 PM

Title:  
Method: EDIP/UMIP 96 (low) / EDIP World/China  
Value: Impact indicator  
Per impact category: Yes  
Skip unused: Never  
Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Global warming (GWP 100)	g CO2	1.83E3	17.4	1.8E3	9.56	0.02842
Ozone depletion	g CFC11	1.6E-7	6.93E-9	1.48E-7	x	5.36E-09
Acidification	g SO2	0.45	0.193	0.14	0.117	0.0001474
Eutrophication	g NO3	0.586	0.169	0.231	0.186	0.0001406
Photochemical smog	g ethene	0.356	0.000372	0.354	0.0022	1.595E-06
Ecotoxicity water chronic	g/m3	1.52E4	0.0137	1.52E4	x	0.0106
Ecotoxicity water acute	g/m3	1.57E3	0.00132	1.57E3	x	0.001024
Ecotoxicity soil chronic	g/m3	0.00654	0.000203	0.00618	x	0.0001568
Human toxicity air	g/m3	1.32E5	1.02E5	2.99E4	71.8	5.03
Human toxicity water	g/m3	50	0.000259	50	0	0.0001421
Human toxicity soil	g/m3	0.0432	0.0241	0.0192	0	1.077E-06
Bulk waste	kg	0.000999	0.000181	0.000678	x	0.0001394
Hazardous waste	kg	8.94E-6	x	8.94E-6	x	x
Radioactive waste	kg	x	x	x	x	x
Slags/ashes	kg	0.000202	x	0.000202	x	x
Resources (all)	kg	1.69E-7	1.77E-8	4.65E-8	1.04E-7	1.111E-09

### Case 1, alt. 2 - results of weighting using EDIP, ST

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:21:17 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Total	Pt	0.446	0.00905	0.43	0.00775	1.171E-05
Global warming (GWP 100)	Pt	0.172	0.00261	0.168	0.00143	4.25E-06
Ozone depletion	Pt	1.83E-5	7.89E-7	1.69E-5	x	6.1E-07
Acidification	Pt	0.00903	0.00391	0.00274	0.00237	2.989E-06
Eutrophication	Pt	0.0069	0.00202	0.00266	0.00222	1.676E-06
Photochemical smog	Pt	0.249	0.000292	0.247	0.00172	1.252E-06
Ecotoxicity water chronic	Pt	0.00623	6.56E-7	0.00623	x	5.08E-07
Ecotoxicity water acute	Pt	0.00289	6.33E-8	0.00289	x	4.89E-08
Ecotoxicity soil chronic	Pt	3.05E-7	9.71E-9	2.88E-7	x	7.51E-09
Human toxicity air	Pt	4.02E-5	3.11E-5	9.06E-6	2.19E-8	1.54E-09
Human toxicity water	Pt	0.000222	1.1E-8	0.000222	0	6.02E-09
Human toxicity soil	Pt	0.000328	0.000194	0.000134	0	8.7E-09
Bulk waste	Pt	2.46E-6	4.46E-7	1.67E-6	x	3.445E-07
Hazardous waste	Pt	2.24E-7	x	2.24E-7	x	x
Radioactive waste	Pt	x	x	x	x	x
Slags/ashes	Pt	6.85E-6	x	6.85E-6	x	x
Resources (all)	Pt	0	0	0	0	0

### Case 1, alt. 2 - results of weighting using EDIP, RT

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:17:54 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Total	Pt	1.38	0.00905	1.36	0.00775	1.171E-05
Global warming (GWP 100)	Pt	0.274	0.00261	0.27	0.00143	4.25E-06
Ozone depletion	Pt	1.83E-5	7.89E-7	1.69E-5	x	6.1E-07
Acidification	Pt	0.00912	0.00391	0.00284	0.00237	2.989E-06
Eutrophication	Pt	0.00701	0.00202	0.00276	0.00222	1.676E-06
Photochemical smog	Pt	0.279	0.000292	0.277	0.00172	1.252E-06
Ecotoxicity water chronic	Pt	0.729	6.56E-7	0.729	x	5.08E-07
Ecotoxicity water acute	Pt	0.0752	6.33E-8	0.0752	x	4.89E-08
Ecotoxicity soil chronic	Pt	3.13E-7	9.71E-9	2.96E-7	x	7.51E-09
Human toxicity air	Pt	4.03E-5	3.11E-5	9.12E-6	2.19E-8	1.54E-09
Human toxicity water	Pt	0.00211	1.1E-8	0.00211	0	6.02E-09
Human toxicity soil	Pt	0.000349	0.000194	0.000155	0	8.7E-09
Bulk waste	Pt	2.46E-6	4.46E-7	1.67E-6	x	3.445E-07
Hazardous waste	Pt	2.24E-7	x	2.24E-7	x	x
Radioactive waste	Pt	x	x	x	x	x
Slags/ashes	Pt	6.85E-6	x	6.85E-6	x	x
Resources (all)	Pt	0	0	0	0	0



**Case 1, alt. 3 - results of characterisation using EDIP, ST**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:28:11 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Impact indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Global warming (GWP 100)	g CO2	1.14E3	7.26	1.12E3	9.56	0.02842
Ozone depletion	g CFC11	-6.08E-5	-6.09E-5	1.48E-7	x	5.36E-09
Acidification	g SO2	-0.958	-1.21	0.135	0.117	0.0001474
Eutrophication	g NO3	0.199	-0.209	0.222	0.186	0.0001406
Photochemical smog	g ethene	0.357	0.0405	0.314	0.0022	1.595E-06
Ecotoxicity water chronic	g/m3	-312	-442	130	x	0.0106
Ecotoxicity water acute	g/m3	32.8	-27.6	60.4	x	0.001024
Ecotoxicity soil chronic	g/m3	-0.656	-0.662	0.00601	x	0.0001568
Human toxicity air	g/m3	-2.45E6	-2.48E6	2.97E4	71.8	5.03
Human toxicity water	g/m3	-545	-550	5.24	0	0.0001421
Human toxicity soil	g/m3	-1.65	-1.66	0.0166	0	1.077E-06
Bulk waste	kg	-0.000291	-0.001	0.000678	x	0.0001394
Hazardous waste	kg	1.76E-5	8.64E-6	8.94E-6	x	x
Radioactive waste	kg	x	x	x	x	x
Slags/ashes	kg	0.000397	0.000195	0.000202	x	x
Resources (all)	kg	-1.45E-6	-1.6E-6	4.65E-8	1.04E-7	1.111E-09

**Case 1, alt. 3 - results of characterisation using EDIP, RT**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:24:18 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Impact indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Global warming (GWP 100)	g CO2	1.9E3	86.5	1.8E3	9.56	0.02842
Ozone depletion	g CFC11	-6.08E-5	-6.09E-5	1.48E-7	x	5.36E-09
Acidification	g SO2	-0.941	-1.2	0.14	0.117	0.0001474
Eutrophication	g NO3	0.234	-0.183	0.231	0.186	0.0001406
Photochemical smog	g ethene	0.396	0.0405	0.354	0.0022	1.595E-06
Ecotoxicity water chronic	g/m3	1.55E4	310	1.52E4	x	0.0106
Ecotoxicity water acute	g/m3	1.62E3	47.6	1.57E3	x	0.001024
Ecotoxicity soil chronic	g/m3	-0.656	-0.662	0.00618	x	0.0001568
Human toxicity air	g/m3	-2.45E6	-2.48E6	2.99E4	71.8	5.03
Human toxicity water	g/m3	-496	-546	50	0	0.0001421
Human toxicity soil	g/m3	-1.64	-1.66	0.0192	0	1.077E-06
Bulk waste	kg	-0.000291	-0.001	0.000678	x	0.0001394
Hazardous waste	kg	1.76E-5	8.64E-6	8.94E-6	x	x
Radioactive waste	kg	x	x	x	x	x
Slags/ashes	kg	0.000397	0.000195	0.000202	x	x
Resources (all)	kg	-1.45E-6	-1.6E-6	4.65E-8	1.04E-7	1.111E-09

### Case 1, alt. 3 - results of weighting using EDIP, ST

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:28:22 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Total	Pt	0.376	-0.061	0.43	0.00775	1.171E-05
Global warming (GWP 100)	Pt	0.171	0.00109	0.168	0.00143	4.25E-06
Ozone depletion	Pt	-0.00692	-0.00694	1.69E-5	x	6.1E-07
Acidification	Pt	-0.0194	-0.0246	0.00274	0.00237	2.989E-06
Eutrophication	Pt	0.00238	-0.0025	0.00266	0.00222	1.676E-06
Photochemical smog	Pt	0.28	0.0318	0.247	0.00172	1.252E-06
Ecotoxicity water chronic	Pt	-0.0149	-0.0211	0.00623	x	5.08E-07
Ecotoxicity water acute	Pt	0.00157	-0.00132	0.00289	x	4.89E-08
Ecotoxicity soil chronic	Pt	-3.14E-5	-3.17E-5	2.88E-7	x	7.51E-09
Human toxicity air	Pt	-0.000747	-0.000756	9.06E-6	2.19E-8	1.54E-09
Human toxicity water	Pt	-0.023	-0.0232	0.000222	0	6.02E-09
Human toxicity soil	Pt	-0.0133	-0.0134	0.000134	0	8.7E-09
Bulk waste	Pt	-7.18E-7	-2.48E-6	1.67E-6	x	3.445E-07
Hazardous waste	Pt	4.39E-7	2.16E-7	2.24E-7	x	x
Radioactive waste	Pt	x	x	x	x	x
Slags/ashes	Pt	1.35E-5	6.61E-6	6.85E-6	x	x
Resources (all)	Pt	0	0	0	0	0

### Case 1, alt. 3 - results of weighting using EDIP, RT

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:24:38 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Biodegr. Waste	Residual waste	Waste collection	Waste separation
Total	Pt	1.36	-0.00887	1.36	0.00775	1.171E-05
Global warming (GWP 100)	Pt	0.284	0.0129	0.27	0.00143	4.25E-06
Ozone depletion	Pt	-0.00692	-0.00694	1.69E-5	x	6.1E-07
Acidification	Pt	-0.0191	-0.0243	0.00284	0.00237	2.989E-06
Eutrophication	Pt	0.0028	-0.00219	0.00276	0.00222	1.676E-06
Photochemical smog	Pt	0.311	0.0318	0.277	0.00172	1.252E-06
Ecotoxicity water chronic	Pt	0.744	0.0148	0.729	x	5.08E-07
Ecotoxicity water acute	Pt	0.0775	0.00228	0.0752	x	4.89E-08
Ecotoxicity soil chronic	Pt	-3.14E-5	-3.17E-5	2.96E-7	x	7.51E-09
Human toxicity air	Pt	-0.000747	-0.000756	9.12E-6	2.19E-8	1.54E-09
Human toxicity water	Pt	-0.021	-0.0231	0.00211	0	6.02E-09
Human toxicity soil	Pt	-0.0133	-0.0134	0.000155	0	8.7E-09
Bulk waste	Pt	-7.18E-7	-2.48E-6	1.67E-6	x	3.445E-07
Hazardous waste	Pt	4.39E-7	2.16E-7	2.24E-7	x	x
Radioactive waste	Pt	x	x	x	x	x
Slags/ashes	Pt	1.35E-5	6.61E-6	6.85E-6	x	x
Resources (all)	Pt	0	0	0	0	0

Nordtest project nr. 1537-01

Guidelines for the use of LCA in the  
waste management sector

## APPENDIX 2

Icelandic descriptive case study  
– landfill without gas collection

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This LCA study is a descriptive study, an environmental report. It is meant to give overview of the resource use and emission from the current household waste management system in South-Iceland where the area is sparsely inhabited. The household waste is landfilled in Kirkjuferjuhjáleiga and the landfill is not equipped with gas collection system. The landfill received about 12.000 tons of household waste in the year 2001, from 21 municipalities in South Iceland and in total 27.800 tons of waste. Inhabitants in these municipalities are approximately 15.500. The area served by the landfill is approximately 4200 km<sup>2</sup> (roughly estimated) and therefore the waste has to be transported long distance to the landfill. However, about 50% of the waste landfilled in Kirkjuferjuhjáleiga comes from towns within 15 km radius from the landfill.

## **1 Goal and scope of the study**

### **1.1 Specification of the goal**

The goal of the study was:

*To use life cycle assessment to assess the environmental impact of the household waste management system in South Iceland.*

The study was made for FENUR as an example of a simple descriptive LCA study, of a typical Icelandic waste management system. Real life data from the waste management in South Iceland were used in the study to make it useful for the municipalities and contractors handling waste in the area.

### **1.2 Functional unit**

The goal of the study was to analyse environmental impact of a household waste management system. Treatment of a specific amount of waste with a specific composition is therefore a suitable unit, which input and output of the system can be related to. Composition of the household waste, which is collected and landfilled in Kirkjuferjuhjáleiga has however not been analysed. The only waste composition analyses that have been performed in Iceland are for the waste treated by SORPA (see appendix 1). It was therefore assumed that the composition of the household waste is the same as by SORPA and the functional unit was chosen to be:

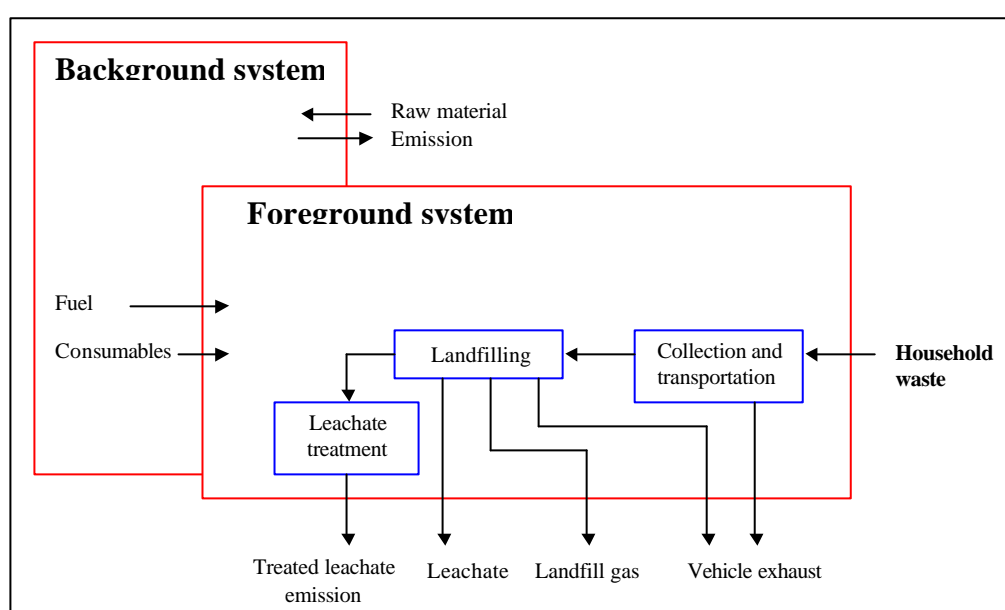
*One ton of household waste collected and landfilled in Kirkjuferjuhjáleiga, with the composition of household waste treated by SORPA.*

The composition of the waste is described in table 1 in appendix 1. Material banks where disposal of recyclable material is provided are similar as in the area served by SORPA. However, the area served by the landfill in Kirkjuferjuhjáleiga is more sparsely inhabited than the area served by SORPA, distances to material banks are longer, farmers are a larger fraction of the population and there are more summerhouses. This may all cause a difference in the composition of the household waste in Kirkjuferjuhjáleiga compared to SORPA. Composition of the waste is further discussed in subsection 2.1.1.

### 1.3 System boundaries

The input to the system is solid waste collected at kerbside or central located containers. The unit processes included in the study are therefore collection and transport of the waste to the landfill and treatment of the waste in the landfill (see Figure 1). No pre-treatment of the waste takes place. The output from the system is emission of leachate and air emission from vehicles and the landfill. No gas is collected at the landfill and therefore there is no product, which credits the system. Like in case study 1 in appendix 1, the waste treatment system is the foreground system of the study. Background processes are production of fuel and material used in the foreground system. Capital equipment is in general not included in the study and so is materials needed for maintenance of equipment (e.g. compactor or garbage trucks).

Figure 1 shows the unit processes in the system of the study.



**Figure 1: System boundaries.**

System boundaries related to time, for degradation and emission from the landfill, are divided into surveyable time (ST) and remaining time (RT). ST is approximately 100 years, which corresponds to the time until a pseudo steady state is reached in the landfill, i.e. until the major part of the methane production is ceased. RT corresponds to complete spreading of all landfilled material, from now to infinity.

In the study, distinction is made between biotic (from renewable sources) and non-biotic carbon (from fossil sources). It is a common practice in LCA for waste management to disregard biotic carbon dioxide (CO<sub>2</sub>-b) emission and that was also done in this study.

### 1.4 Data quality

Like in case study 1 in appendix 1, this study is a screening study and the results of the assessment have not been iterated. Sensitivity studies were performed to see the effect of scarce data and the major assumptions.

Time perspective of the study is several decades. Access to relevant data for such long time-periods is not possible. Therefore data for the current situation are mainly used. Data from the waste management in South Iceland were used as far as possible but when data was missing the gaps were filled up with data from SORPA, other Nordic life cycle assessments and data from the database in the Sima Pro program. Following are discussions on models and data used in the inventory and possible uncertainties in the inventory. The uncertainty is not given in figures but only discussed and the possible effect of them.

As no analyses have been done on household waste composition in South Iceland, data from waste analysis done by SORPA were used. This may cause some error in the results as discussed in section 2.1.1. Like in case study 1 in appendix 1, data on composition of various waste fractions were from Swedish and Norwegian LCA studies.

Data on diesel consumption due to collection and transport of waste are from contractors who collect and transport waste to Kirkjuferjuháleiga. Data were however only available from two of the four contractors who serve the area. The missing data were approximated (see section 2.2.1).

Degradation of waste and emission from the landfill was modelled with a model made for average Swedish landfill /1/. Data for landfill leachate treatment efficiency were uncertain. Limited measurements have been performed on treatment efficiency and literature data for the treatment system cannot be found. The data on leachate treatment were based on the available measurements from Kirkjuferjuháleiga and on educated guess.

### **1.5 The Sima Pro program**

As in case study 1 in appendix 1, the Sima Pro program was used. Data from the inventory database of the program was used for the background processes of the study. In the impact assessment, the EDIP method included in the program was used. A more thorough description of the program, its inventory databases and impact assessment methods can be found in /9/.

### **1.6 Impact categories and methodology**

Like in case study 1 in appendix 1, the EDIP life cycle assessment method, included in Sima Pro, was used (see section 1.6 in appendix 1). The impact categories included were the same as in case study 1 (see table 3 in section 1.6, appendix 1). The lower NO<sub>x</sub> values were used to calculate the photochemical smog formation as in case study 1. A more thorough description of the method can be found in Hauschild and Wenzel /5, 6/.

## 2 Life cycle inventory analysis

### 2.1 Waste composition and separation

#### 2.1.1 Household waste composition

As was discussed in section 1.2 (the functional unit), analyses on composition of the household waste collected and landfilled in Kirkjuferjuháleiga have not been done. The best available data on possible composition of the waste are from analyses done by SORPA. Material banks where disposal of recyclable material is provided are similar to the area served by SORPA but the ratio of summerhouses and farmers are larger in the area served by Kirkjuferjuháleiga. This may cause higher content of packing waste (paper, glass, metal and plastic) in the summer time when the summerhouses are in use. Food waste is probably lower in household waste from farmers compared to urban area because it is fed to the domestic animals. The composition of the household waste collected in Reykjavik and its neighbour municipalities was however used unchanged in this study, as these were the best available data. The composition was as described in table 1:

**Table 1: Composition of the household waste**

Type of waste	%	Type of waste	%
Mixed cardboard	13,1	Wood	0,6
Newspaper	13,5	Garden waste	2,1
Plastics	13,3	Diapers	4,5
Glass	3,5	Food waste	30,5
Textiles	3,8	Hazardous waste	1,0
Metals	3,4	Others	10,7

The composition of the “hazardous waste” and “others” fractions were not known and therefore not covered in this study.

#### 2.1.2 Composition of waste fractions

Compositions of the waste fractions of the household waste are the same as in case study 1 in appendix 1, table 6.

### 2.2 Description of the landfill process and major assumptions

In the following sections, the foreground and background processes in the system analysed are described. The processes are:

- Collection and transport of the waste.
- Landfilling.
- Background processes.

#### 2.2.1 Collection and transport of waste

Waste is collected at kerbside in urban areas in South Iceland. In the rural areas the waste is either collected at kerbside or from central located containers. In the municipalities where waste is collected from central located containers, people living in the area have to transport their waste to the containers themselves, up to 2 km



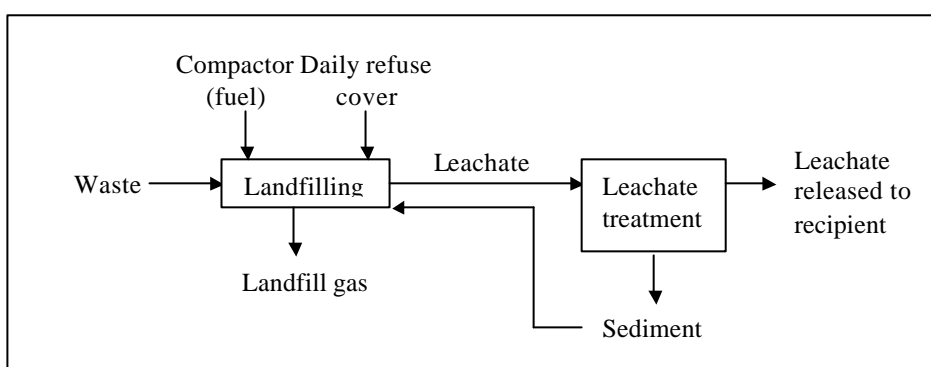
distance. The environmental impact of these transportations were not considered in the study.

Contractors collect the household waste. Data for consumption of diesel due to waste collection and transportation were gathered by personal communication with the contractors. However, data were not available by all the contractors and diesel consumption had to be estimated for some municipalities. The diesel consumption is assumed to be 10,3 L of diesel/ton waste on average. The consumption is approximately 3,5 L diesel/ton waste for the urban areas close to Kirkjuferjuháleiga, which provide about 50% of the household waste landfilled but approximately 17 L diesel/ton waste for the rural areas further from the landfill.

The database BUWAL 132 in Sima Pro was used to calculate emission from garbage trucks due to diesel combustion.

## 2.2.2 Landfilling

Figure 2 shows process flow diagram for the landfill process



**Figure 2: Process flow diagram for the landfill process.**

### 2.2.2.1 Landfilling

At the landfill, waste is unloaded from the garbage trucks into landfill lanes equipped with bentonite bottom barrier and leachate collection system. Each lane is approximately 4000 m<sup>2</sup>. The waste is then compacted with waste compactor to a density of approximately 800 kg/m<sup>3</sup>.

After each day the landfilled waste is covered with refuse from a processing of metal scrapping, which is placed approximately 60 km from the landfill. The refuse consist of shredded seats and plastic material from car scrapping. The refuse is transported to the landfill by a truck. At the same time scrap metal is collected at the landfill.

Approximately 4,5 ton of refuse are transported in each trip, which is approximately 60 km and approximately 0,2 ton of residue are used for each ton of landfilled waste. Environmental impact due to degradation of the daily cover was not allocated to the landfilling of household waste as it would be landfilled anyway. The daily cover refuse would probably be landfilled in Álfsnes (the landfill in case study 1) if not in Kirkjuferjuháleiga. Álfsnes is approximately 20 km from the metal scrapping processing. Extra transportation (i.e. to Kirkjuferjuháleiga vs. Álfsnes) was allocated to the landfill in Kirkjuferjuháleiga. As metal scrap is transported from Kirkjuferjuháleiga with the same truck that transports the daily cover to the landfill, return of the truck is not allocated to the landfilling of household waste in

Kirkjuferjuháleiga. The transport distance allocated to landfilling household waste in Kirkjuferjuháleiga is therefore 20 km. Data on diesel consumption of the truck is taken from Frees and Weideman /2/ and is assumed to be 9,26 MJ/km (light truck, e.g. Volvo FL6). Lower heating value of the diesel is 42,95 MJ/kg /2/ and density 0,84 kg/litre. The database BUWAL 132 in Sima Pro was used to calculate emission from trucks due to diesel combustion.

As in case study 1 in appendix 1, a landfill degradation model described by Björklund /1/ was used to describe degradation of landfilled material and release of leachate and air emission from the landfill. The model describes an average Swedish municipal landfill. Emissions from the landfill were separated into landfill gas and leachate, and emission occurring during surveyable time period (ST) and emission that occur during remaining time period (RT). As noted in section 1.3, the surveyable time period corresponds to the time until a pseudo steady state is reached in the landfill, i.e. until the major part of the methane production is ceased, which is approximately 100 years. The remaining time corresponds to complete spreading of all landfilled material.

Degradation of household waste is modelled as completely anaerobic during ST. Biological carbon will degrade during ST except lignin and 30% of cellulose and hemi-cellulose, which degrades during RT. All material left after ST will be completely degraded or emitted during the RT. At the beginning of RT, the landfill is anaerobic but oxygen will slowly diffuse into the landfill and it will become aerobic. Half of the cellulose and hemi-cellulose left after ST will degrade anaerobically before air intrusion is completed. Plastic, lignin, and half of the remaining cellulose and hemi-cellulose will degrade aerobically during RT. Major part of nitrogen will leach out as ammonium during ST and so will chlorine, potassium and calcium content of the household waste. Only 2% of phosphorus and 0,1-0,3% of metals are emitted during ST but completely emitted to the recipient during RT. It is assumed that all the metals will leach out during RT but it will occur over time period of hundred thousands of years. This may cause overestimate of ecotoxicity impact in the impact assessment and interpretation of the results. A more thorough description of emission partitioning coefficients with reference to primary sources is available in /1/.

No landfill fires have occurred at the landfill since it started operation in 1995. Landfill fires as a degradation process and emission from landfill fires were therefore not considered in this study.

The landfill is not equipped with gas collection system. It was assumed that 15% of the emitted methane would oxidise to carbon dioxide in the topsoil of the landfill /1/. Otherwise all landfill gas emitted is released to the atmosphere.

#### 2.2.2.2 Leachate collection and treatment

The landfill is equipped with bentonite bottom barrier and leachate is collected through a water drainage and collection system. Like in the LCA-Land model (described in section 5.3 in the guidelines) it is assumed that 80% of the leachate produced is collected and the remaining 20% will leak to aquatic recipients /7/.

The leachate is lead through a treatment plant. The treatment plant consists of (in the following order) a grease separator, a settling tank, a sand bed filtration and a lagoon.

The leachate flows through the treatment system by gravity and therefore no energy is used to treat the leachate. The environmental impact of running the treatment plant (i.e. changing sand in the sand bed and cleaning grease from the grease separator) is assumed to be insignificant compared to other processes.

From measurements on leachate composition in Kirkjuferjuháleiga /4/ and comparison with other landfills in Europe /3/ and Iceland, the following treatment efficiency was assumed:

**Table 2: Reduction factors for leachate treatment at Kirkjuferjuháleiga.**

Substance	Reduction factor (%)	Substance	Reduction factor (%)
COD	30	Pb	60
BOD	35	Cd	35
NH3	10	Hg	50
S	20	Cu	40
P	20	Cr	40
Cl	0	Ni	30
K	0	Zn	60
Ca	0	As	60

Sediment from the settling tank, sand from the sand bed and grease from the grease separator are transported back to the landfill. Carbon addition to the landfill due to landfilling of the refuse is insignificant as only 1% of the total landfilled carbon is assumed to end up in leachate in the landfill model /1/.

#### 2.2.2.3 Fuel use at the landfill

As noted in the section above, fuel consumption due to running the leachate treatment plant was considered insignificant. The only fuel consumption considered at the landfill was diesel consumption of the compactor. Data for fuel consumption were from Sorpstöð Suðurlands, which runs the landfill at Kirkjuferjuháleiga. In the year 2001 the compactor used 1,69 L of diesel per ton waste. Other resource uses of the compactor (e.g. lubricating oil or tiers) were not considered.

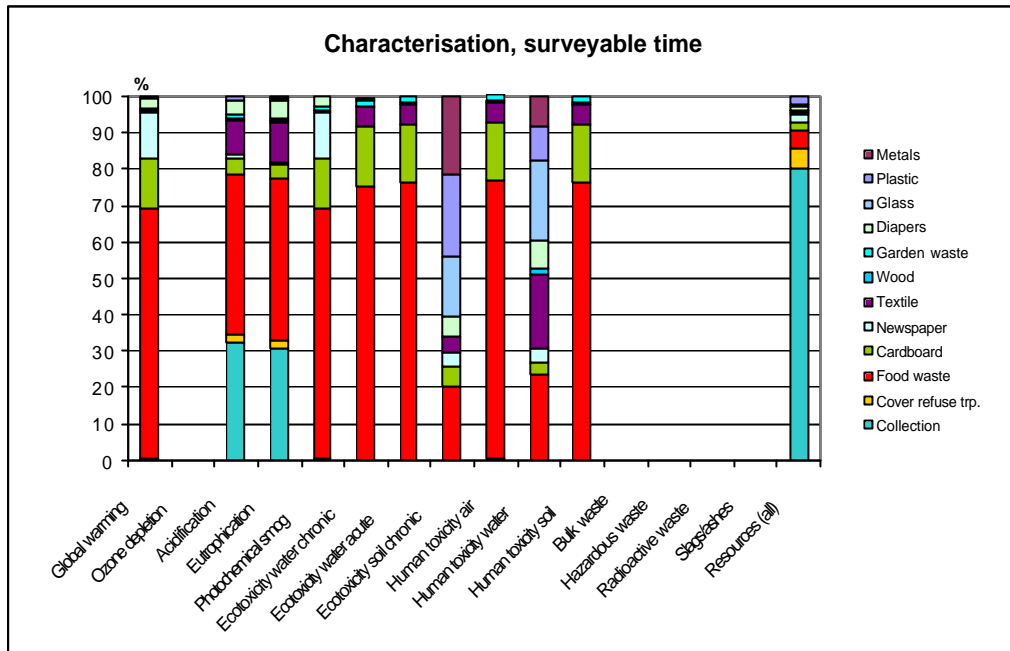
### 2.3 Background processes

The only background process considered in this study is the production of diesel fuel. Electricity is not used in the collection, transporting or landfilling process. Production of the daily cover for the landfill was not considered, as the material would be landfilled independent of where it is in Kirkjuferjuháleiga or other landfills. For production and emission from use of diesel data from the BUWAL 132 database in Sima Pro were used.

## 3 Impact assessment

The results of the impact assessment are presented in column graphs but tables with the impact assessment results are presented at the end of the appendix. All the results are calculated by using the EDIP method in Sima Pro.

Figure 3 shows characterised results for surveyable time.

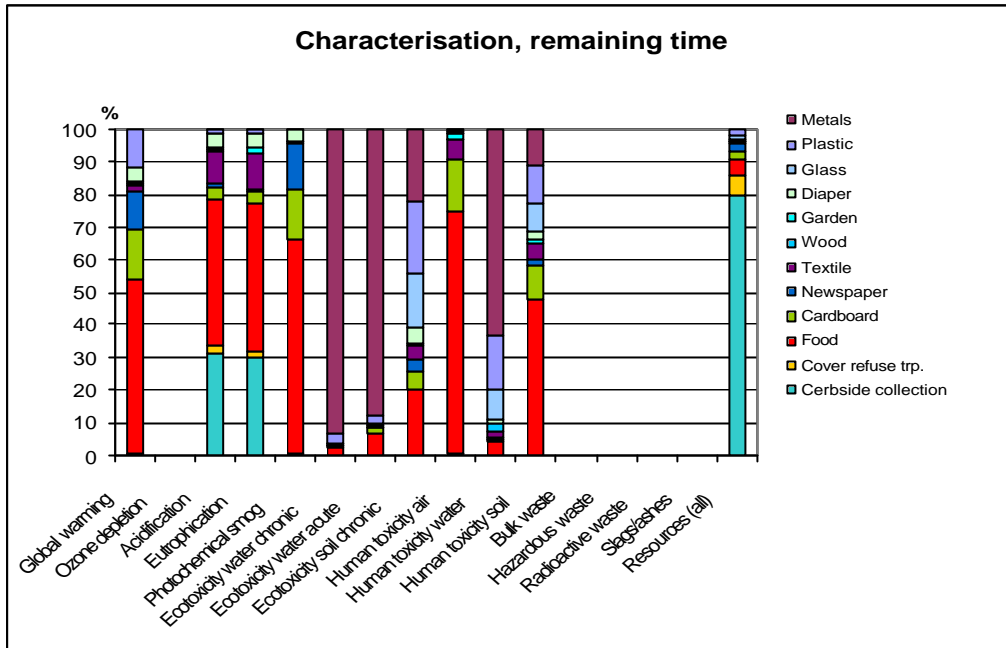


**Figure 3: Results of characterisation for surveyable time (100 years).**

In Figure 3 the relative impact of each waste fraction, waste collection, transport and bailing are shown compared to the total impact (100%) for various impact categories. The impact of the waste fractions is due to degradation of the waste in the landfill and use of a compactor at the landfill.

According to Figure 3, food waste causes most of the impact in eight out of eleven impact categories. The global warming, photochemical smog, ecotoxicity and human air and soil toxicity are mainly caused by the food waste and so is acidification and eutrophication but not to the same extent. The results for different waste fractions are dependent on their respective share of the whole system. The high impact of food waste is therefore in some way due to high percentage of food waste in the household waste. Collection of the waste causes the highest impact in resource use and also a large part of the acidification and eutrophication. Metals and metals leaching from the plastic and glass are mainly causing the chronic soil ecotoxicity and a large part of the human water toxicity.

Figure 4 shows the characterised LCIA results for remaining time



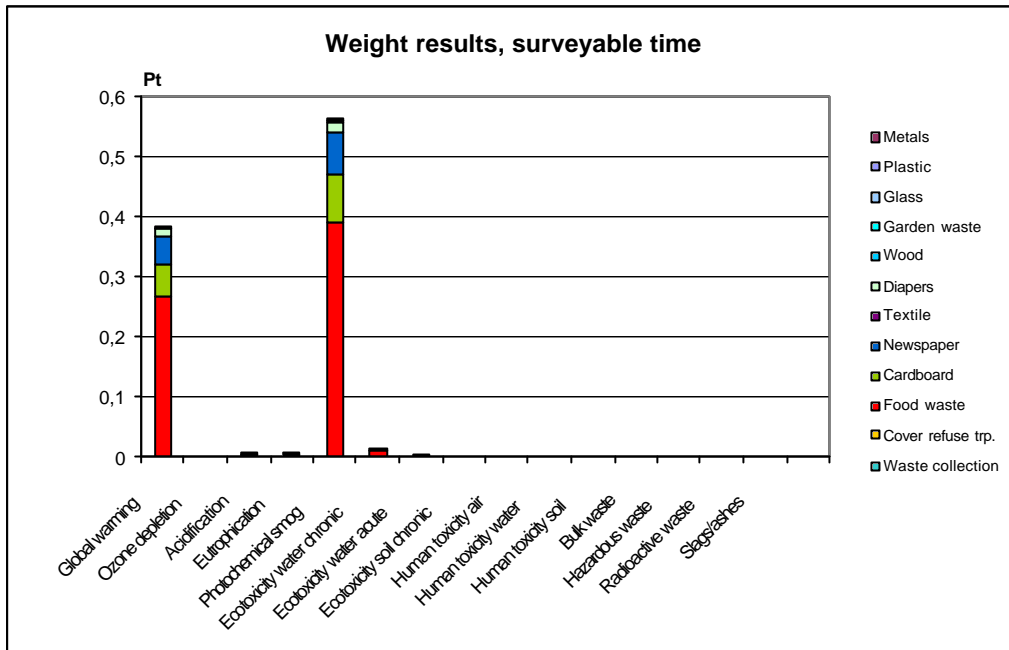
**Figure 4: Results of characterisation, remaining time (infinite time).**

According to Figure 4 the impact of food waste is not as dominating after remaining time like after surveyable time. The metals now cause a large part of the ecotoxicity effects and also human toxicity to water, due to leaching of metals from the landfill during remaining time. During remaining time plastic degrades and causes approximately ten percent of the global warming effect. Newspaper and cardboard cause similar global warming impact but food waste is still dominating in the global warming impact category. The photochemical smog is nearly unchanged from the surveyable time as it is mainly caused by the methane emission during surveyable time and methane emission is insignificant during remaining time. Acidification and eutrophication changes insignificantly.

The weight results for surveyable time are shown in Figure 5. I.e. the seriousness of the results for the various environmental impact categories presented in Figure 5 has been assessed to make them comparable.

The unit “Pt” on the y-axis is the percentage of the person-equivalent, which can be expected if political plans for reduction are achieved /17/. The politically set target emissions are Danish for the regional and the local impact categories but the weighting of global impact categories is based on the accepted global contribution. As resources use a different method of weighting in the EDIP method (based on reserves rather than political targets), it cannot be compared with the other impact categories. Therefore, the weighting factor is set to zero in Sima Pro and the resource use is not displayed in Figure 5.

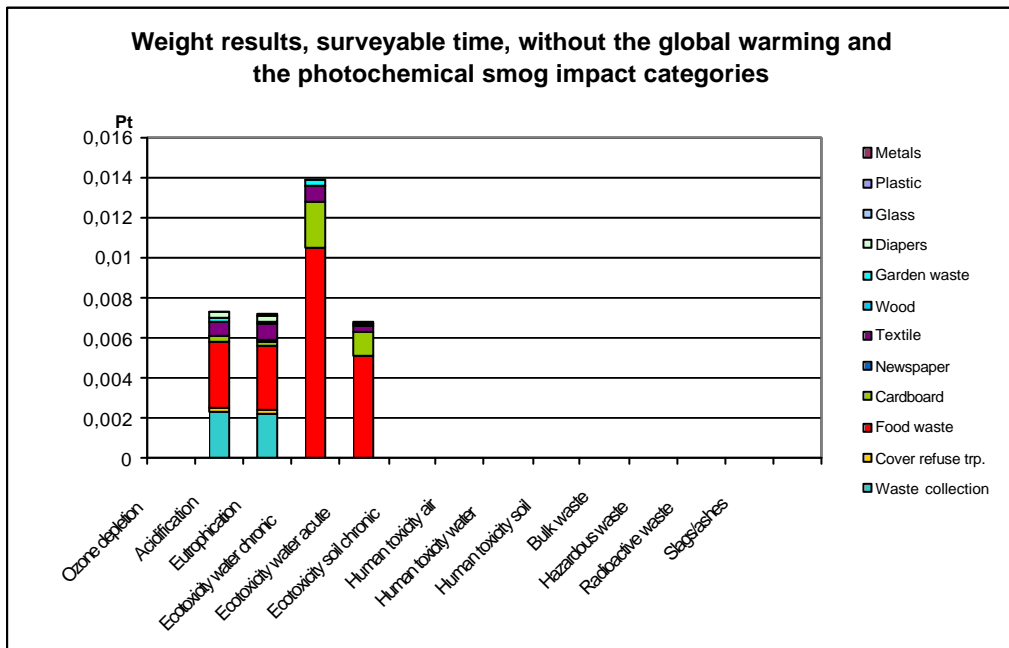
According to Figure 5, global warming and photochemical smog cause the most serious environmental for surveyable time. Photochemical smog formation means here the contribution to photochemical ozone (O<sub>3</sub>) formation. The classification step in the EDIP method defines substances with potential to contribute to photochemical smog formation as volatile organic compounds VOC (e.g. methane), carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>). Like the global warming impact, the high photochemical smog impact is therefore caused by methane release from the landfill due to degradation of biodegradable waste, e.g. food waste and newspaper.



**Figure 5: Weight results for surveyable time (100 years).**

Other impact categories are of very low importance in the total weight results. It is therefore of interest to see what effect gas collection with combustion of the landfill gas would have on these results. Combustion of the landfill gas would decrease the emission of methane significantly and therefore the global warming and photochemical smog, which is mainly caused by methane. If the global warming and photochemical smog impact categories are removed from the graph in Figure 5 the impact of other categories can be seen better.

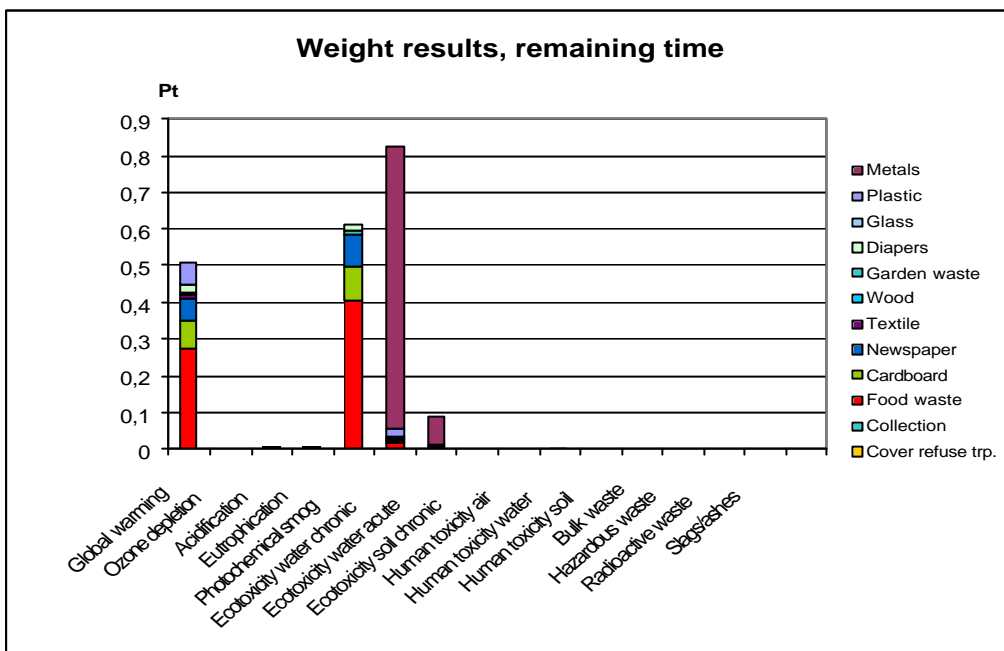
Figure 6 shows the weight results for surveyable time without the global warming and the photochemical smog impacts.



**Figure 6: Weight results for surveyable time (100 years), without the global warming and the photochemical smog impact categories.**

According to Figure 6, chronic water ecotoxicity is the most important impact category when the photochemical smog and the global warming impacts are not included. It weights though ca. 30 times less than global warming. The chronic water ecotoxicity is mainly caused by the food waste and cardboard. Collection of waste causes a part of the acidification and eutrophication but these two impact categories are also causing much less serious impact relative to global warming and photochemical smog. Therefore, low quality of the data for diesel use due to collection of waste has insignificant effect on the weight results but have significant effect on the total resource use of the system according to Figure 3.

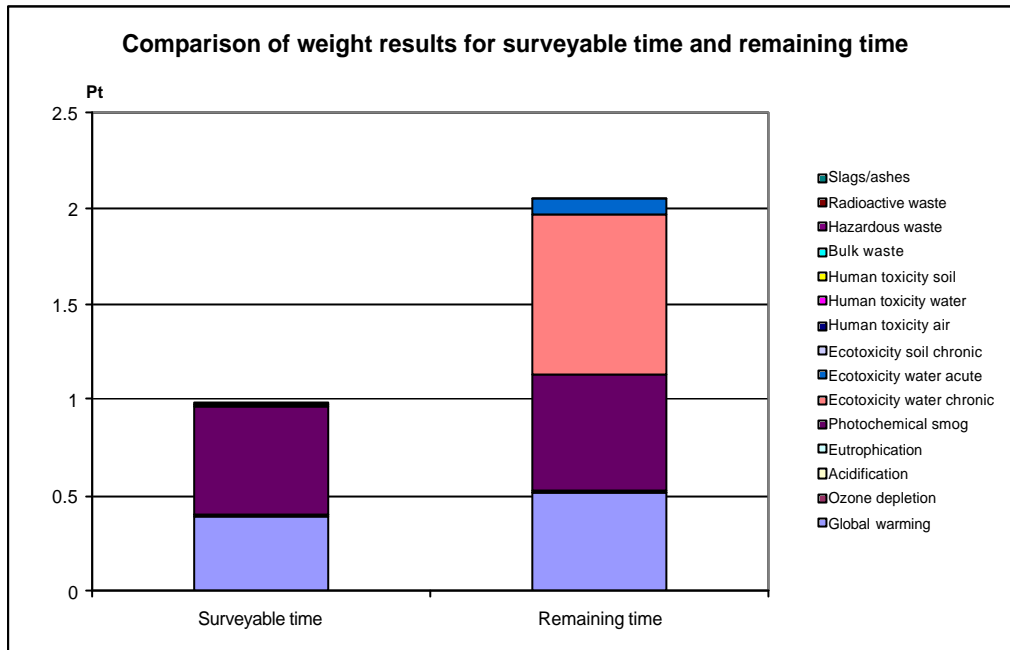
Figure 7 shows the weight results for remaining time.



**Figure 7: Weight results, remaining time.**

Figure 7 shows that metals are causing the largest weight impact for the remaining time due to leaching of metals from the landfill. Global warming and photochemical smog have however also increased due to degradation of plastic, cellulose and lignin, causing emission of carbon dioxide, methane and volatile organic compounds. Acute water ecotoxicity has also increased due to leaching of metals.

The total weight results of surveyable and remaining time are compared in Figure 8.



**Figure 8: Comparison of weight results for surveyable time and remaining time.**

According to Figure 8 the impact during remaining time is twice the impact during surveyable time. The increase is mainly due to leaching of metals from the landfill, causing acute and chronic water ecotoxicity. The global warming and photochemical smog also increase slightly. Other impact categories are of low importance.

## 4 Sensitivity studies

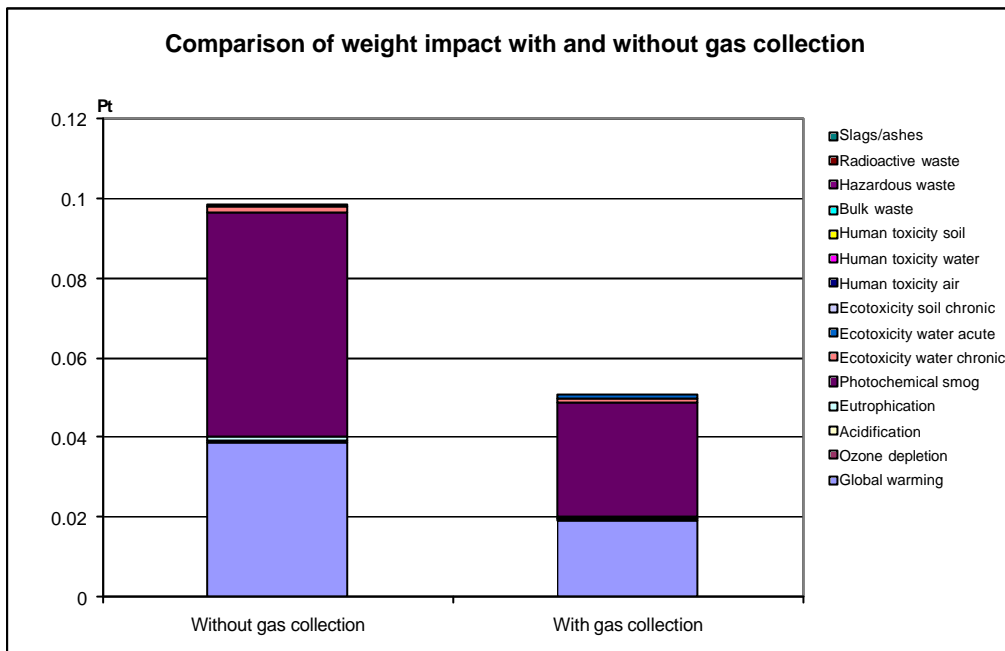
Sensitivity studies were made to assess the importance of introducing landfill gas collection with combustion of the gas and to assess the effect of decreasing the amount of organic waste being landfilled. In the following subsections the results of the sensitivity studies are presented and discussed.

### 4.1 Gas collection with flaring of all collected gas

Landfill gas formed at the landfill in Kirkjuferjuháleiga is not collected or utilised. The results show that the impact categories global warming and photochemical smog are important for the total weight results of the study. It is therefore of interest to see how much the total weight impact of the system would change if gas collection would be implemented and the landfill gas flared. By flaring the gas, methane emission, which causes major part of the former mentioned impact categories, will decrease considerably.



Figure 9 shows comparison of the weight results for surveyable time with and without gas collection system where all the landfill gas is flared.



**Figure 9: Comparison of weight impact with and without gas collection**

According to Figure 9 the total weight impact of the system can be decreased by 49%. The global warming and photochemical smog impact categories are however still the most important.

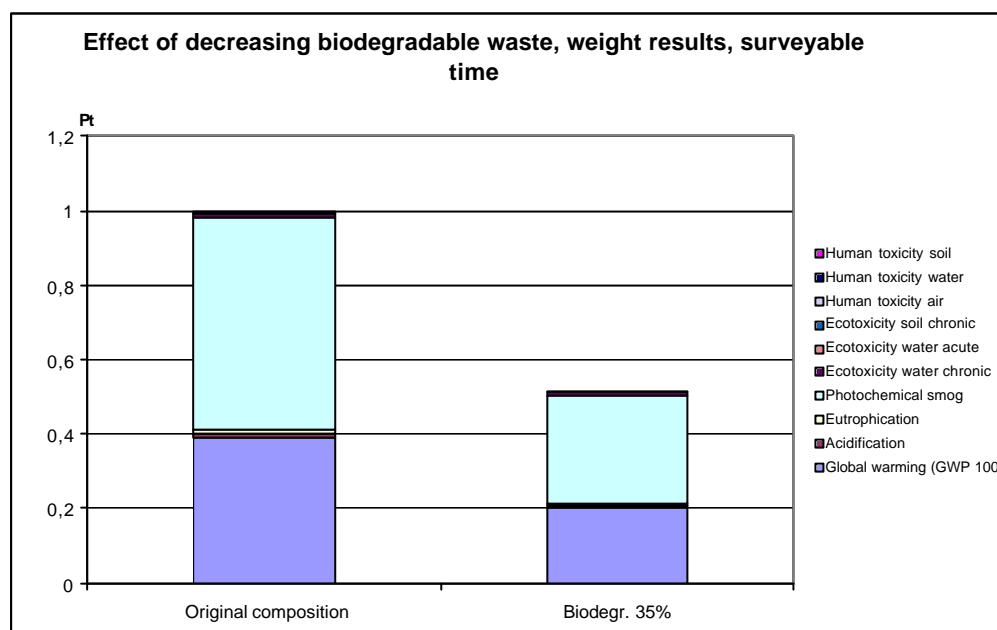
#### 4.2 Decreased amount of organic waste landfilled

According to the European Council Directive of the landfill of waste, biodegradable waste going to landfills has to be reduced to 35% of the total amount landfilled in 1995 at the year 2016. It is of interest to see what effect this decrease would have on the total weight impact of the waste management system in South Iceland. Waste was first landfilled at Kirkjuferjuháleiga in the year 1995. Therefore the best available data for total annual amount landfilled are from 1996. It was assumed that the composition of the waste landfilled in the year 1996 was the same as in the analysis done by SORPA and used in this study (see section 2.1.1 in case study 1, appendix 1). The amount of biodegradable waste landfilled in the year 1996 was therefore approx. 5.500 tons (food waste, cardboard, newspaper, wood, garden waste and diapers). Therefore max 1.925 tons of biodegradable waste can be landfilled in the year 2016. In the year 2000 (the newest data on how much biodegradable waste is being landfilled), approx. 9.500 tons of biodegradable household waste were landfilled in Kirkjuferjuháleiga. If we assume that the amount of waste in the year 2016 is the same as in the year 2000, the decrease in biodegradable waste landfilled has to be 78%. If we then assume that each fraction of the waste that counts as biodegradable waste decreases by 78% and the amount of inorganic waste is unchanged, the composition in the year 2016 would be as listed in table 3.

**Table 3: Composition of waste with lower biodegradable fraction**

Waste fraction	Composition	Waste fraction	Composition
Mixed cardboard	5,8%	Metals	6,8%
Newspaper	6,0%	Wood	0,3%
Plastic	26,7%	Garden waste	0,9%
Glass	7,0%	Diapers	2,0%
Textiles	7,6%	Food waste	13,5%

The total weight results using the composition described in table 3 is shown in Figure 10.



**Figure 10: Effect of decreasing biodegradable waste, weight result, surveyable time.**

According to Figure 10 the impact of the system in the study can be decreased by approximately 50% if the amount of biodegradable waste landfilled at Kirkjuferjuhjáleiga is decreased to 35% of the amount landfilled in the year 1996. Global warming and photochemical smog formation are however still the dominating impact categories.

## 5 Interpretation

The goal of this study was to use life cycle assessment to assess the environmental impact of the household waste management system in South Iceland. The results of the study have not been iterated, i.e. this is only a screening study.

The weighted results of this study (using the EDIP impact assessment method) show that global warming and photochemical smog are causing the most serious impacts of the waste management system in South Iceland during the first 100 years and chronic water ecotoxicity is important during remaining time. The global warming and photochemical smog are mainly caused by degradation of biodegradable waste and emission of landfill gas.

The photochemical smog formation depends on local conditions. The classification step in the EDIP method defines substances with potential to contribute to photochemical smog formation as volatile organic compounds VOC (e.g. methane), carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>). The contribution of NO<sub>x</sub> to the photochemical smog cannot be calculated with the same method as VOC and therefore, in the EDIP method, two sets of values are used, “low NO<sub>x</sub>” and “high NO<sub>x</sub>” depending on areas. For Scandinavia low NO<sub>x</sub> values are recommended /6/ and the lower values were used in this study. Low NO<sub>x</sub> value means concentration of NO<sub>x</sub> over rural areas < 10 ppbv. The land in South Iceland is sparsely populated and there is no heavy industry. At a measuring station in Alviðra, which is approximately 9 km from Kirkjuferjuháleiga, the average NO<sub>x</sub> in the year 2000 was 0,37 ppbv /8/, which is much less than 10 ppbv. Political targets for reduction of the photochemical smog impact are therefore probably lower in the area of Kirkjuferjuháleiga than in weighting factors in the EDIP method. The seriousness of the photochemical smog impact may therefore be overestimated in the characterisation and weighting.

Global warming is mainly caused by methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) emission due to degradation of biodegradable waste. Global warming is a global phenomenon and the political targets for reduction, used in the EDIP method are global. The weighting of global warming relative to other impact categories is therefore not overestimated.

Leaching of metals from the landfill cause the high chronic water ecotoxicity during remaining time (infinite time).

The collection and transport of waste and cover refuse cause the highest resource use impact. As resources use a different method of weighting, it cannot be compared with the other impact categories. However, the eutrophication and acidification impacts caused by the collection of the waste and transportation of cover refuse are very little compared to the impact of degradation of waste in the landfill. Therefore, the transportation distance and diesel combustion has little effect on the total weight results of the system studied. Low quality of the data of diesel consumed by collection and transport of the waste does therefore not have effect on the total weight results of the life cycle assessment (n.b. excluding resource use).

Due to the dominating impact of global warming and photochemical smog in the total weight results, which mainly is caused by the landfill gas, the leachate has very little importance for the result. Low quality of the leachate treatment data does therefore not affect the total weight result of the life cycle assessment.

Methane in the landfill gas causes most of the global warming and photochemical smog impact. The total weight impact of the system studied can therefore be reduced significantly by collection and flaring of the landfill gas collected. A sensitivity study shows that by collecting 50% of the landfill gas formed and flaring the gas the total weight impact of the system can be reduced by 49%. By utilising the landfill gas as fuel or for electricity production the weight impact of the system can be reduced even more due to avoided impact from products, which the methane gas replaces.

A sensitivity study shows that by decreasing the annual amount of biodegradable household waste landfilled in Kirkjuferjuháleiga down to 35% of the amount

landfilled in the year 1996, the impact of the system can be decreased by approximately 50%.

Analysis on the composition of the household waste in South Iceland has not been done and therefore composition of household waste in Reykjavik had to be used. There might be some difference in the composition as more summerhouses and farmers are in the area served by Kirkjuferjuháleiga than in Reykjavik. Due to limited resources it was not possible to do sensitivity studies where composition of the waste would be varied. As noted in the inventory for waste composition (subsection 2.1.1) packing material is probably higher in the summer time while the summerhouses are in use and food waste is probably lower in household waste from farmers compared to urban area because it is fed to the domestic animals. Therefore, biodegradable waste is probably lower percentage of the household waste in South Iceland compared to Reykjavik. The impact of the biodegradable waste is therefore probably a bit overestimated.

## 6 References

- /1/ Björklund A. (1998): *Environmental System Analysis of Waste Management*. Licentiate Thesis, Department of Chemical Engineering and Technology/Industrial Ecology, Royal Institute of Technology, Stockholm Sweden.
- /2/ Frees, N. and B.P. Weideman (1998): *Life Cycle Assessment of Packaging systems for Beer and Soft Drinks – Energy and Transport scenarios*, Technical report No 406, Ministry of Environment and Energy, Danish Environmental Protection Agency.
- /3/ Hjelmar, O., Johannessen, L.M., Knox, K., Ehrig, H.-J., Flyvbjerg, J., Winther, P. and Christensen, T.H. (1994): *Management and Composition of Leachate from Landfills. Final Report for the Commission of the European Communities, DGXI A.4. Waste 92*. Prepared by Water Quality Institute and Carl Bro Environmental a/s in co-operation with Knox Associates, University of Wuppertal and Technical University of Denmark. VKI, Hørsholm, Denmark. Commission of the European Communities DGXI A.4. Waste 92 (1994) Management and composition of Leachate from landfills, Contract No. B4-3040/013665/92 Final report.
- /4/ Ólafsson, G.Tr. (2002): Personal communication with Guðmundur Tryggvi Ólafsson, environmental specialist at Sorpstöð Suðurlands.
- /5/ Hauschild, M. and Wenzel, H. (1997): *Environmental Assessment of Products, Volume 1 – methodology, tools and case studies in product development*. Chapman & Hall, London.
- /6/ Hauschild, M. and Wenzel, H. (1998): *Environmental Assessment of Products, Volume 2 – Scientific background*. Chapman & Hall, London.
- /7/ Nielsen, P.H. and Hauschild M. (1998): *Product Specific Emission from Municipal Solid Waste Landfills*. International Journal of LCA. 3 (3) 158-168.
- /8/ Hollustuvernd (2000): *Loftgæðamælingar á vegum Hollustuverndar ríkisins – niðurstöður 2000*. The Icelandic Environment and Food Agency.
- /9/ PRé (2002): Web-page of PRé Consultants by: [www.pre.nl](http://www.pre.nl)

## 7 Tables with results of the impact assessment

### Case 2 - results of characterisation using EDIP, ST

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:13:56 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Impact indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron	Aluminium	Other metals	Wood
Global warming (GWP 100)	g CO2	2.58E3	354	325	0.199	0.0264	0.0163	0.00813	0.0223	0.0772	0.0406	0.0223	0.00813	13.2
Ozone depletion	g CFC11	x	x	x	x	x	x	x	x	x	x	x	x	x
Acidification	g SO2	0.362	0.0146	0.00336	0.00244	0.000323	0.000199	9.95E-5	0.000273	0.0357	0.000497	0.000273	9.95E-5	0.000448
Eutrophication	g NO3	0.605	0.0197	0.00533	0.00387	0.000513	0.000316	0.000158	0.000434	0.0662	0.000789	0.000434	0.000158	0.000645
Photochemical smog	g ethene	0.72	0.0991	0.0911	4.57E-5	6.06E-6	3.73E-6	1.86E-6	5.13E-6	1.77E-5	9.32E-6	5.13E-6	1.86E-6	0.00369
Ecotoxicity water chronic	g/m3	291	47.2	0.0901	0.201	0.0266	0.0164	0.00819	0.0225	16.3	0.158	0.0242	1.05	1.11
Ecotoxicity water acute	g/m3	142	23.2	0.00901	0.0201	0.00266	0.00164	0.000819	0.00225	7.9	0.0158	0.00242	0.105	0.535
Ecotoxicity soil chronic	g/m3	1.79E-9	1E-10	6.3E-11	2.95E-10	3.91E-11	2.41E-11	1.2E-11	3.31E-11	8.06E-11	1.7E-10	4.66E-11	1.7E-10	7.63E-13
Human toxicity air	g/m3	1.38E4	2.25E3	2.06	1.5	0.198	0.122	0.0611	0.168	761	0.305	0.168	0.0613	51.6
Human toxicity water	g/m3	0.0345	0.00105	0.00137	0.00239	0.000317	0.000195	9.75E-5	0.000268	0.00697	0.00247	0.000232	0.000175	0.000606
Human toxicity soil	g/m3	0.00325	0.000531	9.62E-10	4.51E-9	5.98E-10	3.68E-10	1.84E-10	5.06E-10	0.00018	2.59E-9	7.13E-10	2.59E-9	1.22E-5
Bulk waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Hazardous waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Radioactive waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Resources (all)	kg	1.3E-7	2.88E-9	2.97E-9	2.16E-9	2.86E-10	1.76E-10	8.8E-11	2.42E-10	8.36E-10	4.4E-10	2.42E-10	8.8E-11	1.32E-10

### Case 2 - results of characterisation using EDIP, RT

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:10:40 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Impact indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron	Aluminium	Other metals	Wood
Global warming (GWP 100)	g CO2	3.4E3	510	398	305	30.2	24.8	12.9	16.1	69.2	3.3	0.0223	0.00813	16
Ozone depletion	g CFC11	x	x	x	x	x	x	x	x	x	x	x	x	x
Acidification	g SO2	0.373	0.015	0.00336	0.00244	0.000323	0.000199	9.95E-5	0.000273	0.0375	0.000497	0.000273	9.95E-5	0.00046
Eutrophication	g NO3	0.626	0.0205	0.00533	0.00387	0.000513	0.000316	0.000158	0.000434	0.0698	0.000789	0.000434	0.000158	0.000668
Photochemical smog	g ethene	0.782	0.12	0.11	4.57E-5	6.06E-6	3.73E-6	1.86E-6	5.13E-6	1.77E-5	9.32E-6	5.13E-6	1.86E-6	0.00448
Ecotoxicity water chronic	g/m3	1.73E4	103	69.9	288	38.2	23.5	11.7	32.3	49.6	289	108	1.58E4	14.2
Ecotoxicity water acute	g/m3	1.84E3	28.8	6.99	28.8	3.82	2.35	1.18	3.23	11.2	28.9	10.8	1.58E3	1.84
Ecotoxicity soil chronic	g/m3	0.000224	1.25E-5	7.88E-6	3.69E-5	4.89E-6	3.01E-6	1.5E-6	4.14E-6	1.01E-5	2.12E-5	5.84E-6	2.12E-5	9.55E-8
Human toxicity air	g/m3	1.41E4	2.27E3	12	48.1	6.38	3.93	1.96	5.4	774	27.1	7.55	26.9	51.8
Human toxicity water	g/m3	50.6	0.503	0.399	5.96	0.791	0.487	0.243	0.669	0.548	6.09	4.53	21.4	1.57
Human toxicity soil	g/m3	0.00667	0.000723	0.00012	0.000563	7.47E-5	4.6E-5	2.3E-5	6.32E-5	0.000334	0.000324	8.92E-5	0.000324	1.36E-5
Bulk waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Hazardous waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Radioactive waste	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	kg	x	x	x	x	x	x	x	x	x	x	x	x	x
Resources (all)	kg	1.3E-7	2.88E-9	2.97E-9	2.16E-9	2.86E-10	1.76E-10	8.8E-11	2.42E-10	8.36E-10	4.4E-10	2.42E-10	8.8E-11	1.32E-10

**Case 2 - results of weighting using EDIP, ST**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:14:12 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron	Aluminium	Other metals	Wood
Total	Pt	0.986	0.135	0.12	0.000172	2.28E-5	1.4E-5	7.02E-6	1.93E-5	0.0027	4.13E-5	1.94E-5	6.18E-5	0.00497
Global warming (GWP 100)	Pt	0.385	0.0529	0.0486	2.98E-5	3.95E-6	2.43E-6	1.21E-6	3.34E-6	1.15E-5	6.07E-6	3.34E-6	1.21E-6	0.00197
Ozone depletion	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Acidification	Pt	0.00735	0.000296	6.81E-5	4.94E-5	6.55E-6	4.03E-6	2.02E-6	5.55E-6	0.000724	1.01E-5	5.55E-6	2.02E-6	9.09E-6
Eutrophication	Pt	0.00724	0.000235	6.38E-5	4.63E-5	6.14E-6	3.78E-6	1.89E-6	5.2E-6	0.000792	9.45E-6	5.2E-6	1.89E-6	7.72E-6
Photochemical smog	Pt	0.565	0.0778	0.0715	3.59E-5	4.76E-6	2.93E-6	1.46E-6	4.02E-6	1.39E-5	7.32E-6	4.02E-6	1.46E-6	0.0029
Ecotoxicity water chronic	Pt	0.0139	0.00226	4.31E-6	9.6E-6	1.27E-6	7.84E-7	3.92E-7	1.08E-6	0.000781	7.54E-6	1.16E-6	5.02E-5	5.3E-5
Ecotoxicity water acute	Pt	0.00679	0.00111	4.31E-7	9.6E-7	1.27E-7	7.84E-8	3.92E-8	1.08E-7	0.000378	7.54E-7	1.16E-7	5.02E-6	2.56E-5
Ecotoxicity soil chronic	Pt	8.55E-14	4.78E-15	3.01E-15	1.41E-14	1.87E-15	1.15E-15	5.76E-16	1.58E-15	3.85E-15	8.11E-15	2.23E-15	8.11E-15	3.65E-17
Human toxicity air	Pt	4.23E-6	6.87E-7	6.29E-10	4.57E-10	6.06E-11	3.73E-11	1.86E-11	5.12E-11	2.32E-7	9.32E-11	5.12E-11	1.87E-11	1.58E-8
Human toxicity water	Pt	1.46E-6	4.45E-8	5.78E-8	1.01E-7	1.34E-8	8.24E-9	4.12E-9	1.13E-8	2.95E-7	1.05E-7	9.82E-9	7.38E-9	2.56E-8
Human toxicity soil	Pt	2.63E-5	4.29E-6	7.77E-12	3.64E-11	4.83E-12	2.97E-12	1.49E-12	4.09E-12	1.45E-6	2.09E-11	5.76E-12	2.09E-11	9.84E-8
Bulk waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Hazardous waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Radioactive waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Resources (all)	Pt	0	0	0	0	0	0	0	0	0	0	0	0	0

**Case 2 - results of weighting using EDIP, RT**

SimaPro 5.0 LCIA Profile Date: 7/1/2002 Time: 5:11:02 PM

Title:  
 Method: EDIP/UMIP 96 (low) / EDIP World/China  
 Value: Weighted indicator  
 Per impact category: Yes  
 Skip unused: Never  
 Relative mode: Non

Impact category	Unit	Total	Card-board	News-paper	PE	PET	PP	PS	PVC	Textile	Iron	Aluminium	Other metals	Wood
Total	Pt	2.06	0.178	0.15	0.0611	0.00657	0.00498	0.00257	0.00415	0.0149	0.016	0.0059	0.833	0.00676
Global warming (GWP 100)	Pt	0.509	0.0763	0.0595	0.0456	0.00451	0.00371	0.00193	0.0024	0.0104	0.000493	3.34E-6	1.21E-6	0.00239
Ozone depletion	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Acidification	Pt	0.00757	0.000304	6.81E-5	4.94E-5	6.55E-6	4.03E-6	2.02E-6	5.55E-6	0.000761	1.01E-5	5.55E-6	2.02E-6	9.33E-6
Eutrophication	Pt	0.00749	0.000245	6.38E-5	4.63E-5	6.14E-6	3.78E-6	1.89E-6	5.2E-6	0.000835	9.45E-6	5.2E-6	1.89E-6	7.99E-6
Photochemical smog	Pt	0.614	0.0944	0.0866	3.59E-5	4.76E-6	2.93E-6	1.46E-6	4.02E-6	1.39E-5	7.32E-6	4.02E-6	1.46E-6	0.00352
Ecotoxicity water chronic	Pt	0.828	0.00491	0.00334	0.0138	0.00183	0.00112	0.000562	0.00155	0.00237	0.0138	0.00517	0.757	0.000678
Ecotoxicity water acute	Pt	0.0882	0.00138	0.000335	0.00138	0.000183	0.000112	5.62E-5	0.000155	0.000537	0.00138	0.000517	0.0757	8.82E-5
Ecotoxicity soil chronic	Pt	1.07E-8	5.98E-10	3.77E-10	1.76E-9	2.34E-10	1.44E-10	7.2E-11	1.98E-10	4.81E-10	1.02E-9	2.79E-10	1.02E-9	4.57E-12
Human toxicity air	Pt	4.31E-6	6.92E-7	3.67E-9	1.47E-8	1.95E-9	1.2E-9	5.99E-10	1.65E-9	2.36E-7	8.28E-9	2.3E-9	8.21E-9	1.58E-8
Human toxicity water	Pt	0.00214	2.12E-5	1.69E-5	0.000252	3.34E-5	2.06E-5	1.03E-5	2.83E-5	2.32E-5	0.000257	0.000191	0.000906	6.64E-5
Human toxicity soil	Pt	5.38E-5	5.83E-6	9.72E-7	4.55E-6	6.03E-7	3.71E-7	1.86E-7	5.11E-7	2.69E-6	2.62E-6	7.2E-7	2.62E-6	1.1E-7
Bulk waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Hazardous waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Radioactive waste	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Slags/ashes	Pt	x	x	x	x	x	x	x	x	x	x	x	x	x
Resources (all)	Pt	0	0	0	0	0	0	0	0	0	0	0	0	0

Nordtest project nr. 1537-01

**Guidelines for the use of LCA in the waste  
management sector**

**APPENDIX 3**

Summary of Norwegian case studies



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# 1 Treatment of residual municipal waste from Bærum kommune

## 1.1 Introduction

Reference: Bente Pretlove and Anne Stine G. Estensen, 1999: *Bærum Kommune - livsløpsanalyse for behandling av husholdningsavfall*. Report nr. 99-3126. Det Norske Veritas AS, Høvik, Norway.

Bærum is a municipality in south Norway with approximately 100.000 inhabitants. When the study was made, all household waste from Bærum municipality was incinerated in Fredrikstad, a municipality about 120 km away. In order to assess environmental effects of future waste treatment possibilities, Det Norske Veritas (DNV) made a LCA study for the municipality. Three alternatives of waste collection and treatment are assessed and compared based on the principles and framework of the ISO 14040 standard.

## 1.2 Goal

The goal of the study is to compare treatment alternatives for residual municipal waste from Bærum. The waste to be treated is household waste after separation of paper, cardboard, glass, metal, garden waste and hazardous waste. The treatment alternatives are:

**Alternative 1:** Collection of all household waste and incineration.

**Alternative 2:** Collection of all household waste and mechanical separation into an organic and an inorganic fraction. The organic fraction is composted or treated with anaerobic digestion and the inorganic fraction is incinerated or landfilled.

**Alternative 3:** Separation at source into organic and inorganic fractions. The organic fraction is composted or treated with anaerobic digestion. The inorganic fraction is incinerated or landfilled.

For each alternative, three different alternatives for incineration, three for anaerobic digestion and three for aerobic composting are assessed.

## 1.3 Functional unit

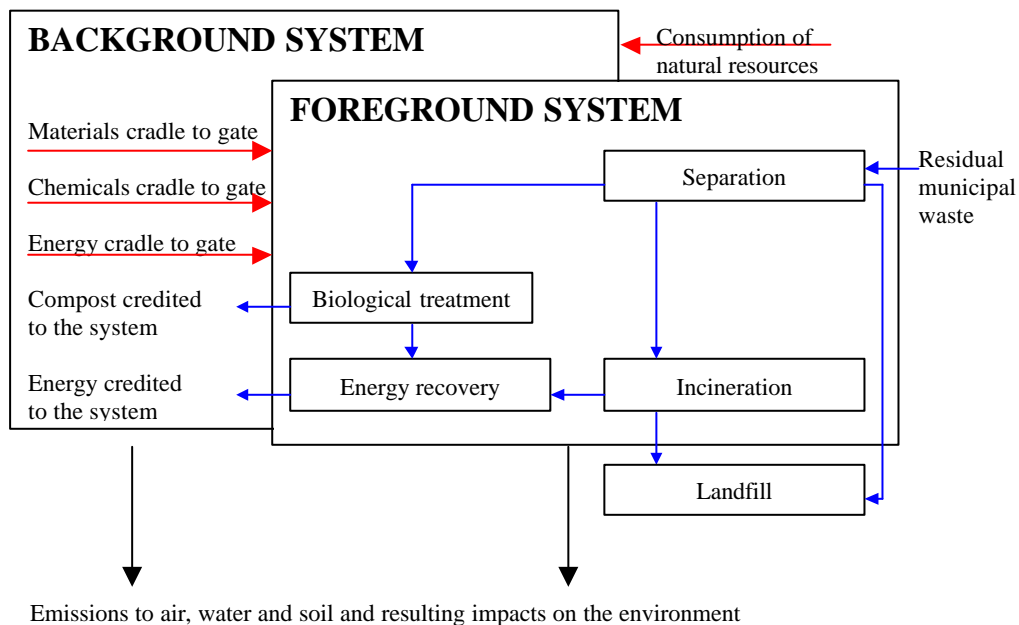
The annual residual municipal waste produced. 19500 ton produced in 1997 is used as a representative figure for average annual production. The waste had an approximate composition as shown in Table 1.

**Table 1: Composition of household waste**

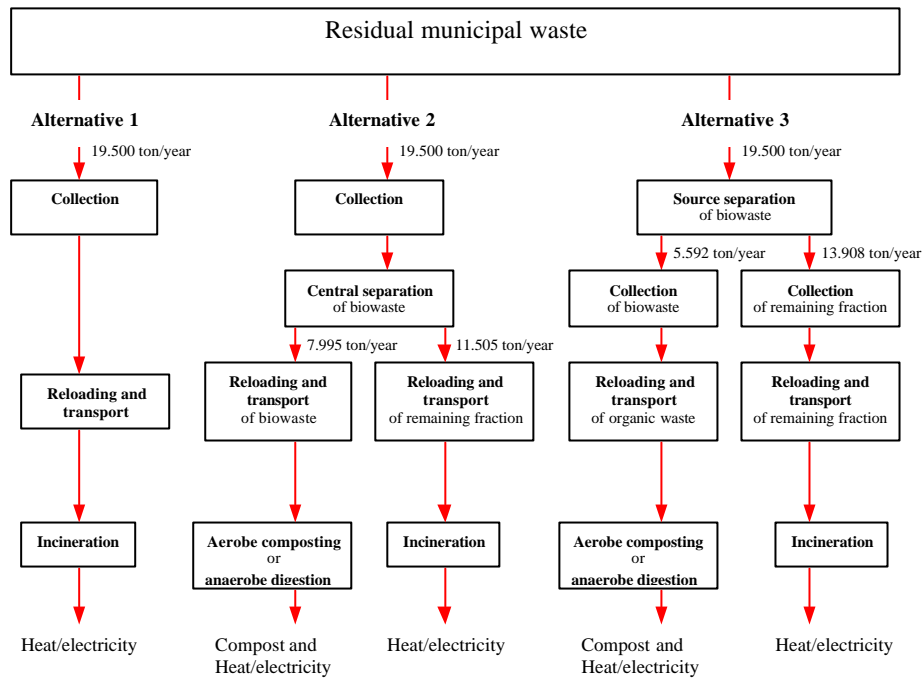
Waste fraction	Weight percentage (%)
Cardboard/carton	2,4
Paper	19,4
Glass	4,1
Plastic	13,8
Metals	2,9
Food waste	33,4
Wood	2,9
Textiles	3,4
Soil, gavel, rocks	4,6
Diapers	9,8
Drinking cartons	2,1
Hazardous waste	0,2
Other	1,2

### 1.4 System boundaries

The general boundaries of the systems to be studied are illustrated in Figure 1. The separation between foreground and background systems is made to illustrate which processes specific data that are gathered to the degree possible. The system does not include treatment of waste produced by the waste treatment methods, e.g. sludge from wastewater treatment, fly ash, and bottom ash. Figure 2 illustrates the three main alternatives in detail.



**Figure 1: General system boundaries for the Bærum kommune system**



Flytskjema Bærum.doc

**Figure 2: Illustration of waste treatment alternatives for the Bærum kommune study**

It is seen from Figure 2 that for the 2<sup>nd</sup> alternative, 41% of the waste mass is separated as biowaste (biodegradable waste). The biowaste fraction for the 3<sup>rd</sup> alternative is 29%.

## 1.5 Data collection

Transport related data are annual driving distance, capacity of vehicles, exploited capacity and fuel consumption. All data are given by the relevant local transport companies. Emissions are calculated based on emission factors for the relevant vehicle size. Cradle-to-gate emission data and combustion emission data for fuel (diesel) are taken from the database of the LCA computer program SimaPro.

Data for the incineration and biological treatment processes are gathered from plants in operation in the Nordic countries. Cradle-to-gate emission data for energy, chemical and materials consumed by these processes are taken from SimaPro. So is also environmental impact data for the compost and energy that is replaced by the produced compost and recovered energy.

## 1.6 Allocation

Multi-input allocation problems do not exist for the systems under study as long as the landfill environmental impacts are kept outside the system boundaries (see Figure 1).

Open loop allocation is relevant with respect to the following flows:

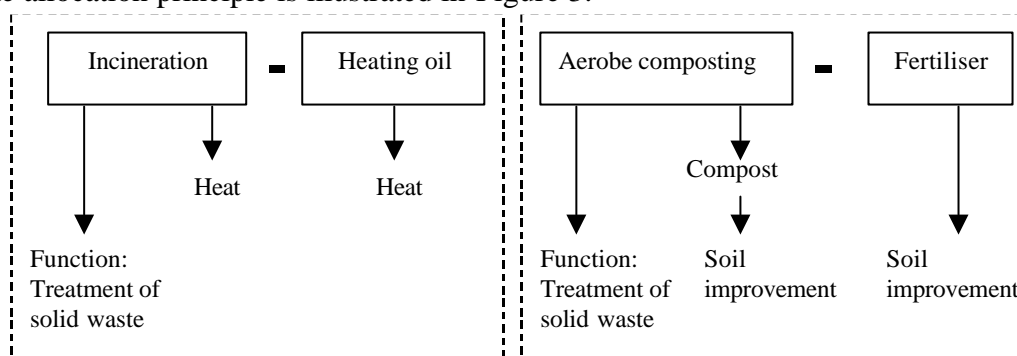
- Energy recovered in waste incineration plants.
- Energy recovered from biogas combustion.
- Compost from biological treatment.

The allocation principle applied for energy flows is to subtract from the system under study the environmental impacts associated with the replaced energy. In the reference systems this means that all recovered energy replace the production and use of oil for heating. I.e. 1 MJ recovered energy gives credit to the system equal to production and combustion of 1 MJ oil.

The allocation principle applied for compost is to subtract from the system under study the environmental impacts associated with the replaced fertiliser. Applied data are:

- Compost based on source separated biowaste: 14 kg fertiliser/ton compost
- Compost based on central separated biowaste: 8 kg fertiliser/ton compost

The allocation principle is illustrated in Figure 3.



**Figure 3: Illustration of applied allocation principle for recovered energy**

## 1.7 Results

The impact categories taken into account is waste generation, human toxicity, ecological toxicity, photochemical smog, acidification, global warming, eutrophication and energy use. All impact categories give approximately the same ranking, where alternative 1 is the best and alternative 2 the worst. The exception is waste generation when landfilling of residual waste in alternative 2 and 3 is not used, and photochemical smog when the incineration plant located the longest distance from Bærum is selected.

To enable an overall comparison, all impact categories are given the same weight. When the three alternatives are compared there is some decisive factors that influenced the result.

- If the residual waste is deposited or incinerated with energy recovery.
- If the biogas from the anaerobe composting is used as district heating plant (fossil fuel substituted) or to produce electricity (hydropower substituted).

Alternative 1 comes best out with one exception. When the biogas in alternative 3 is used as a district heating plant (substitution of heating oil), alternative 3 is better than alternative 1, given that the incineration in alternative 1 is carried out at the incineration plant with the highest emissions and lowest degree of energy recovery (one out of three Norwegian plants considered in the study).

When comparing composting to incineration, the energy utilisation of recovered energy from incineration had higher credits than use of compost as fertiliser.

Incineration gets higher credits given high energy recovery ratio, and that the recovered energy substitute fossil fuels.

Alternative 3 is better than alternative 2 when the residual waste from sorting is incinerated, while the result became opposite when the residual waste is deposited. This, given that the biogas energy potential is not utilised. When the composting alternative is chosen, incineration of the inorganic waste fraction after separation is important to maximise the credit to the system. As long as the biogas is utilised alternative 3 is the better. It is presumed that the compost of satisfactory quality is produced both in alternative 2 and 3.

## **2 Treatment of sludge from a municipal waste water treatment plant**

### **2.1 Introduction**

Reference: Bente Pretlove, 1998: *A/S Sentralrenseanlegget RA-2. Livsløpsanalyse av metoder for slambehandling*. Report nr. 98-3414. Det Norske Veritas AS. Høvik, Norway.

RA-2 is a wastewater treatment plant for 5 municipalities about 20 km north of Oslo. The wastewater treatment plant (RA-2) generates sludge, which, at the time the study was carried out, was added lime and used in the local agriculture. Due to an increasing sceptical attitude among farmers with respect to the level of pollutants in the sludge, the interest for the sludge was decreasing.

The study is carried out to investigate the environmental impacts of alternative utilisation methods.

### **2.2 Goal**

The goal of the study is to compare treatment alternatives for sludge from the sewage treatment plant. The treatment alternatives are:

**Alternative 1:** Liming of the sludge and scattering into the agriculture.

**Alternative 2:** Liming, composting and scattering into the agriculture.

**Alternative 3:** Drying to 90% DS, make pellets and scattering into agriculture.

**Alternative 4:** Drying to 34% DS and then incinerated.

**Alternative 5:** Drying to 54% DS and then incinerated.

**Alternative 6:** Drying to 90% DS and then incinerated.

Aspects that are varied are that the compost in alternative 2 is incinerated in stead of scattered into agriculture, pellets in alternative 3 are incinerated in stead of scattered into agriculture.

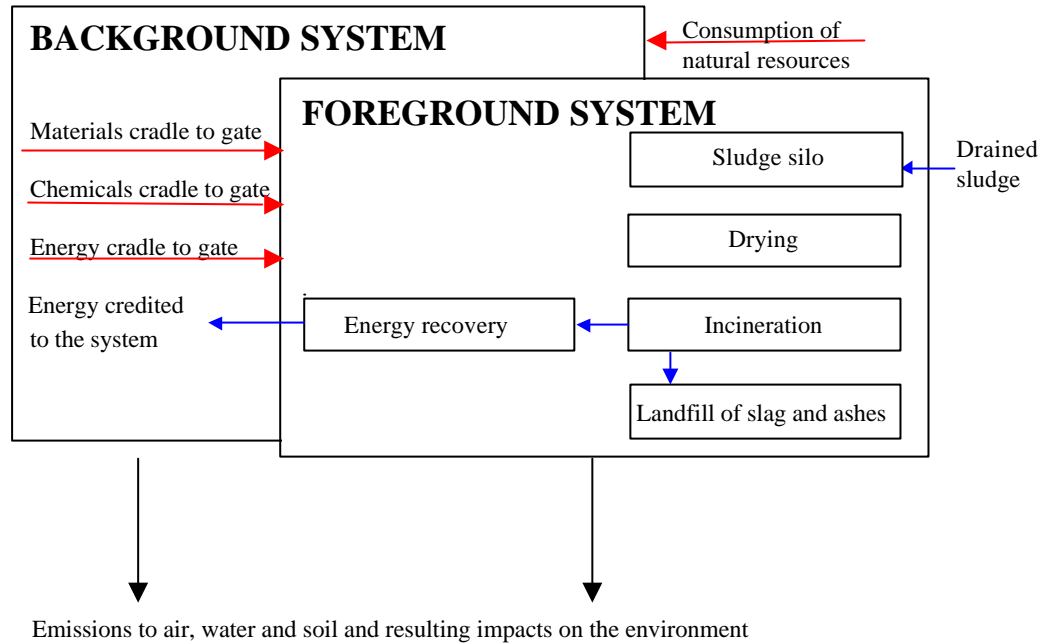
In the drying process use of oil and use of non-exploited landfill gas is considered as energy sources.

### **2.3 Functional unit**

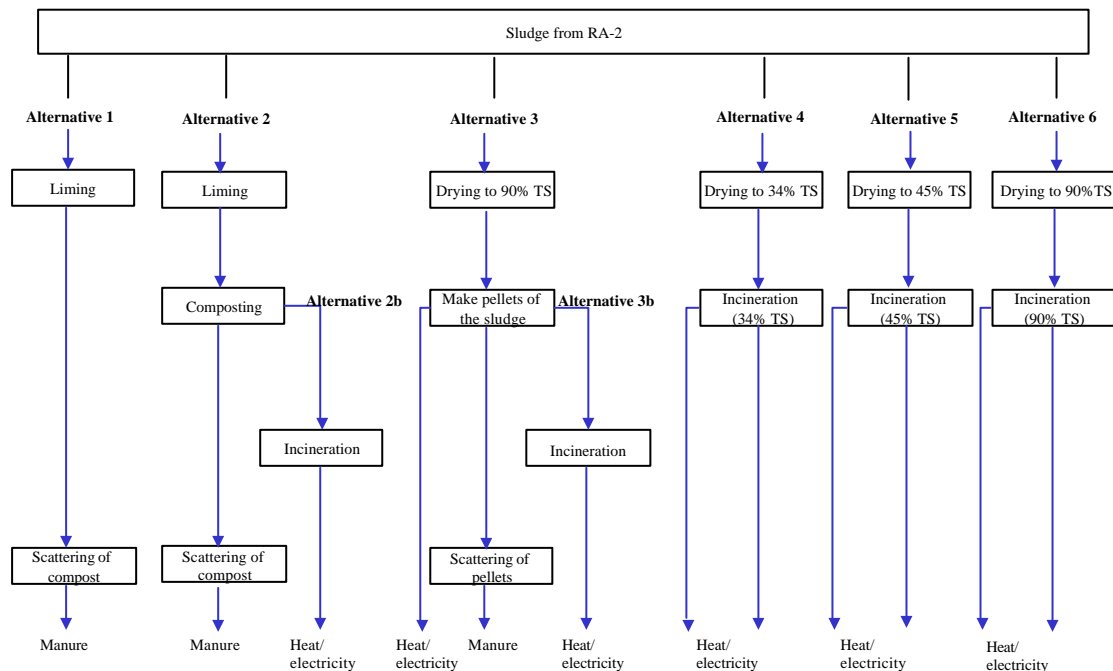
The functional unit the annual amount of sludge produced from RA-2. 17220 ton in 1997 is used as a representative figure.

## 2.4 System boundaries

The general boundaries of the systems to be studied are illustrated in Figure 4. . The separation between foreground and background systems is made to illustrate which processes specific data are gather to the degree possible. Figure 5 illustrates the main alternatives in detail.



**Figure 4: General system boundaries for the RA-2 system**



**Figure 5: Illustration of waste treatment alternatives for the RA-2 study**

Energy recovered from incineration is assumed used for district heating and substitutes heating oil.

## **2.5 Data collection**

Process- and transportation data for limed sludge and compost is gathered from the experience from the RA-2 plant. Data for other processes in the foreground system are gathered from specific plants in operation in the Nordic countries.

Cradle-to-gate emission data and combustion emission data for fuel are taken from the database of the LCA computer program SimaPro. So is also cradle-to-gate emission data for energy, chemical and materials consumed by these processes are taken from SimaPro. The same counts for environmental impact data for the compost and energy that is replaced by the produced exploitable sludge and recovered energy.

## **2.6 Allocation**

The same allocation principles are applied as in the study presented in section 1.6. For sludge products substituting artificial fertilisers the following data are applied:

- Limed sludge: 22 kg fertiliser per ton (dry substance).
- Composted sludge: 18 kg fertiliser per ton (dry substance).
- Sludge pellets: 55 kg fertiliser per ton (dry substance).

## **2.7 Results**

The same impact categories are assessed as those given in section 1.7. The results are given based on weighting of impact categories that gives equal weight to all categories. The following main findings are given:

- Incinerated dried sludge 90% TS gave most positive result from the LCA.
- Composted and limed sludge gave most impact on the environment
- The three others are comparable solutions.
- For alternative 1 the lime production gave the largest contribution to the total environmental impacts.
- For alternative 2 the lime production and the composting process gave the largest contribution to the total environmental impacts.
- For the incineration alternatives the contribution from the incineration process itself is low. Production of additives contributes more.

# **3 Treatment of municipal waste and sludge**

## **3.1 Introduction**

Reference: Bente Pretlove, 2000: Skedsmo kommune - livsløpsanalyse av behandlingsalternativer for restavfall og avløpsslam i Skedsmo. Report nr. 2000-3395. Det Norske Veritas AS, Høvik, Norway

Skedsmo is a municipality close to Oslo in Norway with approximately 39.000 inhabitants. In relation to the future waste treatment possibilities the municipality found it interesting to know the environmental effect of different treatment possibilities. Det Norske Veritas was therefore asked to do a LCA study for the overall treatment of household waste, industrial waste and sludge produced in the



municipality. Four alternatives of waste collection and treatment are compared and the assessment based on the principles and framework of the ISO 14040 standard.

### **3.2 Goal**

The goal of the study is to compare treatment alternatives for sludge and waste from Skedsmo kommune. Sludge is a residual product from the central waste treatment plant RA-2 (see section 2). The waste means the fraction of municipal waste after the existing source separation of cardboard, paper, glass, metal, garden waste and hazardous waste. It is presumed the treatment for this separated waste will be equal for all alternatives.

The treatment alternatives are:

**Alternative 1:** Incineration of waste in Oslo and separate treatment of sludge (added lime and scattered in agriculture).

**Alternative 2:** Incineration of waste in a planned local incineration plant (Dyno) and separate treatment of sludge (added lime and scattered in agriculture).

**Alternative 3:** Incineration of waste and 10% of dewatered sludge (Total solids (TS) 24%) in a possible future local incineration plant (Berger-North).

**Alternative 4:** Incineration of waste and 22% dried sludge (TS 34%) in a possible future local incineration plant (Berger-North).

Energy recovery ratios are varied for incineration plants and both heating oil (heavy and light) and electricity (hydropower) is used as substituted energy sources.

### **3.3 Functional unit**

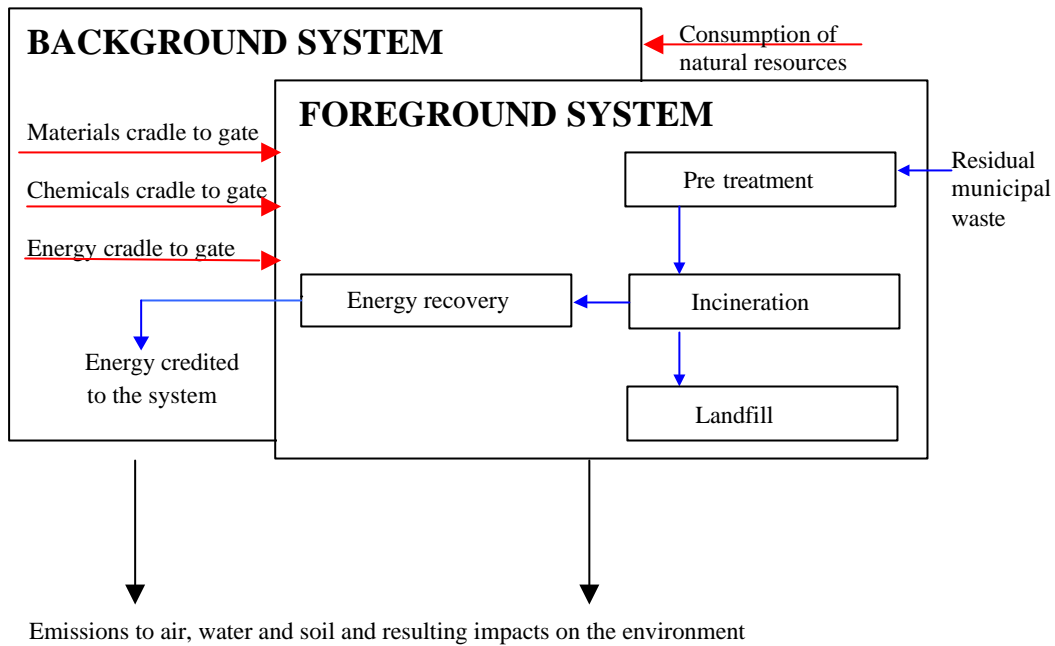
35000 ton waste and 17220 ton sludge/ year (TS 24%) was delivered in 1997. This is approximately the annual generation within the community and is applied as the functional unit.

The waste consists of 28.000 tons of household waste, 7.000 tons of combustible industrial waste.

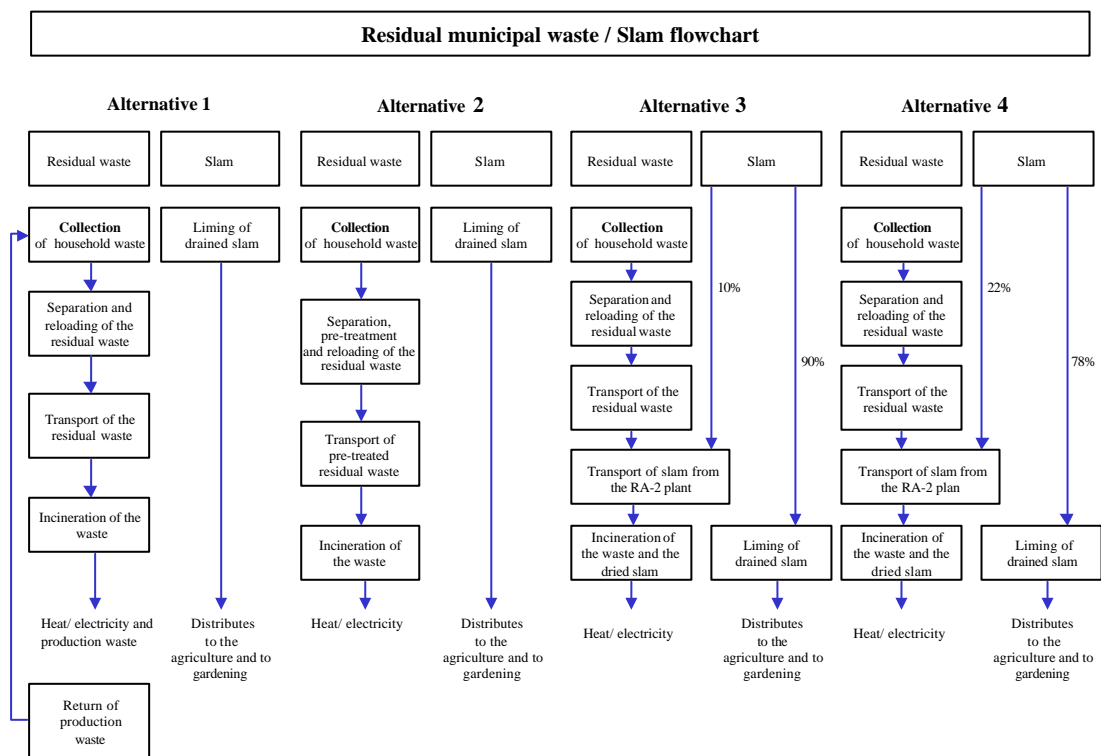
### **3.4 System boundaries**

The general boundaries of the systems to be studied are illustrated in Figure 6. The study focuses on the foreground system with respect to collection of specific data. The waste treatment alternatives that are studied and related processes are illustrated in further detail in Figure 7.

Collection or separation of waste is not part of the study.



**Figure 6: General system boundaries for the Skedsmo kommune system**



**Figure 7: Illustration of waste treatment alternatives for the Skedsmo kommune study**

### 3.5 Data collection

The following criteria are fulfilled in the data collection.

- The current situation is described with data from the actual plant, if possible.
- Planned plant get described with empirical data from similar project.
- The data must be relevant for Norwegian conditions.
- Collected data must describe a normal situation at the plant.
- Data for the foreground system will be collected particularly for this project.
- Data for the background system will be gathered from available databases.
- If the data holds extensive uncertainty, conservative methods for estimating will be used.

### 3.6 Allocation

The same allocation principles are applied as in the study presented in section 1.6. For sludge products substituting artificial fertilisers the following data are applied:

- Limed sludge: 22 kg fertiliser per ton (dry substance).

Multi-input allocation problems do not exist for the systems under study as long as the composition of waste going to landfill is not varied.

### 3.7 Results

Environmental profile consisting of contribution to seven different impact categories is made for each of the above alternatives to compare the alternatives. The categories are solid waste to be deposit, photo-oxidant formation, acidification, global warming, human and ecotoxicological impacts and eutrophication. The profiles of the alternatives are then compared for different energy utilisation efficiency of the incineration plants (60, 70 and 80%). The energy is credited to the system by substituting electricity and different combustion material used for energy production. In Alternative 1, 3 and 4 the energy from the incineration substituted light oil (n. "lett fyringsolje") and alternative 2 heavy oil (n. "tung fyringsolje"). The environmental impact categories are all given the same weight i.e. the alternatives are not compared with different weight of each environmental effect.

When the energy utilisation of the incineration plants is 80% for all alternatives, alternative 2 had the lowest profile for all the effect categories except photo-oxidant formation where alternative 4 is lowest due to shorter transport and less spreading of sludge. The result is the same when energy utilisation is 70%. With energy utilisation above 70%, the environmental profile is negative in all the effect categories and for all the alternatives due to substitution of energy from oil combustion and electricity production. However, when the energy utilisation is below 65% the global warming of alternative 4 is positive due to more sludge combusted. If the energy produced in alternative 2 substituted light oil instead of heavy oil, and energy utilisation is 80%, alternative 4 had the lowest profile in all effect categories except for global warming i.e. the ranking of the alternatives is highly affected by which oil type is substituted.

If 80% of the produced energy from the incineration plant reuses in a district heating plant, and heat compensate for the use of heavy oil the alternative 2 is the best solution. But if 80% of the energy from the incineration plant reuses in a district heating plant and the heavy oil replaces with fuel oil the alternative 4 comes best out of this evaluation.

There is also a possibility that only 60% of the heat from the incineration plant can be reused. If that is the case alternative 2 will be the best alternative irrespective of what the heavy fuel oil is replaced with.

These results are evaluated with no differentiation of the influenced factors.